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Survey on defeating of safeguards on machinery

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Abstract
Despite the risk for the safety and health of the machine operator, safeguards on machinery are regularly defeated. As a survey of the Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA) shows, this is often tolerated by managers. How this behavior affects the safety of employees, survey results, measures and available resources are discussed in this paper.

1 Introduction

If hazards emanating from machinery cannot be eliminated or sufficiently reduced by an inherently safe design, the residual risks must be mitigated by safeguards and/or the application of complimentary protective measures [1]. However, despite the associated risk, safeguards are regularly bypassed, dismantled or otherwise rendered ineffective by machine operators. In most cases, the incentive for defeating a safeguard is to optimize work processes in terms of time, precision or efficiency with the aim of improving the performance of the machine. However, the consequences of tampering are severe: occupational safety and health experts across all industries assume, that around a quarter of all work-related accidents on stationary machinery is caused by the defeating of safeguards.

A study carried out by the former Institute for Occupational Safety and Health of the German Social Accident Insurance (BGIA) and the former German Social Accident Insurance Institutions for the metalworking industry was the first to examine the causes and underlying issues related to the defeating of safeguards on machinery of the metalworking industry in Germany [2]. The study, published in 2006, showed that more than a third of all safeguards on machines of the metalworking industry were regularly or constantly bypassed. In response to the study, both the German Social Accident Insurance (DGUV) and the International Social Security Association (ISSA) set up permanent expert working groups with the aim of raising the awareness of the risks related to the defeating of safeguards and developing practical guidance for manufacturers and operators of machinery [3][4]. The issue is now increasingly being addressed in regulations and standards on national and international level ([5][6][1][7][8]). However, despite this progress, accidents due to safeguards being defeated continue to occur, and occupational safety and health experts across all industries report the problem of tampering with the safeguards on machinery to persist.

2 Current Survey

In order to obtain reliable figures on this matter, the IFA conducted a cross sector survey among occupational safety and health experts from machine operating companies [9]. Almost 850 persons participated. In a total of 16 questions, questionees were asked for their assessment of the current incidence of defeating in the company they are working for or which they supervise. The answers show that the issue still requires comprehensive prevention efforts, on the part of manufacturers, operators and occupational safety and health professionals. One detail in particular stands out: Half of the questionees stated that in their company a safeguard had already been defeated with a manager's sufferance, while only one in every six participants could clearly deny the question. Whether and how this circumstance affects the overall incidence and safety of employees will be discussed in 2.2.

2.1 Current Figures

The questionees estimate, that on average around a quarter of all machines are defeated. On 17.2% of the machines, safeguards are defeated temporarily and solely for the performance of certain tasks, with the original state of the machine being subsequently restored. On 10%, the defeating is not reversed, even though this is usually possible without any technical or timely effort.

Safeguards that present a physical barrier between the working zone and the operator, such as interlocked guards, are predominantly defeated, as these are most likely to be perceived as hindrance or obstacle in the work process. Accordingly, defeating is most likely in activities that require a manual intervention in the hazard area behind the separating guards of the machine, while the machine is still moving, or movements of the machine can still be triggered. Safeguards are usually not defeated to perform standard tasks. For this purpose, the manufacturer usually provides a functioning and balanced safety concept in which safeguards are not likely to be perceived as an obstacle. However, when it comes to undesirable or unplanned events like repeated malfunctions, the elimination of which would require shutting down the machine or the entire production chain, defeating safeguards is often seen as an effective means to avoid the workflow from being delayed. Accordingly, the main activities that – from the operator's viewpoint – require the safeguard to be bypassed or dismantled, are fault rectification (63.3%), set up and adjustment (52.1%), and repair and maintenance (51.1%).

As seen above, in more than one in every three cases that a safeguard has been defeated the action is not reversed. Such machinery presents a particularly high risk-potential, as it also endangers operators who are not aware that its safeguards were made ineffective. Consequently, work-related accidents due to defeated safeguards happen quite regularly: Half of the questionees state they have already made experiences with accidents or near accidents on machines the safeguards of which

had been defeated. 25.7% state, that there has been at least one accident related to defeated safeguards within their company, while 27.1% can report near accidents.

2.2 Management Behavior

The correlation of managers tolerating the defeating of machinery with the actual incidence shows, that a lack of or inconsistent preventive leadership behavior has severe consequences for the safety of employees. For example, in companies where the defeating of a safeguard has been tolerated by a manager in at least one case, the percentage of machines with defeated safeguards (33%) is one and a half times higher than in companies where this is not the case (22.9%). The average proportion of permanently defeated machinery (10.9%) is almost twice as high (for comparison: 5.7%). Also, the impact of manager's behavior on defeating-related accidents is significant: In companies, where defeated safeguards are tolerated by managers, the proportion of questionees who can report one or more factual accident due to a safeguard being defeated is 35.9 per cent (for comparison: 17.9 per cent).

2.3 Company Size

Another significant correlation exists between the company size and the incidence of defeating. This becomes particularly apparent when comparing small and micro-enterprises of 1 to 49 employees with large companies of over 250 employees. As the survey shows, tampering with safeguards is much more likely to be tolerated by managers in small companies than in large ones: Almost 60% of questionees from small and micro enterprises confirmed that at least in one case a manager has been aware of a safeguard being defeated, while in large companies it is been 45%. This automatically leads to a significantly higher proportion of machines being defeated permanently or temporarily (37.1% in small and micro-enterprises vs. 23.1% in large companies).

2.4 Measures Against Defeating

Preventing safeguards from being defeated is the responsibility of both the manufacturer and the operator of the machine. While for manufacturers, technical measures planned and implemented during the design and construction of the machine predominate, organizational and personal measures and the company's general safety climate are the primary means for the operator to prevent the defeating of safeguards in the long term.

However, in some cases, an eventual retrofit of the machine may become unavoidable. Despite the need, operators often hesitate to implement the necessary technical measures. The reason for this hesitation lies within European legislation, since a substantially modified machine must be regarded as a new product, making it a subject to the full conformity assessment procedure of the machinery directive [5] or the machinery regulation [6] (from 2027 on). However, when a retrofit solely enhances the product safety and doesn't introduce risks, that cannot be sufficiently

reduced by already existing or fixed safeguarding, the recent regulation clarifies, that these measures are not to be regarded as substantial, making it easier for operators to implement the needed technical measures.

Best Practice – Example 1

In practice, it is sometimes small changes to the machine that can still have a great impact on the safety of the employees. An example: On flat glass processing machines, manual resharpening of diamond tools often leads to safeguards being tampered with, since the task can only be carried out with the tools moving. In a German company, employees and the occupational safety and health expert came up with an easy and safe solution, which was then tested and implemented on all glass processing machines in the company [10]. To allow for a safe performance of the work task, the whetstone was attached to a rod, which can be inserted through a finger-safe opening in the guard door. By this simple measure, the procedure can be carried out during normal operation without any additional risk, while still retaining the safety of the machine operator, eliminating the incentive to defeat the safeguard.

3 Manufacturers

In the survey, questionees were asked, what measures they believe contribute in particular to prevent the defeating of safeguards. Their responses show that measures on the part of manufacturers and operators are regarded as complementary and equally valued.

Intelligent safeguards (72.4%) rank first among the measures in the manufacturer's responsibility. Examples are plausibility checks or dynamic safety signals, which detect when a safeguard has been defeated.

Best practice – Example 2

A best practice design example for intelligent safeguarding is the camera-based assistant system for dimension saws which uses artificial intelligence to inspect camera images for the presence of human hands [11]. When a hand is detected near the saw blade, the blade is lowered beneath the worktable to prevent the operator from being injured. From this safe state, the machine can quickly be returned to operation without damage to the blade or the material, which enhances the user's acceptance and minimizes the incentive to defeat the safeguard.

Best Practice – Example 3

The usage of a safety light curtain with adjustable blanking function on a hand-operated cold press is another best practice example for intelligent safeguarding [12]: Here, the safety concept consists of a light curtain, that can be adjusted in the sensitivity of the beam distance to prevent the press from running up as soon as a hand or object larger than specified appears in the protective field. The handles of the forging tongs can remain in the protective field between the light curtains, and can be moved horizontally, vertically or at an angle without interrupting the light barrier. However, if a hand is moved into the protective field, the lift release is blocked and an injury is prevented. With the protective device staying effective without the user having to remove the forging tongs from the protective field, the safety concept presents a commendable blend of safety and usability.

Second among measures to be taken by manufacturers are safeguards that are *difficult to defeat* (53.5%). This especially refers to interlocking devices with applied supplementary measures to ISO 14119 [7], that serve to prevent them from being bypassed, e.g. by obstructing the operators access by placing in a concealed position, using actuators with high coding level to prevent the usage of substitute actuators, and preventing the disassembly by means of non-detachable fastening methods for the actuator and the actuation system.
Ergonomic safeguards that are easier to operate are ranked third among measures to be taken by manufactures (41.5%). According to the initially mentioned study carried out by the former Institute for Occupational Safety and Health (BGIA) and the former German Social Accident Insurance Institutions of the Metalworking Industry an ergonomically poor machine design in general and a poor safety concept in particular stand out as one of the main incentives for safeguards being defeated [2].
Reducing the *occasions for defeating* (troubleshooting, fault clearance and repair) by use of machinery with a lower maintenance overhead is also acknowledged as an effective measure for preventing defeating (29.3%). Regarding the fact, that work tasks related to the machine maintenance make up for the main occasions in which safeguards are being defeated, this measure actually cannot be ranked high enough (see 2.1).

Operators

According to the questionees, the most important measure for operators is a *clear commitment by management* (66.9%). As shown, the correlation of leadership sufferance of defeating with other results of the survey indicates that the attitude of managers has an immense influence on the safety-related behavior of their employees. What implies a clear leadership commitment? Ultimately, a clear commitment means proactive leadership [13], where the company management doesn't only declare safety as its highest principle, but also acts consistently according to this maxim.

An essential part is the development of a positive error culture, in which reports of critical events and other potentially safety-threatening conditions are not seen as a flaw, but as an opportunity to achieve a permanently safer condition. To facilitate a proactive communication for employees, the establishment of a reporting system is recommended, which allows employees to report anomalies, problems and complaints quickly and unbureaucratically to the responsible safety specialist and the manager. Employee participation, in which employees proactively contribute to maintaining the safety of their workplace, is an essential parameter of effective workplace accident prevention [14][15].
Also, questionees would like management to take *tougher action* in response to defeating incidents (48.8%) and address the topic more regularly in *safety instruction* (43.8%) in general and *machine briefings* (36.8%) in particular. Underestimation of risks and ignorance of hazards are a major factor, in fact, among reasons for unsafe behavior. This can be rectified only by measures for increasing safety awareness, such as dedicated instruction, training in safety, and in general by a company atmosphere that promotes safety (as shown above).

4 Stop Defeating

The frequently updated website stop-defeating.org [16] offers an extensive collection of valuable resources both for manufacturers and operators of machinery to prevent the defeating of safeguards:

(1) Cross sector best practice design examples, that highlight (non-substantial) retrofits on machinery with the aim to lower existing incentives for, obstruct or detect the defeating of safeguards
(2) Cross sector examples of accidents caused by defeated safeguards
(3) A procedure to determine the incentive for defeating safeguards
(4) Downloadable tuition modules, that can be used in safety instructions and trainings
(5) A collection of educational films dedicated to manufacturers, operators and managers
(6) A download section for further informational material and publications by the German Social Accident Insurance Institutions [17][18][19]

Future efforts towards minimizing the defeating of safeguards must increasingly focus on management behavior. Best practice examples available at stop-defeating.org must be extended to good corporate culture and describe measures that help tackle the issue on an organizational and individual level.
The website is under continuous development. To help extending the website, everybody is invited to participate, e.g. by preparing short descriptions of good machine designs or good methods, sending feedback to the website or describing

their experience regarding the issue. Interested parties are welcome to contact info@stop-defeating.org or the author of this paper.

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Materials for the new technologies related to hydrogen storage

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Abstract
In the hydrogen supply chain, hydrogen storage technologies represent one of the relevant building blocks. Research initiatives are needed to develop hybrid hydrogen storage solutions for energy communities and production districts obtained through the exploitation of complementary storage technologies such as those for cryo-adsorption, those using nanostructured metal hydrides and, for higher capacity, ammonia. Several storage technologies can be adopted depending on the scenario and service conditions. Among these, the following are worth mentioning: (i) Physical storage of Compressed hydrogen gas (CGH_2) in high-pressure tanks (up to 700 bar), (ii) Physical storage of Liquid hydrogen (LGH_2) and Cold/Cryo Compressed (cooled to -253°C, at pressures of 6-350 bar) in insulated tanks, (iii) Storage in materials: metal hydrides and other chemical compounds, liquids, ultramicroporous materials. The paper reviews hydrogen storage technologies, highlighting application fields and the different solutions' pros and cons, and regulations addressing safety in hydrogen storage. A specific focus is on hydrogen storage in metal hydrides and porous materials. In this respect, crucial aspects to be considered in the design of such storage systems are related to the materials and storage vessel and their respective interaction with hydrogen which can have a detrimental effect on service life and safety as well, depending on the chemical/physical conditions of the system and the damage mechanisms typical of the storage vessels. These aspects are objects of investigation in the NoMaH project, a national funded project concerning the development of hybrid hydrogen storage solutions for energy communities and districts. One of the NoMaH research lines is focused on materials and devices to contain physical and chemical hydrogen storage systems. The present paper reports the preliminary results of the activity carried out. A review of the main damaging mechanisms has been performed, considering the interaction between hydrogen and storage vessel (e.g. hydrogen embrittlement), which are correlated to the material characteristics and the process chemical-physical parameters, the interaction between the internal storage materials, hydrides in particular, and the storage vessel due to the features of the hydrides and to the adsorption/desorption phenomena during operation.

Moreover, a research activity on the scaling up in the production of FeTi materials is presented. The scope is to study adsorption materials and the whole system to enhance the TRL of this solution and to investigate potential scaling up of the production, targeting a massive real-scale application.

1 Introduction

H2 has the highest energy content per unit mass (120 MJ/kg H_2), but its volumetric energy density is quite low owing to its extremely low density at ordinary temperature and pressure conditions. [1] For this reason, achieving efficient storage, in both mobile and stationary applications is crucial to address the H_2 economy and is one of the principal research topics. Regarding stationary applications, the greatest technical barriers are represented by inadequate materials and the availability of few standards, contrary to mobile systems that are well-defined by the U.S. Department of Energy. Different storage techniques have been developed: gas compression (cGH_2), liquefaction (lH_2), cryo-compressed (CcH_2), liquid (LSMs), and solid-state materials (SSMs), which involve the H_2 interaction with the bulk (Chemisorption—Chem) or the surface (Physisorption—Phys) of materials.

Recently, LSMs and SSMs have been considered as good options considering storage capacity, despite they present low temperatures for Phys, high desorption temperature for Chem, complex kinetics and thermodynamics of the processes.

Among SSMs, metal hydrides (MHs) represent a set of materials which promise to meet the targets for H_2 storage. MHs can store larger quantities of H_2 than other SSMs, at lower pressures than cGH_2 and higher temperatures than lH_2. So, MH storage has been identified as a safer and more space-efficient option for several applications. The main drawbacks of MHs are related to mechanical effects on the tanks, the slow kinetics during H_2 absorption-desorption, and the thermal management of the processes.

The paper presents a review of H_2 storage technologies highlighting the pros and cons of the different solutions. A specific focus is given to H_2 storage in MHs, with particular attention to the main damaging mechanisms. Moreover, preliminary results of research activities carried out in NoMaH, a national funded project, on a storage system based on TiFe materials are presented.

2 H_2 storage methods

Current hydrogen storage methods are divided into physical (cGH_2, lH_2, CcH_2) and Material-based H_2 storage (SSMs and LSMs), each with pros and cons.

The cGH_2, the most popular storage solution for both stationary and mobile applications, offers high rates of H_2 filling and release, but the compression of H_2 to a high pressure consumes about 10% of the lower heating value of H_2 which affects the overall economics of the process. H_2 is stored in cylindrical vessels classified into four types depending on the materials they are made of. Vessel materials must be able to resist H_2 diffusion and the H_2 embrittlement (HE) caused by H_2 interaction. To date, most cylinders are made in austenitic stainless steel, Cu or Al alloys, which are

largely immune to H_2 effects at ambient temperatures. However, vessel geometry must be accurately considered, because the wall thickness and the outer diameter ratio increase with increasing pressure, as does the volumetric storage density, resulting in a reduction of the gravimetric density and an increase in the weight of the container.

lH_2 is a well-established technology allowing to storage more H_2 than cGH_2, but it requires even higher energy expenditure for liquefaction of the gas at -250°C and the insulation of the vessel, necessary to avoid the boiling of H_2. The lost energy content is estimated as 40% in contrast to 10% of energy lost for cGH_2 [1].

The CcH_2 combines the properties of cGH_2 and lH_2 systems to minimize the boil-off rate and maintain a high energy density. The CcH_2 use insulated tanks that can accept cryogenic temperatures as lH_2, and high pressure (at least 300 bar) as cGH_2. The limitations are the energy density by volume, the cost of pressure vessels (high as the vessel requires composite which composed 75% of the vessel cost) and the production rate of H_2 (high because of the intensive energy consumed for compressing and liquefaction of H_2). [1] [2]

In LSM systems, H_2 is stored by chemically bonding with H_2-lean molecules and it is released by going through catalytic dehydrogenation. They are attractive because they can be managed easily in ambient conditions, the storing and release processes are carbon-free, and the carrier liquid is not consumed and can be used repeatedly. The main drawbacks are the requirement for different catalysts, high operating temperatures, and high costs.

About SSMs, different types have been proposed as new H_2 storage systems, including metal-organic frameworks (MOFs), zeolites, metal hydrides (MHs), polymers and carbon-based materials. [3] Depending on the type of H_2-material interaction, the storage method is defined as Phys, when the interaction depends on physical forces between H_2 and the material surface, such as in the case of MOF or carbon-based materials, or Chem when there are chemical forces between H_2 and material such as in the case of MHs. The main advantages of the Phys process are high energy efficiency, fast adsorption/desorption cycles, low H_2 binding energy and low cost of the materials. On the other hand, the issues are the low gravimetric and volumetric H_2 density, cryogenic temperatures (typically -196°C) and high pressures due to weak Van der-Waals forces involved (4–10 kJ*mol-1), which limit its commercial development. As of today, Phys technologies are far from being widely used since all experiments have been conducted at a small-scale level and the performance criteria (like volumetric/gravimetric H_2 density, pressure and temperature) are not satisfactory.

In Chem, H_2 molecules are split into atoms and integrated with the chemical structure of the material and among all materials, MHs are the most famous. Unlike Phys, Chem has stronger binding energy (50–100 kJ*mol-1) and allows to absorb of a larger amount of gas but it is not a reversible process and requires high temperatures to release the absorbed gas. So, lowering the cost, weight, and operating temperature, enhancing the charge-discharge kinetics and controlling the formation of unwanted gases during desorption are the main remaining challenges facing chemical sorption materials.

In general, SSM-based storage is safer, less expensive and with lower energy consumption. The drawback of these systems is represented by the necessity of a suitable heat management system, which requires several design considerations for the cylinder and the entire storage system.
In conclusion, there is not an optimal solution for H_2 storage, this must be carefully designed and selected to address specific applications depending on geometry characteristics, working conditions, storage equipment, technical performances, costs, and safety requirements.
In literature, several papers compare the technical characteristics of the different storage methods, [4] [5] in terms of gravimetric and volumetric capacity and operating conditions. The latter, in addition to influencing the storage capacity, can have a significant impact on the container and the entire storage system. As cited, the container for cGH_2 must be able to withstand high pressures while the one for lH_2 must be able to operate at low temperatures, both must be able to withstand cyclic loads. In the case of storage in SSMs and LSMs, things get complicated due to the material used, which can involve thermal, corrosion and mechanical issues. So, H_2 container materials and their interaction with H_2 are critical issues to ensure reliability and safety, so their characterization is essential to evaluate the H_2 effect on them under specific conditions.

3 Legislation for safety of hydrogen vessels

Italy has developed its own regulatory framework for hydrogen to support the transition towards clean energy since 2016, the year in which hydrogen was recognized as a renewable energy source through Legislative Decree no. 257, which implemented EU Directive 2014/94/EU. The National Integrated Plan for Energy and Climate to 2030 (PNIEC) includes objectives to increase the production and use of hydrogen, particularly in transport. Italy's National Recovery and Resilience Plan (PNRRP) has allocated significant funds for hydrogen projects, including the development of Hydrogen Valleys and the Important Project of Common European Interest (IPCEI) Hydrogen 4.
With the decree of 24 February 2023, n. 13 "Urgent provisions for the implementation of the National Recovery and Resilience Plan (PNRR) and the National Investment Plan complementary to the PNRR (PNC), as well as for the implementation of cohesion policies and the common agricultural policy" the "Central Committee for the technical safety of the energy transition and for the management of risks related to climate change" was established as a consultative and proactive technical body regarding technical safety issues concerning systems and plants powered by hydrogen.
As regards the rules for the safe management of hydrogen, reference must be made to the Decree of the President of the Republic n.151/2011 containing the regulations relating to authorizations for fire prevention and to the Ministerial Decree of 7 July 2023 "Technical rule for fire prevention for the identification of methodologies for risk analysis and fire safety measures to be adopted for the design, construction and operation of hydrogen production plants through electrolysis and related storage systems". This latest decree defines homogeneous requirements on the national territory to encourage the diffusion and use of alternative fuels on the national

territory, in line with the strategic objectives established by the National Recovery and Resilience Plan. The provisions contained in the decree may also be applied, subject to risk assessment, to gaseous hydrogen production and storage activities other than those defined in the technical regulation.

4 Metal Hydride H_2 storage

MHs storage is considered promising for both mobile and stationary storage, especially in terms of safety since they require lower operating parameters. Despite this, currently, many of these materials are still under study and few have been verified for scaling up to "industrial" systems, highlighting how this can substantially influence the performance of powders and tanks. Jensen et al. [6] have shown that when scaling up MHs, it is necessary to consider the possible changes in performance, the production technique, thermal phenomena due to the production process, the composition of the alloy and the geometry and filling state of the tanks. The technique chosen for material preparation plays an important role. Although ball milling is the most widely used synthetic route for MHs on a small scale, induction melting represents an appreciated technique for preparing MHs at kilogram scales. One technique for improving the performance of a hydride is to add specific elements to the alloy, which is efficient at the laboratory scale, but at the industrial scale, some materials have shown reduced absorption. So, each composition must be carefully tested both at the laboratory and large scale. Besides it is important to consider the geometry and filling state of the tanks which influence the thermodynamic and mechanical properties of the MHs. Hydride tends to undergo volume changes during the absorption-desorption phases, resulting in a reduction in particle size that tends to self-densify in some spaces, leading to lower capacity and high stresses, as well as deformations of the tank wall with consequent safety issues. Therefore, it is necessary to build and test different tank geometries to optimize the storage system and improve the long-term cycling properties. Finally, it has been shown that the thermal management of large-scale tank systems has a significant impact on the kinetics, where an increase in the thermal conductivity of the system significantly improves the system kinetics. An important role is played by how MHs are filled in the tank. Here, both experiments and simulations have indicated that by compressing MHs, both thermal heat transfer and thermal conductivity are substantially increased, improving H_2 filling and release times, as well as the capacity of storage systems. So, MHs can be one of the essential players in future H_2 storage systems, provided that their scale-up aspects are considered.

4.1 TiFe Alloy

Among MHs, TiFe offers the advantage of operating at temperatures below 100°C and pressures around 50 bar H_2. Furthermore, the high H_2 storage capacity, related to the composition and presence of secondary phases, the non-toxicity and the cost competitiveness make this alloy a potential candidate for energy storage applications. [7] TiFe alloys have been produced using several techniques, but the melting methods are those that allow the production of an optimum alloy in terms of H_2 storage capacity. [8] The main disadvantage of TiFe is the hard treatment required

after synthesis to promote the first absorption of H_2, called "activation". The role of activation is to break down the native oxide layer and powder particles promoting the creation of new fresh surfaces. The first description of a TiFe activation process was reported by Reilly et al. [9] which performed a sequence of absorption (up to 65 bar) and desorption (vacuum) cycles at both elevated (400–450°C) and room temperatures. However, the activation occurring at high temperatures up to 400 °C is the key problem limiting the practical use of TiFe-based systems. Since then, many efforts have been made to improve the activation in TiFe by modifying the Ti/Fe ratios, which influence activation parameters beyond storage capabilities; using partial replacement of the TiFe building blocks with a third transition metal, which however can lead to a loss of H_2 storage capacity; subjecting the alloy to mechanical treatments that modify the microstructure of the TiFe generating new unreacted TiFe surfaces.

4.2 H_2 & Material Interactions

H_2 interaction with materials is a crucial aspect in the analysis of all storage systems. H_2, due to its small size, can be easily absorbed and/or diffused into materials leading to a degradation of the mechanical properties of the material, resulting in unwanted H_2 losses up to structural failures. So, the correct choice of suitable materials for the different components is the first aspect to consider in designing a safe H_2 storage system. For SSM storage systems, two types of interactions must be considered: between H_2 and the tank material and between the SSMs and the tank.

Literature shows different types of vessels for H_2 storage, and the most widespread are those of Type I, entirely metallic tanks for which it is essential to understand the interactions of H_2 with metallic surfaces. [10] Four types of H_2 damage can occur for metallic materials, among these, HE is the most common. It is caused by atomic H_2 diffusing through the metal structure, concentrating at points where the local stress is higher and, once a critical stress is reached, it leads to the formation of cracks, which cause the loss of structural integrity. HE was discovered in 1875 by W. Johnson [11] and to date, a full understanding of the details of the mechanism has not yet been achieved. After analyzing numerous failures of metal components in H_2-containing environments, it was possible to establish that HE occurs when three conditions are met: the presence of H_2; the sensitivity of the material to H_2; and the presence of an applied stress. The source of H_2 can be gaseous or H_2 ions (aqueous environments). Most metals are sensitive to H_2, including steels and cast irons. Stress can be applied due to internal gas pressure in a vessel, or residual, for example, due to cold working or due to residual stress from welding. Consequently, to eliminate or reduce the risk of HE in a component, at least one of the three components should be removed. HE is also related to other factors: environmental (the method of H_2 introduction, the pressure and temperature of the H_2); mechanical (the type of applied stress and its characteristics) and some aspects of the materials themselves (the composition, the specific microstructure of the material and structural characteristics of metals). In practical application, H_2 tanks are also subjected to loading/unloading cycles and thus are directly subjected to the cyclic loading of both high pressure and temperature. Therefore, the fatigue performance of the tank materials is important. Several works have shown the results of fatigue tests on steels

used for H_2 tanks and have revealed that the growth rate of fatigue cracks in the material increases with increasing H_2 pressure and decreasing loading rate, presumably because there is enough time for H_2 to diffuse and concentrate at the crack tip. [12] In conclusion, the materials for H_2 tanks must be carefully chosen and the dimensions precisely designed, also according to specific standards [13] [14] [15]. Regarding the SSMs–tank interaction, the tanks must be able to confine H_2 and also handle conditions and effects related to the storage process in SSMs. In the case of MHs, the container must be able to manage the effects related to the exothermicity (or endothermicity) of the hydriting (or dehydration) reaction [16]. In addition, the phenomenon of breathing or swelling/shrinkage must be considered in the design, that is, the hydride respiration which consists of the swelling and shrinkage of the MH during the absorption and desorption of H_2. This phenomenon arises from the change between the non-hydrated and hydrated form of the material, which is accompanied by an increase in volume from the non-hydrated phase to the hydrated one, characterized by different values of the volume of the crystalline lattice. Some authors have evaluated the variation of the crystalline volume on different MHs, [17] [18] and Ulate-Kolitsky et al. have estimated a 21% increase in volume for a TiFe sample [19]. Charlas et al. [20] have highlighted how the increase in volume on the microscopic scale corresponds to an increase in volume on the macroscopic scale, related to the temperature variation, the sign of an ongoing adsorption-desorption process. The study has linked these volume variations with the structural transformations of the crystal lattice induced by the hydride reaction, but also with the rearrangement of the powder grains in the hydride. Indeed, the change in the powder volume can be separated into two parts: a cyclic change in volume during each H_2 adsorption/desorption cycle and a reduction in the powder volume from one cycle to the other, which involves an intergranular rearrangement in the volume occupied by the powder. Galvis et al. [18] have come to similar conclusions and linked such volume changes to the mechanisms of particle rearrangement and decrepitation. Such fragmentation of MH particles causes agglomeration, leading to an increase in mechanical stresses in the hydride bed and on the tank surface. This phenomenon is much less studied than the thermal problem but becomes important when it is necessary to preserve the mechanical integrity of the storage tank. The mechanical integrity of containers was highlighted by Lynch at the beginning of the 1980s, during an experimental study on the charging rates of cylindrical containers filled with LaNi, where a tube, originally having an external diameter of 2.22 cm, increased its diameter of 0.30 cm after about 17 hydriding cycles. [21] Subsequently, few studies have aimed to measure this mechanical stress and showed its strength, linked to a variation of about 10-30% of the crystalline structure of the MHs. Gillia [17], analyzing these works have highlighted that: stress increases with the increasing number of cycles and with the increasing of the slenderness ratio and packing fraction; for vertical containers, stress is higher at the bottom of the containers, probably due to the segregation of particles that fall downwards and create a higher packing density at the bottom; stresses appear to influence the kinetics of absorption-desorption and the H_2 storage capacity, but it is not clear the mechanism. The problem of MH swelling is also considered in the UNI ISO 16111 standard which

considers it in addition to the design stress for the sizing of the container.

5 NoMaH - Research activity and preliminary results

NoMaH project is focused on the fundamental research to develop hybrid hydrogen storage solutions for energy communities and production districts obtained through the exploitation of complementary storage technologies such as those for cryo-adsorption, those using nanostructured metal hydrides and, for higher capacity, ammonia.

The project aims to fill the gap between existing technologies for hydrogen storage and the real need for its effective diffusion for applications in energy communities that currently use high-pressure or low temperature.

In this framework one of the research lines is focused on “Materials and devices for the containment of physical and chemical hydrogen storage systems" dealing with both the

scaling up in the production of solid materials for hydrogen storage (i.e. FeTi alloy materials) and the design of a vessel suitable to contain the materials that will be verified through specifically set up functionality test. In the present paper, preliminary results about the production of FeTi alloy materials at pilot scale level are presented

5.1 FeTi sample preparation and characterization

Starting from raw elements inserted into the graphite crucible of an induction melting system, two ingots, named BZ1518 and BZ1519, of about 500 g of FeTi were prepared with a composition of TiFe0.90. The obtained samples were subjected to SEM-EDS analysis to evaluate the morphology and the chemical composition. Phase structure of the samples was examined through X-ray powder diffraction (XRD) patterns measured on a Siemens D500 RX diffractometer, using Co-Kα radiation (λ = 1.7903 Å), in a 2θ range of 10°–105° at room temperature. Finally, the samples were ground to reduce the samples dimensions since it has been reported in literature that reducing the size of FeTi powders can improve their H_2 uptake rate. The milled samples were then subjected to small-scale H_2 absorption measurements by an f-PcT volumetric apparatus after the activation process. The samples were activated with two different procedures: the first was activated at 50 bar and 200°C for 24h, while the second was activated at 35 bar and 150°C for 24 h.

5.2 Results and discussion

The chemical analysis confirms the composition of the BZ1519, while the BZ1518 shows a slight prevalence of Fe, in both samples there is a low amount of carbon, indicating that there was almost no contamination by the crucible.

Fig. 1 shows the SEM micrographs of the samples, where the grey background is indicated as the TiFe alloy matrix, the darker areas can be associated with areas with a prevalence of Ti, while the light grey areas can be attributed to areas with a prevalence of Fe. The EDS maps at the different points of the BZ1518 sample confirm, excluding the points with a prevalence of one of the two elements, the average

composition that was reported by the chemical analyses, with a slight prevalence of Fe.

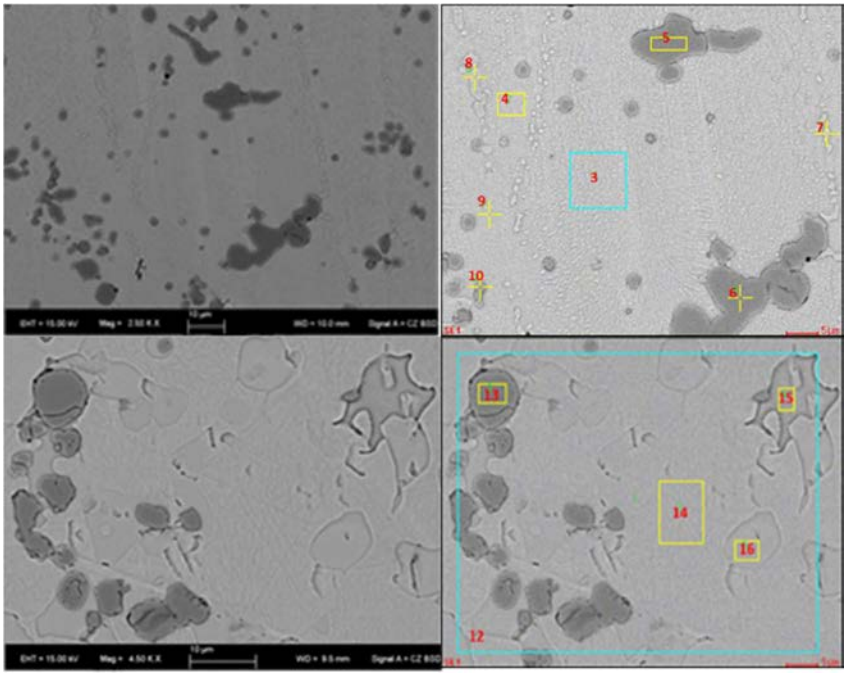

Fig. 1 - Up) SEM -EDS image of BZ1518; Down) SEM-EDS Image of BZ1519

The prevalence of Fe within the intermetallic matrix is confirmed by the XRD analyses (Fig. *2* Left), which shows the XRD spectrum of the sample. The main diffraction peaks are found to be TiFe (87.2%), while the minor low-intensity peaks are attributed to the TiFe2 phase (12.8%). The small shoulder on the right side of the main TiFe peak is a TiFe2 peak, which corresponds to the light grey areas of the micrographs.

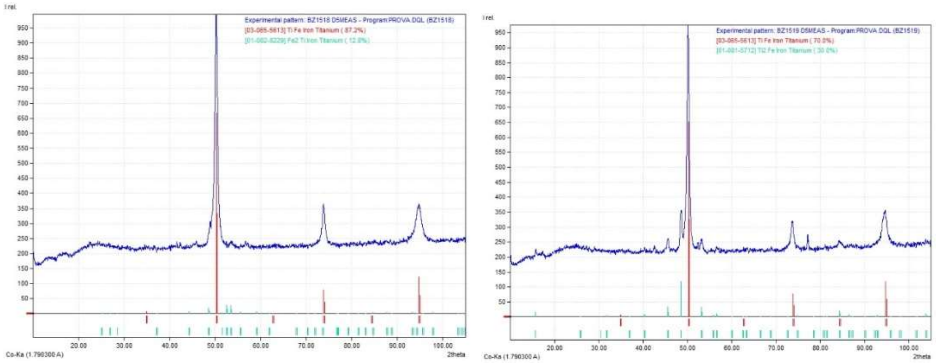

Fig. 2 - Left) XRD spectrum of BZ1518; Right) XRD spectrum of BZ1519

Similarly, the SEM micrographs of the BZ1519 sample show a consistent background of the TiFe alloy, and some darker and lighter areas with a prevalence of Ti and Fe respectively. The EDS mappings show a different composition from the BZ1518 sample with a prevalence of Ti. Also, in this case, the XRD analysis confirms what was

shown by the SEM-EDS analyses. The prevalence of Ti inside the intermetallic matrix is confirmed by the XRD analyses. The main diffraction peaks are found to be TiFe (70%), while the minor low-intensity peaks to the right and left of the main peak are attributed to the Ti2Fe phase (30%). The small peak on the left side of the main TiFe peak is a Ti2Fe peak, which corresponds to the dark grey areas of the micrographs.
To have a preliminary small-scale estimation of the H_2 storage capacity of the samples, H_2 adsorption/desorption measurements were performed.
The preliminary tests showed that the sample BZ1518 displayed a maximum absorption of 0.53 wt%, which is about one-third of the value reported in the literature, while the value is twice for the sample BZ1519. This difference can be attributed to the difference in grain size of the two samples.
In conclusion, the work shows that a critical point for the H_2 economy development is the selection of the suitable storage method for a specific application, the vessel materials compatibility with gas and the SSMs used to store H_2. Besides, the work highlights that the scale-up of SSMs is a process yet to be investigated.

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A novel representation of the Seveso III Directive to manage dangerous substances in modern industrial plants

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Abstract

The industrial use of dangerous substances represents a significant concern in the safety domain, because it has the potential to cause accidents with severe consequences for both humans and the environment. The prevention of these accidents is further complicated by the intricate nature of modern industrial processes, which involve a diverse range of technological and social factors. Hence, the 2012/18/EU Directive – best known as the Seveso III Directive – applies in the EU territory establishing obligations and responsibilities for the operators of industrial plants where dangerous substances are used, handled, produced, and/or stored. The Directive aims to prevent major accidents and mitigate their impacts, by putting into action a set of processes to guide and enhance the plants' safety management practices (e.g., the organization of inspections, the development and implementation of a Major-Accident Prevention Policy). Nevertheless, the ever-evolving interactions among technological, human, and organizational elements in such critical settings may lower the effectiveness of these practices. This research has the objective of investigating this problem: it aims to translate the Directive into a Knowledge Graph (KG) starting from a Safety Control Structure (SCS) of the system. The SCS offers a hierarchical representation of the system following the principles of systems theory and control theory. However, SCSs end up being really complicated and unusable representations when depicting large and complex systems. To this purpose, a KG is constructed to ease the use of SCS, eventually enabling enhanced possibilities for its analysis. This research provides a novel representation of the Directive that captures the evolving socio-technical complexity of modern industrial plants. The presented solution may serve as a reference for the

various stakeholders involved in the safety management of industrial establishments dealing with dangerous substances.

1 Introduction

The industrial landscape has undergone a radical transformation with the advent of Industry 5.0 and the continuous advancement of human-centered technology. This transformation has resulted in industrial systems being recognized as complex Socio-Technical Systems (STSs): they comprise interrelated and interdependent social and technological elements that influence each other to develop their operations and to chase their objectives. However, this transformation has triggered an increased level of complexity, giving rise to novel challenges relating to social factors, technical elements, and environmental contexts (Dekker et al., 2011; Elmaraghy et al., 2012). These new industrial innovations introduce emerging risks in the STSs, where hazardous substances may be used, handled, produced, and/or stored.

In such a context, safety management plays a fundamental role, since unexpected events could have devastating consequences for people and organization, as well as for the surrounding environment. Indeed, this concern guided the draft of the 2012/18/EU Directive by European Union (2012), also called the Seveso III Directive. The Directive reiterates the concept of potential major accident hazards and highlights the obligation to implement an effective Safety Management System (SMS) to manage an industrial establishment involving hazardous substances. It also emphasizes the importance of the flow of information within and among organizations, as well as the communication of such information to the competent authorities and the establishment operator, thereby enhancing safety and transparency in the industrial processes within European Union (EU) territories.

Nevertheless, the intricate and evolving nature of the industrial establishments and their associated processes present an ongoing challenge in the management of such facilities and the mitigation of unforeseen occurrences. This is due to the inherent complexity of identifying and evaluating all potential sources of risk (Leveson, 2004, 2011a).

Novel safety approaches based on system theory, such as the System-Theoretic Accident Model and Process (STAMP), have been developed to deal with this need. STAMP allows modeling a complex STS as a set of interrelated system agents held in a state of dynamic equilibrium characterized by an exchange of information through the definition of control actions and feedback loops. A STAMP model highlights the mutual dependencies of each system agent, which jointly shapes the interactions among social factors (e.g., human behavior, organizational structure), technical elements, and the tasks associated with operating industrial processes. Therefore, the STAMP underlies the synergies among the system agents, rather than focusing on the immediate triggers. Then, the model allows the adoption of a proactive approach to safety risk assessment and

management. This entails the implementation of preventive measures prior to an unforeseen event and the reduction of its potential consequences (Leveson, 2011b).
For this purpose, this research aims to translate the Directive into a SCS, further converted in a KG. The STAMP principles have been applied to construct the SCS to explore the synergies among the stakeholders involved in the Directive, while Knowledge Graph (KG) allows supporting the analysis of large and complex SCSs. This joint analysis will focus on the processes for managing inspections within an industrial establishment, as described in the Directive.
The remainder of the paper is organized as follows. Section 2 summarizes the methodology comprises of STAMP and KG. The results obtained are presented and discussed in Section 3. Concluding remarks are provided in the final section.

2 Methodology

The methodology of this paper integrates STAMP as a model with KG as a technique for ensuring a data-driven assessment.

2.1 System-Theoretic Accident Model and Process

STAMP is a model that investigates the interactions among agents in a system process. It is the basis of a couple of techniques, such as Causal Analysis based on System Theory (CAST) and System-Theoretic Process Analysis (STPA). In particular, CAST investigates the causes of accidents, considering them as unplanned or undesirable loss events, whereas STPA analyzes the system design to guarantee the performance of the system and prevent future unexpected events. These techniques consider an accident not only related to technological component failures, but also to external disturbances, interactions among components, and behaviors deviating from normal operating conditions (Leveson & Thomas, 2018). Therefore, the STAMP model addresses these challenges by relying on some principles in terms of safety constraints, which are rules or limits imposed by a controller (Leveson, 2004; Nakhal A et al., 2022). The model conceptualizes a control structure wherein higher levels of control oversee and regulate lower levels through control actions aimed at satisfying imposed safety constraints, thereby preventing accidents.
Fig. *1* depicts a generic SCS, highlighting the control actions, feedback loops, and relationships that underpin the safety processes within a system (Biswal, 2019; Leveson & Thomas, 2018). At the bottom level, there is the physical process that is controlled by an automated controller. The latter constitutes an intermediate agent that is further controlled by a higher controller (in the figure: human controller). The human controller functions as the primary control mechanism for the automated system, which oversees the physical process.

At the next level, the automated controller, managed by the human controller, oversees the physical process. For instance, it collects data through sensors, which feed into the control algorithm—comprising rules and commands to generate control actions based on feedback and the process model.

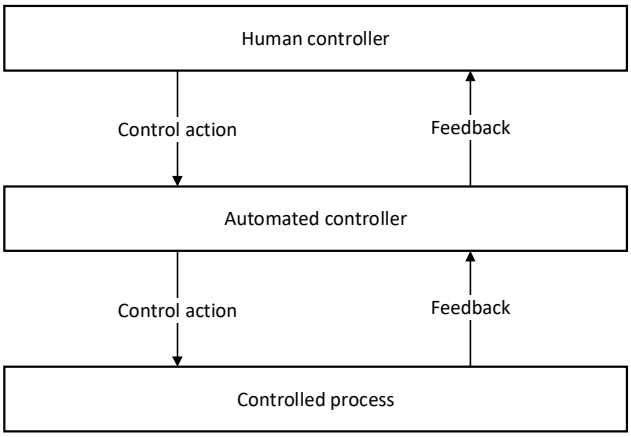

Fig. 1. Safety Control Structure (SCS) for an Operator – Automation – Controlled Process system.

The final level in the system is the technical-operational process, which is responsible for transforming process inputs into outputs. The automated controller monitors this process to prevent accidents and enhance the safety of the system.

a. Knowledge Graph

KGs are semantic networks designed to represent real-world entities and their relationships in a way that is easily understandable both to humans and machines. Typically, a KG is stored in a graph database and presented as a graph where the data is organized as interconnected entities rather than in tables (as in traditional relational databases). To enable this understanding, a KG relies on an organizing principle that allows users to interpret the underlying data in a different way. This principle is what distinguishes a KG from a simple graph, as it introduces an additional layer of metadata for contextualization. This extra layer supports processes like knowledge reasoning and knowledge discovery, and it is often based on an ontology, or in general on a characterization of knowledge. This principle is guided by the rules outlined in an ontology, which serves as a formal representation of knowledge within a specific domain, delineating a set of concepts and the relationships between them. Basen on the STAMP model, the proposed ontology translates the information contained in a SCS into a KG. The proposed ontology encompasses only the categories and their interrelations. Therefore, a representation of this ontology is depicted in **Fig.** *2*.

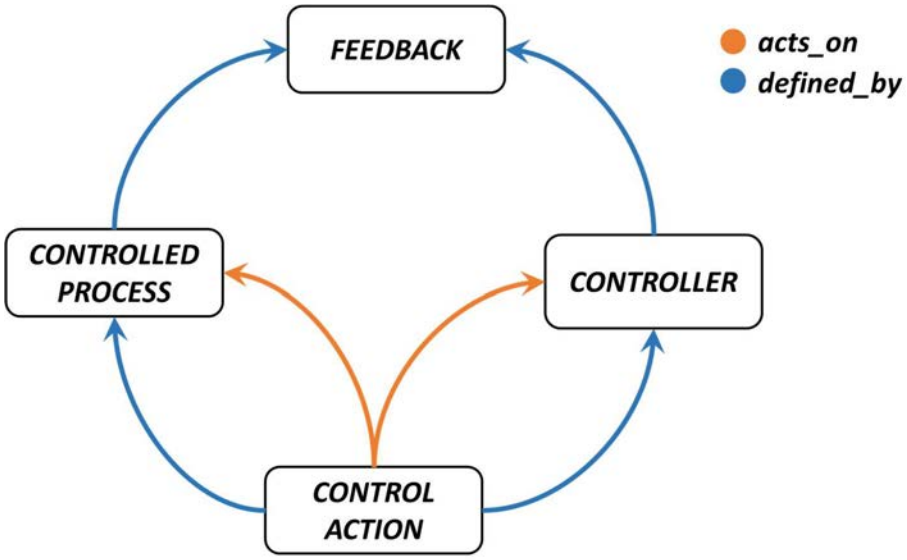

Fig. 2. Simplified version of the ontology model to transform a SCS into a KG (category labels are denoted with italic capital letters, relationship labels are reported with italic lower-case font).

Summarizing the ontology, there are four different nodes labels (i.e., controlled process, controller, control action, and feedback) in which the label controller could be defined as human or automated controller. On the other hand, the ontology defines two relationships labels: "defined by", and "acts on". **Table 1** shows the possible relationships among each label defined in the ontology.

Table 1. Ontology's labels defined by relationship

Label	Relationship	Label
Control action	acts_on	Controlled process
Control action	acts_on	Controller
Controlled process	defined_by	Feedback
Controller	defined_by	Feedback
Control action	defined_by	Controlled process
Control action	defined_by	Controller

Furthermore, the process of creating a KG involves a process of knowledge extraction, which includes labeling and classifying raw data, thus adding context. This process can handle data in any format, whether structured or unstructured. The output of the knowledge extraction process typically results in the generation of triplet files, where graph nodes are linked in pairs according to the Resource Description Framework (RDF) format, which can be easily employed and loaded to construct the actual KG.

3 Results

Following these two approaches, in this section, we introduce their application to model the Seveso Directive via STAMP and translate the obtained model into a KG.

3.1 The SCS of Seveso Directive

The Seveso Directive is a European regulation that was formulated with the intention of establishing precise processes for the management of industrial processes and the prevention of major accidents in facilities utilizing hazardous substances (European Union, 2012). A critical analysis of the Directive and its prescribed processes, the technical standards related to the safety management system for the prevention of major accidents, and examples of production processes from Seveso-sector companies, enabled the development of a preliminary version of the SCS. **Fig.** *3* depicts the interactions among agents within the SCS. This SCS is a system-theoretic representation of a chemical industrial establishment, more specifically a refinery that uses fuel oil (as a hazardous substance) in their industrial processes to satisfy the operational requirements.

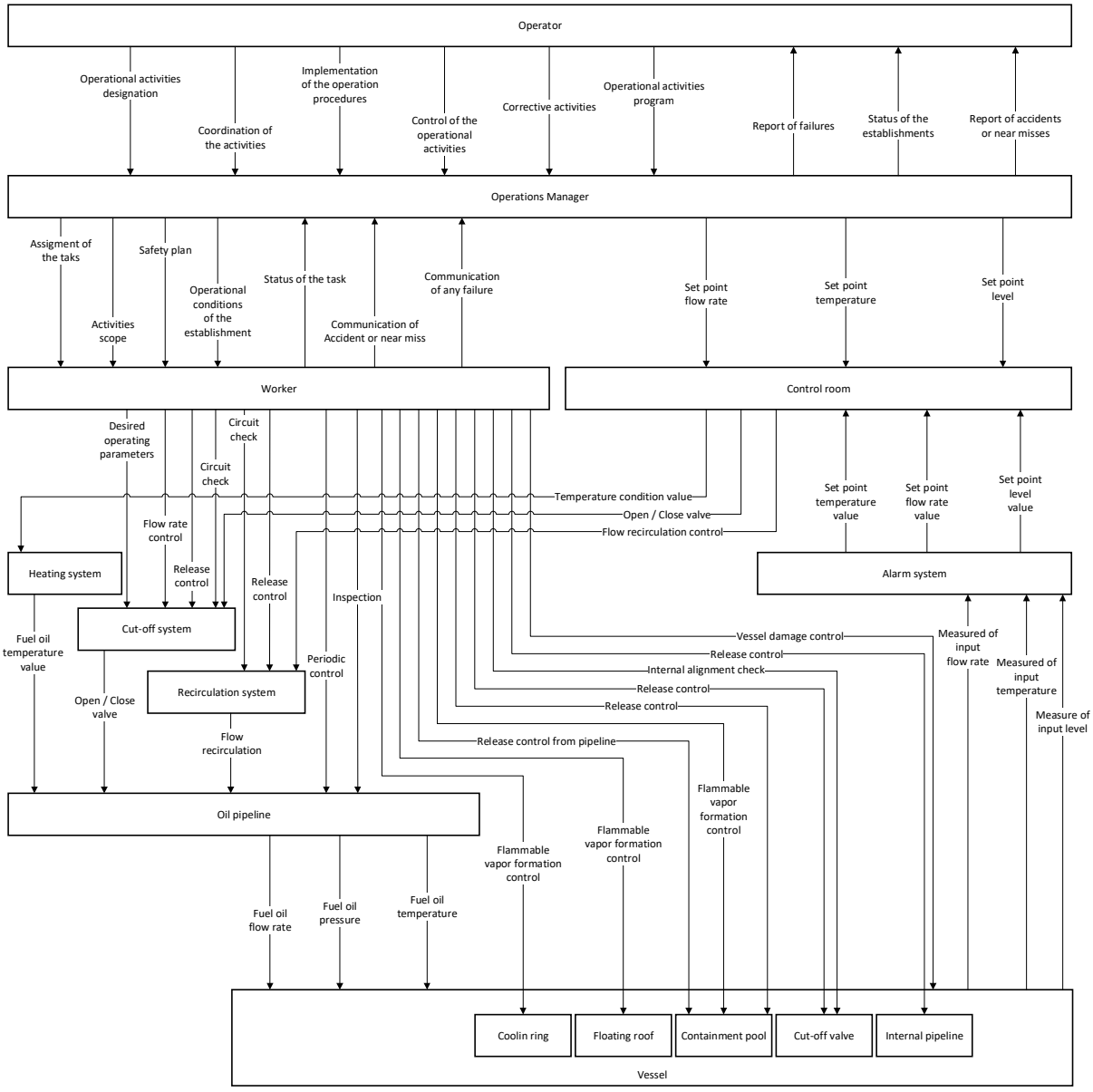

Fig. 3. SCS for the Implementation of a Safety Management System in an industrial establishment

The system agents involved include the establishment operator, operations manager, control room personnel, workers, and various physical processes, such as heating systems, cut-off systems, recirculation systems, oil pipelines, alarms, vessels, and their components. Each of these system components is depicted as a black box in **Fig.** *3*.
Such SCS offers a detailed map of the relationships existing among these stakeholders, with a particular focus on the activities specified in the Directive. The operator is responsible for the day-to-day operational functioning and safety of the industrial

processes, while the operations manager oversees the broader management and ensures compliance with safety protocols. The control room monitors operations in real-time, and coordinates responses to any anomalies. Workers directly engage in the physical processes, implementing safety procedures and maintaining equipment safe and operating. The physical processes, including heating, cut-off, and recirculation systems, as well as oil pipelines and alarms, play crucial roles in maintaining the operational integrity and safety of the establishment by delivering the desired services to satisfy the customer requirements. These mutual interactions are crucial for understanding how safety is managed and maintained within industrial environments. By detailing the relationships among these stakeholders, the model provides insights into the socio-technical complexity of safety management and highlights areas for potential improvements and interventions.

3.2 The knowledge graph of Seveso Directive

Knowledge extraction was performed through the development of a Python script capable of automatizing the labeling of elements within the SCS. The script took as input an .XML file, easily obtainable by software to design schematic representations (e.g., Microsoft Visio), to then return a .CSV file containing the triplets in RDF format. The obtained .CSV file was used to load data within a graph database. The Neo4j software was used to store the KG, being worldwide recognized as a flagship software for graph database management. An import algorithm was developed in Neo4j to punctually store each element being retrieved and labeled through the knowledge extraction procedure within the graph database.

By applying these procedures, a KG referred to the SCS in **Fig.** *3* was obtained and reported in **Fig.** *4*, in which: (i) orange nodes represent feedback, (ii) blue nodes represent control actions, (iii) yellow nodes represent controllers, and (iv) purple nodes represent controlled process. Note that a node could have more than one label as it can be both controlled process or controller simultaneously, and this information is stored in the graph. However, in **Fig.** *4*, such nodes are colored yellow, thus emphasizing their role as controllers. The resulting KG counts 53 nodes and 172 relationships.

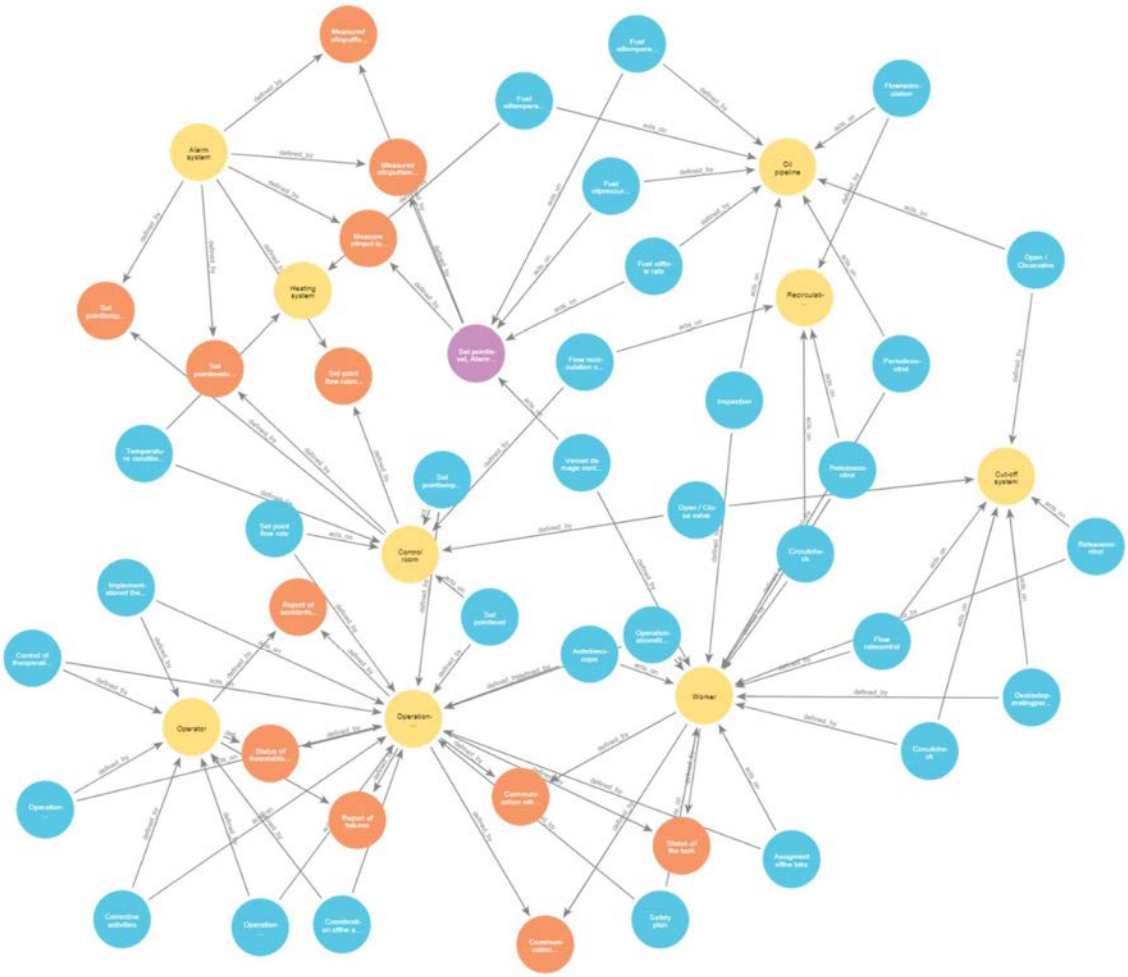

Fig. 4. KG of the SCS from Figure 2. Orange nodes represent feedback, blue nodes represent control actions, yellow nodes represent controllers (or joint controller and controlled process nodes), and purple nodes represent controlled process.

The KG obtained from the SCS enables a set of new possibilities for its analysis. Firstly, the graph database could be used to easily extract contextual information. For example, one could ask how many agents in the system have control responsibilities, or, conversely, how many of them are somehow controlled. Furthermore, one could be interested in how much feedback is exchanged or whether control actions are imposed. Therefore, by analyzing the information within the graph, the results have been presented in **Table 2** by highlighting the presence of much more control actions than feedback, exchanged by an even number of agents. In addition, it could support answering to different questions, e.g., *"Is this feedback enough to ensure this high number of controls?"*. The enhanced accessibility to such type of information could foster reasoning of this type among system's managers.

Table 2. Number of nodes per label.

Label	Number of nodes
Controlled process	9
Controller	9
Feedback	12
Control action	31

Beyond simple descriptive analytics, the graph structure permits the user to leverage on a wide range of mathematical tools from Network Theory, which tells information about what the KG is modeling. One could rely on topological metrics to acquire additional knowledge about the system. For example, the betweenness centrality metric could be computed, defined as it follows:

$$B_k = \frac{\sigma_{ij}(k)}{\sigma_{ij}}$$

where B_k represents the betweenness value of the k-th node, $\sigma_{ij}(k)$ is the number of shortest paths in which the k-th node is involved, and σ_{ij} is the total number of shortest paths.

Note that the shortest path represents the smallest number of links to connect one node to another, while in the presented use case it could represent the shortest number of information to be exchanged between two agents to let them communicate. The betweenness metric could be used to spot critical agents by means of their importance within the flow of information taking place in the system. The higher the betweenness of the node, the higher its importance because it is involved in more exchanges of information. The reliability of such agents must be ensured, as their role in the system could deeply affect the whole system's functioning. To this end, **Fig.** *5* shows the KG represented in **Fig.** *4* but adding the information about betweenness centrality. Indeed, the darker and bigger the node, the higher its betweenness centrality value. For the sake of clarity, the top five nodes with higher betweenness centrality are reported in **Table 3**. It is possible to notice how the operations manager plays a crucial role within the system, while also the responsibilities of the worker are quite high. An interesting result is represented by the fact that the alarm system has higher betweenness centrality than the control room, suggesting an overreliance on the apparatus.

Table 3. Top five nodes with respect to their betweenness centrality.

Agent	Betweenness centrality	
Operations manager	31.5	
Worker	16.5	
Alarm system	12	
Control room	9	
Operator	4.5	

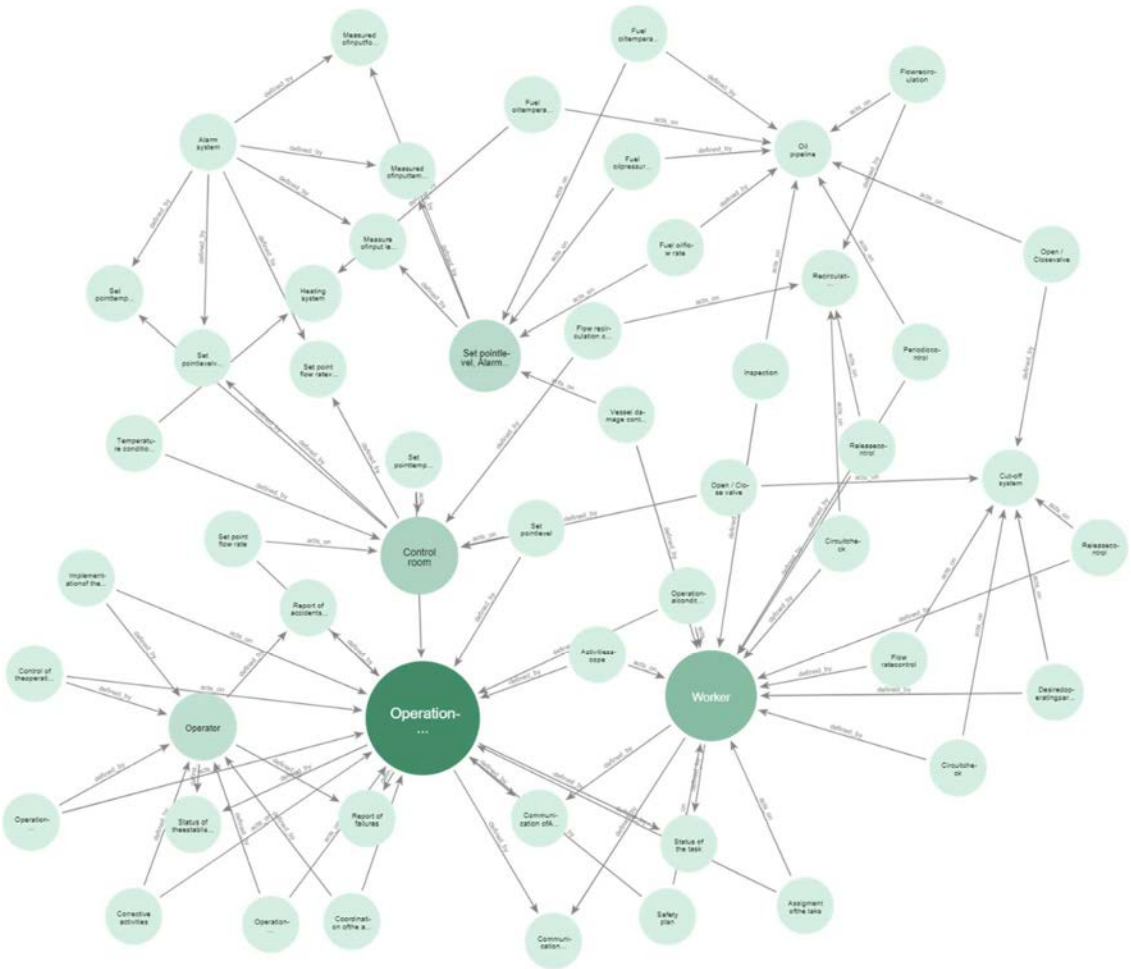

Fig. 5. KG of the SCS from Figure 2 enriched with the calculation of the betweenness centrality for each node. Bigger and darker nodes have higher betweenness centrality.

4 Discussion

The obtained representation of the KGs (**Figure 4** and **Figure 5**) highlight the presence of many nodes and relationships, which are derived and extracted from the pieces of

information within the SCS. In this regard, these graphs provide a powerful tool to understand the mutual dependencies among the agents involved in the processes related to the Seveso Directive. However, this integrated analysis based on a systemic perspective could be further refined to better capture the complexity of an industrial establishments and its safety management system.
Indeed, the actual case study can be roughly approximated as a Topping Refinery, i.e., a simple crude oil distillation unit. Starting from its obtained SCS, additional agents and interactions can be incorporated in order to build a comprehensive SCS of the Directive able to model more complex industrial processes, including those performed in a Hydroskimming Oil Refinery or a Cracking Oil Refinery (that incorporates all the pieces of equipment existing in Topping and Hydroskimming refineries). For instance, "Reformer furnace", "Desulfurization unit", "Hydrotreating unit", and "Cracking furnace" represent examples of additional equipment that could be investigated and introduced. The introduction of specific agents and relationships in the SCS requires the development of an enhanced ontology able to represent the knowledge characterizing the different Seveso industrial establishments. Then, this could allow for the creation of a comprehensive KG that further supports systemic analyses of the establishment. For this purpose, an enhanced ontology should comprise the entities and attributes outlined below.

- The substances should be properly characterized in terms of pressure, temperature, chemical composition, and needed leak checks. They can connect the processes units mentioned above with "Worker", "Control Room", and "Alarm System", i.e., system agents already modeled in the SCS and KG. It represents a valuable insight into both the examination of designed and actual control actions and feedback loops among process units within an industrial establishment, and the identification of measures to assure its safe operation.
- Damage mechanisms and integrity control techniques should be emphasized. Indeed, damage mechanisms (e.g., creep, corrosion, and hydrogen cracking) may severely impact pressure vessels and piping, leading to catastrophic failures if specific conditions are not early detected or properly monitored. Accordingly, the current generic activities (e.g., "Inspection", "Periodic Control") in the SCS could be detailed and employed to make the relationships among the "Worker" agent and the above process units explicit and clear. This will permit an increase in the level of detail of the assessment process that could be effectively used for the development and improvement of the plant's safety management system.
- Specific monitoring activities of some process parameters should be also highlighted. For instance, the continuous monitoring of the vessel temperature values allows early detecting possible overheating and local hot spots (that trigger creep damage). Similarly, monitoring the chemical composition of process fluids

helps to identify deviations at an early stage, preventing potential undesired side reactions and material degradation effects (e.g., corrosion, hydrogen cracking).

5 Conclusions

This research focuses on a novel representation of the Directive for supporting operators of modern industrial plants in the management of dangerous substances. In particular, it provides a systematic perspective of the Directive, by highlighting the upper-level stakeholders involved in the safety management processes and their interactions. The complexity raised from the developed SCS was managed thanks to its translation into a KG. This allowed for in-depth (quantitative) analyses on critical agents and paths, paving the way for navigating the evolving socio-technical complexity of industrial systems. It also represents a further step towards the development of proactive risk assessment processes and safety management systems within modern industrial plants.

Although the use case reported in this paper regards a chemical establishment, the approach remains general and applicable to various types of Seveso facilities. In this regard, future research activities could be devoted to the development of a comprehensive ontology for a detailed translation of the SCS into a KG. Additionally, the application of the approach in different systems and organizations could be leveraged on for analyzing the results from the safety management perspective. Finally, the adoption of further systemic techniques could provide other relevant stimuli for the system analysis.

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Technologies and procedures for the removal of asbestos-cement pipes

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Abstract
Asbestos-containing materials have been widely used worldwide. In the past, considerable attention has been given to their removal, primarily focusing on the ACMs (Asbestos Containing Materials) with higher risk and/or greater abundance. Although they constitute significant percentages of the total (in Italy about 10% of the pipes for drinking water are made of asbestos cement) there are still no specific standardized technologies and procedures for the removal of buried asbestos cement pipes, used for water, sewage and gas networks, among others. This work will describe new technologies and procedures for their safe removal. Specifically, the paper will outline a systematic set of procedures and guidelines to follow for the safe removal/maintenance of buried asbestos cement pipes to ensure maximum protection for workers and the surrounding living environment. Such products are not inherently a primary source of health hazard when buried, intact, and still in place, as the main health risk associated with asbestos is inhalation. However, they can pose a risk during removal or maintenance activities that involve their partial or total exposure to ambient air, with the potential release of asbestos fibers into the atmosphere. This is particularly true when the external surface of the product is degraded, even partially, leading to the disintegration of the cement matrix and the release of fibers, or when the pipes are cut and/or handled incorrectly. As a result, hazardous situations may arise for workers and/or for the surrounding living environment if specific prevention and safety measures are not adopted. This paper will present safety guidelines to enhance worker protection. Additionally, an overview concerning issues and preliminary evidences from a monitoring campaign conducted during the removal of asbestos cement pipes using trenchless technologies will be provided to highlight the advantages and associated risks of this technique, that still require validation for ACM due to the lack of specific regulations.

1 Introduction

Asbestos refers to a group of naturally occurring fibrous minerals, including serpentine and amphibole varieties, valued historically for their tensile strength, poor

heat conduction, and chemical resistance [1]. These properties have made asbestos widely used for insulation, fire resistance, soundproofing, and tensile strength. Although its extraction has declined, global reserves remain substantial (Table 1) [2].

	Mine production		**Reserves**
	2022	**2023**	
United States	-	-	Small
Brazil	197.100	190.000	11.000.000
China	130.000	200.000	18.000.000
Kazakhstan	250.100	260.000	Large
Russia	750.000	630.000	110.000.000
World total (rounded)	**1.330.000**	**1.300.000**	**Large**

Table 1 - World Mine Asbestos Production and Reserves (Mineral Commodity Summaries 2024 [2]).

In 2006, the International Labour Organization (ILO) and World Health Organization (WHO) declared that the most efficient way to eliminate asbestos-related diseases is to stop using all types of asbestos and ACMs (Asbestos Containing Materials). Nevertheless, current use varies widely. Some countries enforce strict regulations or outright bans, while others continue to use asbestos in varying amounts. The European Commission banned the marketing and use of asbestos products in 2005 and, in March 2014, launched the Program “free the EU from asbestos” aimed at eradicating asbestos from the EU. The European Economic and Social Committee (EESC) supported this effort with an opinion adopted in January 2015 [3].

Controlling asbestos exposure remains difficult, particularly with in situ materials, which may deteriorate and pose health risks during construction, maintenance, or demolition. As a result, the European Community encouraged measures to prepare action plans for the safe removal of all asbestos and ACMs by 2028.

Asbestos cement pipes, widely used in water, sewage, and gas networks, still make up a significant portion of infrastructure in many countries—about 10% of drinking water pipes in Italy, for example. While these buried pipes typically pose minimal health risks when intact, their removal or maintenance can release hazardous asbestos fibers into the air, particularly if the external surface is degraded or improper handling occurs. Despite these risks, standardized technologies and procedures for the safe removal of buried asbestos cement pipes remain underdeveloped.

This work outlines a systematic set of procedures and guidelines designed to protect workers and the surrounding environment during these activities, conducted through ‘traditional’ or trenchless technics. It also explores innovative trenchless technologies and the use of fiberglass pipes as a safer alternative for replacing or rehabilitating asbestos cement pipelines. Trenchless technologies are a range of techniques that

do not use open trenches for pipe replacement, but instead insert a new pipe inside the existing pipe. This can be either a 'sleeve' lining, using the resistance of the existing pipe, or a new smaller diameter pipe with its own resistance (Hose Lining, Cured in Places Pipes - CIPP).
The Hose Lining involves the use of glass fiber mixed with resin and cured by UV lamps as a safer alternative for replacing or rehabilitating asbestos cement pipelines. By minimising disruption and ensuring rigorous safety measures, these modern approaches aim to address the challenges posed by ageing asbestos cement infrastructure while reducing the associated health risks.
However, even with these techniques, there are still risks to the health and safety of operators, particularly during the opening and management of intermediate shafts (necessary for the passage of the new pipeline), the flushing of the section to be rehabilitated and the cleaning phases.

2 Materials and Methods

After digging and identifying the material type, the primary maintenance action involves sealing the pipe with a stainless steel repair clamp to stop leaks. Italian law mandates notifying the Local Public Health Service (LPHS) Authority for maintenance activities with potential asbestos exposure.
Once the presence of asbestos is confirmed, actions must be taken to remove the pipe in compliance with the general safety principles. If asbestos is confirmed, the pipe must be removed following safety regulations. Remediation companies must develop a plan detailing asbestos risks and measures to ensure worker safety and environmental protection. Urgent cases, defined as serious threats to public health, natural disasters, or emergencies, require compliance with regulations and may involve inspections by the Control Body.
When multiple companies operate on the site, each must submit its Work Plan (WP) for their subcontracted tasks, demonstrating proper intervention planning [4], [5].
More technical details concerning removal of underground asbestos-cement pipes or parts thereof, which refer to “programmable” and “emergency” activities, are outlined in detail in the chapters below. Planned activities, including network renewal, renovation, or functional upgrades, are scheduled and may use open-cut or trenchless methods. In contrast, emergency operations address structural collapses, leaks, or network disruptions requiring immediate response, twenty-four hours a day, all year round.
The majority of “emergency” activities are performed in urban areas and require small road work sites to be opened for limited periods, with the aim of avoiding disruption to traffic. They require smooth organisation, with the rapid set-up and disassembly of worksites and the initiation and completion of work in as short a time as possible for the service to be restored [3], [5]. In this case it’s not possible to adopt trenchless technologies.

3 Results

a. Open-Cut Pipeline Installation (OCPI) - Programmable and Emergency activities

The removal of asbestos-containing materials (ACMs), such as asbestos-cement pipes, demands a meticulously planned and regulated approach to safeguard workers, the public, and the environment. This process involves the integration of precise identification, characterization, and handling protocols to mitigate the risks associated with asbestos exposure. Whether through programmed activities or emergency interventions, ensuring safety requires a combination of thorough preliminary analysis, the use of specialized tools, and strict adherence to personal protective equipment (PPE) requirements. By prioritizing health and environmental protection, these removal protocols are designed to minimize the release of asbestos fibers and ensure compliance with legal and safety standards.

3.1.1 Technical operating instructions

Managing asbestos-cement pipes requires a comprehensive approach for both programmable and emergency operations. For programmable activities, detailed preparation involves gathering information on utility networks, assessing pipe uniformity, and conducting preliminary analyses using field instruments like infrared spectrometers and XRD devices. Material samples may be taken for laboratory confirmation, and if asbestos-containing materials (ACMs) are identified, further surveys might be needed. Workers must use asbestos-specific PPE, and the Employer Manager (EM) must submit a work plan (WP) to the Local Public Health Service (LPHS), detailing safety and environmental measures.

In emergencies, precise planning is often unfeasible. If asbestos-cement pipes are unexpectedly encountered during repairs, immediate actions include covering the area with polyethylene sheets and notifying the EM to implement safety protocols. Emergency interventions require flexible adaptation to unforeseen challenges while adhering to general safety guidelines.

In both cases, the goal is to handle asbestos-cement pipes safely, minimizing health risks and environmental impact while complying with regulations.

First, secure the work area by surrounding it with fencing to prevent unauthorized access. For emergency operations, deploy removable devices such as signs, cones, and tape quickly to secure the site due to time constraints. Efforts should focus on reducing the stages and time frame for removing pipes and excavation materials to a minimum, thereby limiting exposure risks. Reinforcements such as formwork or pillars must be used to stabilize trench walls, depending on the depth and soil conditions.

Surface milling and asphalt layer removal are essential to locate the pipe's position and depth using a probe. Excavation should proceed to within 15 cm of the pipe’s upper surface, allowing for lateral trench deepening as necessary (Fig. 1). The parts of the pipe affected by separation, breakage, or cutting should be uncovered using

hand tools, such as shovels or spades, to avoid scraping the outer surface of the asbestos-cement pipe.

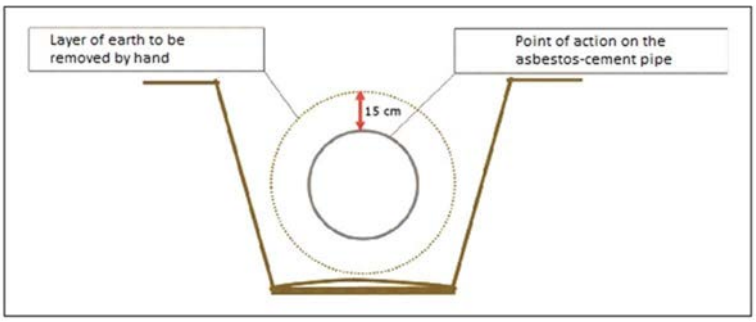

Fig. 1 - Uncovering an asbestos-cement water pipe

To prevent soil contamination, lay a high-density polyethylene or geotextile sheet at least 0.15 mm thick under the pipe, especially in areas of separation, breakage, or cutting. Avoid dispersing water on impermeable surfaces, instead collecting and disposing of it as hazardous waste (EWL code 16.10.01*). In emergencies involving mud or water, use pumps to remove liquid and dispose of it appropriately (Fig. 2).

Fig. 2 - Channelling the water at the bottom of the dig and discharging into the sewer

Thorough cleaning of the pipe, particularly around breaks or cutting points, is critical. If feasible, isolate the section to be removed without cutting or breaking, while spraying the operation area with a mist cannon during excavation to suppress airborne fibers (Fig. 3). For cutting operations, tools such as hand saws (Fig. 4), low-speed jigsaws (Fig. 5), or hand chain cutters (Fig. 6) should be used. These tools must either be integrated with aspirator using HEPA H13 filters or utilize encapsulating sprays with biodegradable Type D coatings. Collect all visible swarf, whether in powder or mud form, produced during cutting (Fig. 7). Medium or high-speed cutting tools, even with water sprays, should not be used. For emergencies, adapt cutting methods to the site-specific conditions.
When appropriate for site conditions, use the “glove-bag” method to remove pipe sections. Soil excavated within approximately 15 cm of the pipe should be treated as

hazardous waste if exposed to fiber contamination and packaged for disposal. For emergencies, the amount of soil removed may vary depending on environmental factors. During repairs, it is recommended to replace entire pipe sections (joint-to-joint) to ensure system integrity and safety (Fig. 8).

Fig. 3 - Mist cannon in the operation area.

Fig. 4 - Cutting a pipe with a hand saw (INAIL DIT).

Fig. 5 - Cutting a pipe with a low-speed petrol jigsaw.

Fig. 6 - Cutting a pipe with hand chain pipe cutters.

Fig. 7 - Residue after cutting.

Fig. 8 - Detail of the connecting joint (left); section of new pipe replacing the damaged pipe (right).

All removed pipe sections, particularly those with breaks or cutting points, should be sprayed with encapsulating liquid before being wrapped in sealed packages. These packages must be labeled with asbestos warnings, the hazardous waste code R, and the EWL code 17.06.05* (Fig. 9). Waste materials, including pipes, contaminated soil and hand saw, must be properly packaged, labeled, and transported to designated hazardous waste facilities, ideally on the same day or when a first payload is ready.

Fig. 9 - Detail of waste packaging.

In the same way, polyethylene or geotextile sheets removed from the excavation must also be sprayed with Type D encapsulating liquid and placed in sealed, labelled containers as waste (EWL code 15.02.02). Conduct a thorough visual inspection to confirm the removal of all potentially contaminated materials. Soil samples (1 kg per 20 linear meters of pipe, or 1 per 100 meters for longer sections) must be taken for asbestos analysis. Sampling plans may be adjusted based on site-specific evaluations by the LPHS, and triplicate samples must be prepared for control checks by relevant authorities. Samples must be packaged and sent to an approved laboratory for asbestos content analysis.
If emergency work extends beyond one day, ensure the excavation is covered and secured to prevent unauthorized access or environmental contamination.

3.1.2 Safety procedures, protection equipment, controls

When asbestos-cement pipes are identified, a supervisor responsible for the network or section must be appointed within 60 days. Appropriate Personal Protection Equipment (PPE) must be used according to the results of a risk assessment, including high-visibility clothing, helmets, protective glasses, and ear protection. Workers who

come into direct contact with asbestos-cement pipes must wear Category III PPE, which should be individually labelled with their names if the equipment is reusable.
All personnel using Category III PPE must receive practical training to ensure compliance with safety standards and regulations. Operators should wear non-woven, disposable bodysuits with hoods (Category 3, Type 4-5, or similar), along with gloves and waterproof safety footwear. For added protection during operations without a dedicated decontamination unit (DCU), workers are advised to use double bodysuits. Respiratory protection should include disposable P3 filter masks (FFP3) or half-face masks with P3 filters, worn under the hood to ensure proper decontamination.
For prolonged operations lasting more than three consecutive days or involving the removal of over 300 linear meters of pipe, a 4-stage DCU is recommended to ensure enhanced worker safety. However, in cases of short-term operations without a specific DCU, PPE removal must follow a strict sequence, particularly during emergency operations:

(1) Wet the outside of PPE with water.
(2) Remove the tape used to seal the gloves and footwear.
(3) Undo the velcro parts of the bodysuit (at the neck and along the zip).
(4) Remove the gloves.
(5) Open the bodysuit zip and take down the hood.
(6) Roll down the bodysuit from top to bottom and towards the outside to contain the contaminated part.
(7) Remove the feet out of the bodysuit.
(8) Place it immediately into a sealed disposable bag together with any removed tape and gloves. Transfer the sealed bag into a larger designated sack for later disposal in Big Bags.
(9) Thoroughly clean work footwear with water before removal.
(10) If wearing double bodysuits, the one underneath must be removed in a non-contaminated zone whilst still wearing the FFP3 mask, which should only be removed last.

PPE used during direct contact with asbestos-containing materials must be carefully packaged and labelled with the producer's name, an asbestos warning, the hazardous waste identification code (R), and the appropriate EWC code. Tools used during operations must also be decontaminated manually or mechanically, preferably at the bottom of the excavation.
Workers handling asbestos-containing waste within the site must clean the waste packages thoroughly before removing their PPE. Operations must be suspended during adverse climatic conditions, such as strong winds, to ensure worker safety.
All work stages should be coordinated and supervised by an "Asbestos Coordinator" who has completed at least 50 hours of specialized training. While adhering to Italian standards, technical operating instructions, safety procedures, and protection

equipment must be adapted to specific site conditions to ensure the highest levels of safety and efficiency.

b. Trenchless Technology

New studies are currently exploring the application of trenchless technologies using fiberglass pipes to rehabilitate asbestos cement pipelines. Replacing asbestos cement pipes presents unique challenges, particularly in urban or sensitive areas where traditional methods, such as OCPI, may not be practical. This older method, which involves extensive excavation, is labour-intensive and fraught with risks due to the proximity of other utilities like water, gas, and electrical lines. It also increases the likelihood of structural damage and pavement failures [6].

Trenchless technology encompasses two main areas: installation and renewal, with renewal further divided into repair and replacement techniques [7]. This versatility enables tailored solutions for pipeline projects while significantly reducing the social and environmental costs of construction. These techniques are particularly suitable in challenging environments, such as in historic centers or in other sensitive areas, where traditional excavation methods are not feasible.

Broadly speaking, the procedure entails the excavation of two intermediate points (Fig. 10) along the length of the pipe to be covered. Through these points, the liner is then passed in order to establish a connection between the two points and complete the covering process (Fig. 11 and Fig. 12).

INAIL in collaboration with the IATT (Italian Association for Trenchless Technology) and "La Sapienza" University of Rome, are actively monitoring these innovations, focusing on assessing the risks posed to workers during their application. These evaluations specifically examine the use of reinforced fiberglass pipes placed inside existing asbestos cement pipes.

During the works, Inail collected some air and bulk samples during the site preparation phases (washing, purging, and pre-lining) that were analysed both with microscopic (Phase Contrast Optical and Scanning Electron Microscopy – PCOM and SEM) and image analysis (HyperSpectral imaging – HSI) techniques, to evaluate the occupational exposures to asbestos fibers and the possibility of mixed fiber dispersion, where asbestos and fiberglass particles might coexist. HSI is a novel technique useful for quickly characterizing samples from maintenance/removal pipeline sites without manipulation, whether using trenchless methods or open-cut excavations.

Fig. 10 - Preparation of intermediate manholes

Fig. 11 - Site setup

Fig. 12 - Liner insertion

The first analytical results, following a monitoring campaign conducted by Inail at a worksite in Padova, indicate the presence of asbestos fibers combined with glass fibers. Hence, the next stage will be to assess the presence of asbestos for each work phase by isolating it from the mineral fibers. Some new monitoring campaigns will be conducted in spring 2025.
Many of the safety measures described for OCPIs can also be applied to trenchless technologies. However, studies are currently underway with the aim of issuing specific guidelines and operating instructions for such techniques.

4 Discussion

The document reports safety measures to adopt during asbestos pipes removal/maintenance operations to ensure maximum protection of workers and the environment surrounding the area of operations. The study also has the aim of encouraging the collection of data on underground asbestos-cement pipes and their remediation, with subsequent notification of the public authorities. The purpose of this is to implement the mapping of areas affected by the presence of this kind of ACMs and avoid asbestos exposure for workers or living environments. Indeed, knowledge of specific data on the diffusion of underground utility networks in asbestos-cement and their georeferencing may enable the medium and long-term planning of pipe removal operations, on national, regional and local scale.
This study highlights the importance of a better regulation of the use of trenchless technologies, which represent a modern and efficient alternative to OCPI, enabling new pipe installations or pipeline renewals with minimal surface disruption. These methods are particularly valuable in urban settings or under busy highways, where road closures would cause significant traffic and environmental impacts. Trenchless techniques reduce air and noise pollution and reduce cost and time; however they should be better monitored to evaluate the workers risks and the safety measures to adopt in each operational phase to avoid new workers asbestos exposures [8].

5 Conclusions

Over time, asbestos-cement pipes are becoming increasingly obsolete and require gradual replacement. Such planning is important in order to prevent the continuation of spot operations involving the partial removal of certain sections of pipe that lead to greater overall costs, in the long term, of remediation operations.

This publication, even if is a result of the Italian experience, could be useful at international scale and, in particular, it is commended to ministers, government officials, water network operators and other stakeholders who may provide advice related to asbestos exposure and the health consequences or apply advanced safety procedures. This is also in light of the recent European regulation on asbestos, Directive 2023/2668, which introduces significantly lower exposure limit values, reduced by at least one order of magnitude. [9]

These preliminary indications, intended to enhance safety standards in traditional excavation and trenchless technologies activities for pipes removal/maintenance, will be the subject of further field experimentation activities that will lead to the acquisition of more reliable data and the development of specific guidelines for trenchless technologies.

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The position of safety science: fundamental challenges in assessing safety

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Abstract
The structure of safety science is based on an approach that is many years old (e.g. [1], [2]). Safety science is an interdisciplinary field that deals with hazards, risks and protection strategies. The rapid developments in our society, which encompass everything from the environment and humanity to organisation and technology, pose a challenge for this comprehensive approach. At the same time, this comprehensive and interdisciplinary approach is precisely what these developments require, since it offers solutions for the needs of today and the future. The situation is constantly changing, and this requires a continuous discussion of safety [3]. This article outlines the philosophy of safety science and the challenges encountered in assessing safety. On this basis, the article focuses on the risk-based effect analysis [4] as a relevant part of the interdisciplinary approach of safety science.

1 The philosophy of an interdisciplinary safety science

Accidents, disasters and disruptions were long accepted as random strokes of fate due to their supposedly sudden occurrence (cf. [1], [2]). This understanding has changed over time. Hazards are no longer seen as acts of "force majeure" but as impending phenomena subject to similar conditions. This view has opened up a systematic and methodological approach to dealing with hazards and risks. The resulting safety science encompasses the teaching and research of the methodical and systematic assessment and control of hazards and risks for the purpose of preventing or reducing losses (cf. [3], [5]). In this context, knowledge about the nature of hazards, risks and the protection of systems is developed, compiled and communicated ([2], [3], [6]). Safety science represents the scientific structure for the discussion of hazards and risks (cf. [5], [7], [8]) as well as protection strategies [4]. It is an independent, self-contained science ([2], see [9]) and is based on all other disciplines (see figure 1) with its own set of e.g. terminologies, methodologies and principles (cf. [1]).

Hazards to people and their environment have always existed [10]. Starting from incidents and accidents, safety science has, over the course of time, approached the surrounding problems by differentiating them from other types of events (such as impairments to wellbeing, stress, illness, fear, functional and technical defects or malfunctions of systems) as well as from differently weighted events (such as trivialities and disasters). In this context, the perspective changed from primarily

technical to dynamic socio-technical systems (cf. [5], [6], [11]). The scientific subject of safety spans a level between chances and risks as well as the type, frequency of events and their degree of severity, each with objective and subjective components (cf. [12]). This combines safety and security (an interesting question is how defence is included here, which is becoming increasingly important due to numerous conflicts involving military action).

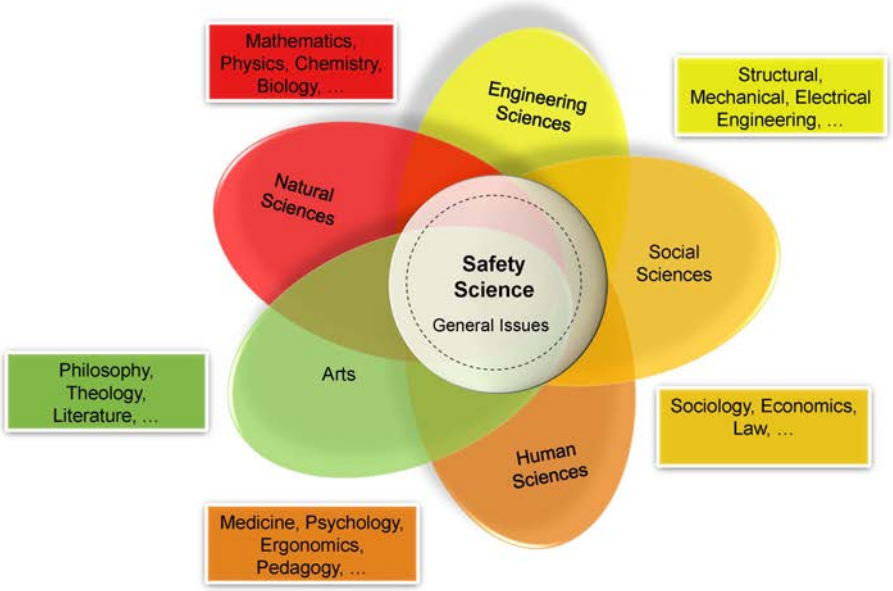

Fig. 1. Structure of safety science [1]

Within safety science, knowledge about hazards and risks, ranging from the triggers to the processes and outcomes, is compiled, collected, organised and (critically) evaluated. Countermeasures for loss prevention are then (systematically) derived on this basis. The entire complex of topics can be described as *riskology* [2] on the basis of the risk approach.

2 Risk approach and fundamental challenges in assessing safety

Riskology was initially broken down into *risk analysis* and *risk control* [2] but it is now differentiated as *risk identification*, *risk analysis*, *risk evaluation* and *risk treatment* (control) as iterative processes involving *monitoring/review* and *communication/consultation* [13]. The concept of risk (R) is often described [14, p. 348] as a combination of the frequency (H) and severity (S) of an event, whereby the mathematical function is simplified as follows (eq. 1).

$$R = H \cdot S \quad \text{or} \quad R = W \cdot S \quad \text{where} \quad W = n_i/N \qquad (1)$$

H is sometimes expressed as the probability of occurrence (where W = 0 is impossible, $0 \leq W \leq 1$ is probable and $W > 1$ is real [11, p. 66]). As part of the

probability, n_i is the number of observed events and N the number of all possible events [4]. Risks can be represented in different functions and mathematically in much more detail and complexity. In simple terms, they can be calculated using eq. 1 and represented in the form of F-N diagrams (see figure 2).
Approaches such as security or resilience are based on the same risk approach, but with different perspectives and focuses [4, p. 38 ff.]. Essentially, safety deals with stochastic, unintentional hazards in the sense of random variables (cf. [15], [16]), while security focuses on intentionally triggered events (e.g. attacks, sabotage and terrorism) [16]. On the other hand, resilience (engineering) is understood as the (generic) ability of systems to respond to complex system changes (risks) so that the systems can withstand and adapt to them (cf. [17], [18], [19]).

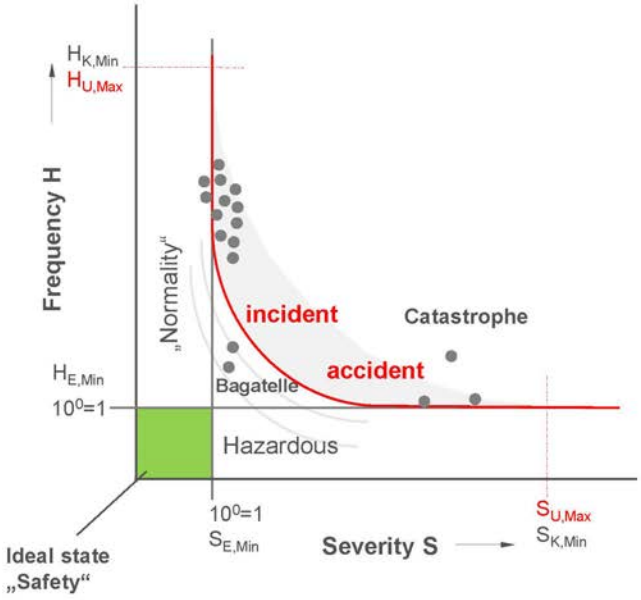

Fig. 2. Representation of the simplified risk concept as “Farmer diagram” [11]

In simple terms, a *hazard* exists when there is a possibility of loss [2]. This is also referred to as the event (or condition, circumstance or process) from which damage can arise. This can be explained with five causes: (1) energy, (2) substance/matter, (3) microorganisms, (4) power and (5) information [20]. Hazards are about "[...] possibilities for the occurrence of damage and loss [...]“ (see [21], [22]).
In terms of its vector of action, safety science goes beyond the general progress in knowledge. As an interdisciplinary applied science, it researches and systematises the effective conditions and regularities of hazards and risks across the board and deals with the acquisition of knowledge on the one hand and with the limitations of established knowledge on the other, thereby allowing rules of action to be established for collectives [23].

With regard to the development of the risk situation, it is clear that safety has achieved enormous success. In important areas, however, the reduction in accident damage has been declining for several years – at least in Germany. In some cases, damage has stagnated, yet in some other cases it has actually increased, as can be seen from the simplest comparison of damage based on accidental fatalities due to work, fire and traffic [24] or the registered occurrence of catastrophes (worldwide) [25] and major accidents in plant safety in the EU [26] or Germany [27], see figure 3. The number of disasters worldwide is increasing – a fact that is mainly attributable to natural hazards (influenced by humans). The registered number of major accidents in plant safety is declining in Europe (albeit with a questionable data basis and with a high degree of fluctuation). In Germany, the number of major accidents in plant safety has, overall, been increasing in recent years following an initially declining and subsequently stagnating trend – although changes in the definition of the major accident ordinance are influencing the development of events [4].

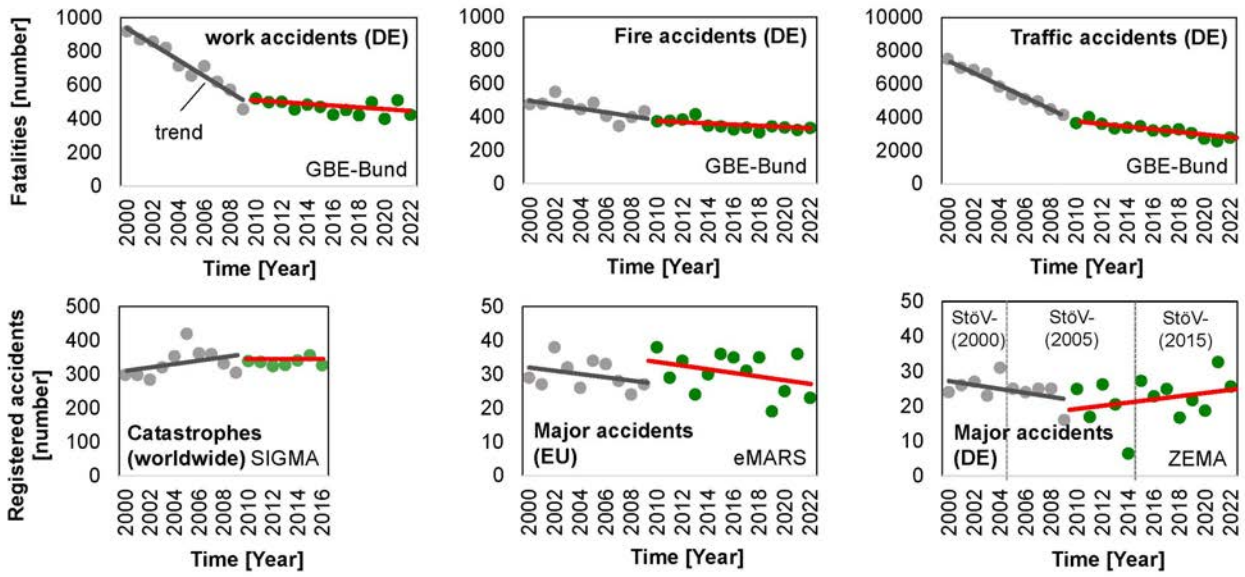

Fig. 3. Development of registered fatalities [24], catastrophes [25] and accidents ([26], [27])

In short, it is clear that despite all efforts as well as technical and scientific progress, the successes in safety in recent years have been limited. In some cases, an asymptotic trend in the development of damage is to be expected. Nevertheless, the situation has prompted us to question fundamental issues. This in turn gives rise to methodological considerations at the very heart of safety science, specifically in the context of hazard and risk assessment. It is important to mention, of course, that there are numerous factors affecting the situation. These developments can be approached from two perspectives: the *system view* and the *trend view*. We will start by looking at the *system view*: In the area of risk, the "technology-organisation-person" model [28] was established, and this was followed by similar models (cf.

[11], [29]). Based on this, the system approach has developed further in the direction of "multifactorial models" [30], taking into account the time-dependent behaviour of systems and components [31] (see figure 4). This means that systems are constantly changing due to continuous internal (e.g. learning and aging processes) and external changes (e.g. market forces, natural influences, politics).

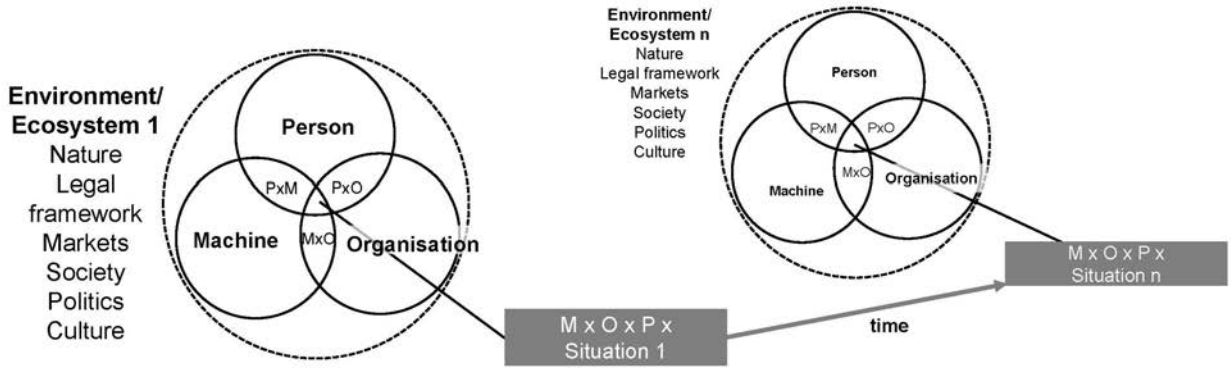

Fig. 4. Multifactorial models [30]

The *trend view* shows that our systems are facing serious changes and transformations. This means that new organisational forms and technologies are being introduced (see figure 5). This has implications for safety and security.

Fig. 5. Megatrend map [32]

As figure 5 shows, many different factors are influencing the current and future situation. While different predictions exist, the main trends shown in figure 5 (urbanisation, knowledge edge culture, gender shift, individualisation, globalisation, new work, health, silver society, neo ecology, safety and security, connectivity, mobility) have become particularly popular. The various trends influencing our systems carry a lot of implications for safety and security. The world is constantly changing on many different levels. Protection strategies must keep pace with these developments so that the level of protection can be adapted in a targeted manner.
Now, this brings us to the fundamental and methodological considerations mentioned above at the core of safety, particularly in the context of hazard and risk assessment.

3 Focus: risk-based effect analysis (effectiveness control)

On the one hand, the situation described requires dealing with new developments, hazards, risks (e.g. cultural changes in new organisational forms, new technologies such as drones, autonomous systems, digital twins, robotics, open and big data, artificial intelligence and cyber risks) and protection strategies. Established procedures for hazard and risk assessment (cf. [13], [32], [33], [34]) can help with this. On the other hand, more attention must be paid to one particular step in the process: *risk-based effect analysis (effectiveness control)* [4]. This step helps to assess the actual performance of an initiated measure. While this is particularly difficult due to the highly dynamic nature of developments, it is also extremely important. The *risk-based effect analysis* is included in all established procedures (see figure 6).

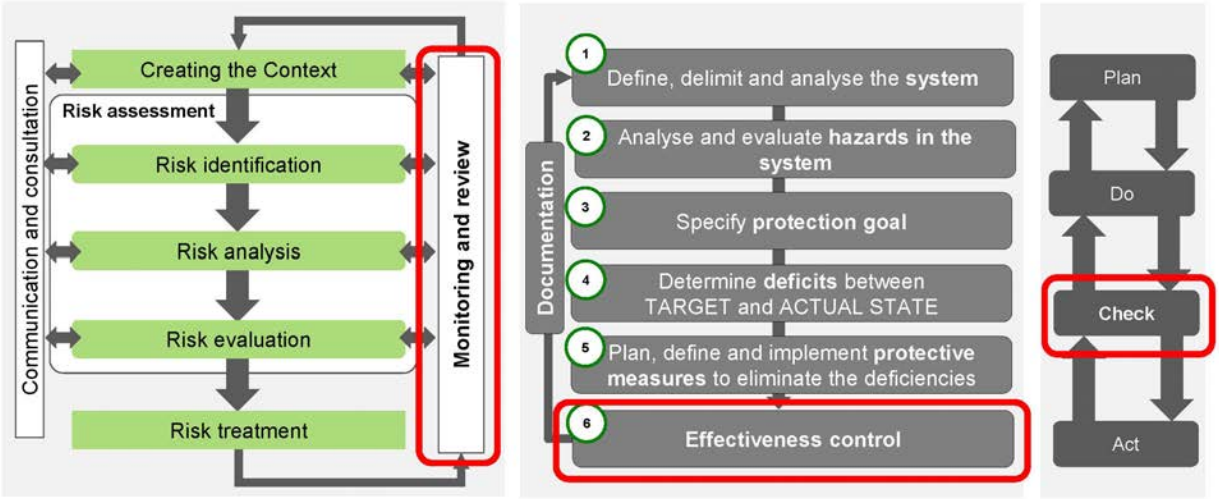

Fig. 6. Exemplary methodological approaches (cf. [13], [32], [34])

The evaluation of the effect/effectiveness of measures demonstrates that there are protective measures with a wide range of effects, from highly effective to counterproductive [3]. In [4], you will find a guide for putting the *risk-based effect*

analysis with a theoretical fundament into practice, along with corresponding examples. Fundamentally, *risk-based effect analysis* relates to the real application of the measure and is structured into a planning and implementation phase. The planning phase is linked to the prospective effect analysis and takes place as early as possible in the process. The initiation of a measure is followed by the *risk-based effect analysis*. The timing of this should also be determined as early as possible in the process. Assessment criteria forming part of a *risk-based effect analysis* must be derived from the objective of the measurements, the specific procedures and the availability of information. The criteria must be related to the protection objectives and serve as reference systems for evaluation (e.g. before/after, with/without). A wide range of protective measures and requirements exists for *risk-based effect analysis*. In some cases, questioning the effects is already an important step, while in other cases, valid assessments are required. In order to meet the requirements from practice, three *performance classes* with increasing requirements for *risk-based effect analysis* are defined: qualitative assessments (*performance class 1*), quantitative assessments (*performance class 2*) and quantitative assessments based on significance tests (*performance class 3*).

The *risk-based effect analysis* based on *performance class 1* is a qualitative assessment of the effectiveness of measures. It evaluates the hazard or risk situation that arises under the influence of the protective measure (e.g. better/worse, more/less). Evaluations in this performance class allow us to draw conclusions about the direction of effect of a measure (positive, neutral, negative). These are often easy to carry out [36]. The *risk-based effect analysis* of *performance class 2* includes quantitative assessment procedures that provide information about the degree of effectiveness. Quantitative assessment criteria complement the qualitative control of *performance class 1*. The results from performance class 2 indicate how much the hazard or risk situation changes due to the impact of the protective measure (e.g. how much better/worse, how much more/less, limit exceeded or undercut). It should be noted that quantitative values place limits on what can be counted or measured, which is sometimes intended when a situation is simplified to what is actually relevant. In evaluations of *performance class 3*, statistical significance tests are used in addition to class 2. These tests help to identify findings against “random” influences. The results of *performance class 3* provide information about the significance of the results.

If we break the analysis results down into the individual performance classes 1 to 3 and rate the effectiveness on a scale from effective to ineffective and counterproductive, this produces a matrix (see figure 7 for an example). Protective measures with proven high effectiveness are to be preferred, as shown in the matrix at the top right.

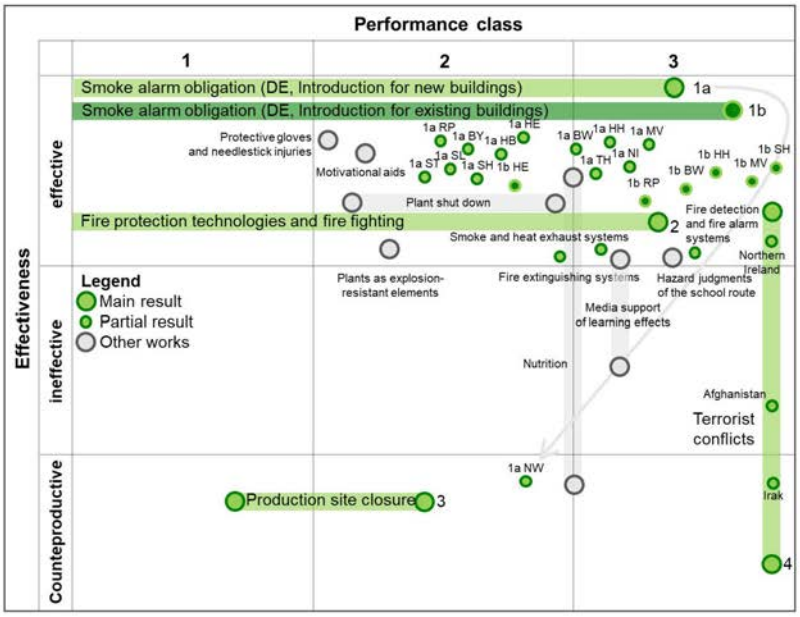

Fig. 7. Exemplary results of *risk-based effect analysis* [4]

4 Conclusion

The discussion of hazards and risks has its own discipline in the form of safety science, which provides terminologies, principles, methods and findings for the protection of systems. This discipline combines knowledge from other disciplines in the context of hazards, risks, safety and security. The risk approach is of central importance here and serves as the foundation for the established and newer approaches for dealing with safety. The enormous successes in reducing risks, as measured by indicators, appear to be declining due to a lot of development. This situation is influenced by numerous factors, both now and in future, so that maintaining the high level of protection will be a particular challenge in this context. Changes and the contribution of protective measures to managing the risks of these developments must be consistently assessed. The *risk-based effect analysis* is a decisive step in the achievement of protection goals, as it reveals the actual contribution of a protection measure. This methodical framework is used wherever protective measures are implemented. The *risk-based effect analysis (effectiveness control*) must be given more attention to facilitate the reduction of hazards and risks through a methodical cross-sectional contribution.

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Systematic analysis of fatal collisions between mobile equipment and pedestrian workers to inform the use of proximity detection devices

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Abstract

Context. Collisions between mobile industrial equipment and pedestrian workers (PWs) are a major occupational health and safety concern, particularly on construction sites (e.g., during earth-moving operations). The use of driver aids, such as proximity warning devices designed to alert workers and drivers of potential collisions, is a growing and constantly developing avenue of prevention (e.g., AI-enhanced cameras; RFID tags). However, structured feedback to guide the implementation of these technologies on mobile equipment remains rare (e.g., technology choice, installation and settings). **Objective/Methodology.** In this context, a systematic analysis of all fatal accident reports related to this issue for the province of Quebec (Canada) over the period 2013-2023 was carried out to provide insight into field constraints (n=34). A database was developed through a detailed review of these reports, capturing variables such as time, location, established causes, equipment type, PW status, work activities, regulatory compliance, equipment movement, PW position, and the awareness of both the driver and PW just before the accident.
Results. The results outline all the circumstances of these accidents, as described in the methodology. For example, the driver was unable to see the PW in 76% of cases, and the PW was unaware of the mobile equipment in 38% of cases. The underlying reasons for these accidents were also analysed.
Discussion. In 88% of cases, a PW proximity detection and warning device could potentially have prevented the accident. However, analysis of the reports also highlighted challenges in the implementation of these devices, such as 1) ensuring coverage of the entire danger zone (motion-, steering- and speed-dependent), 2) managing environmental constraints, 3) maintaining the effectiveness of warnings in situations where cohabitation is intended, or 4) accounting for subcontracting and open worksite conditions that complicate the use of certain technologies (e.g., requiring the wearing of a tag).

Context

Mobile equipment (ME) typically includes loaders, forklifts, excavators, dump trucks, etc. ME is a particularly dangerous type of machinery. For instance, in the United

States between 1992 and 2010, the machines most involved in accidents across various sector were all classified as ME [1]. Among the different types of accidents, collisions between a ME and a pedestrian worker (PW) are particularly concerning. The following statistics provide a general idea of the extent and severity of such accidents:

- In Canada, between 2020 and 2022, there was an average of 25 deaths per year specifically linked to collisions between a ME and a PW (include accidents on road construction sites by a third party). This represents 2.5% of all fatalities at work. The most affected sectors are construction, transportation, and warehousing [2].
- In the United States, an average of 33 deaths per year on construction sites between 1990 and 2007 were due to visibility issues involving moving ME. This represents 4% of deaths in the construction sector [3].
- In France, across all sectors, [4] recorded an average of at least 10 deaths per year between 1997 and 2008 in a non-exhaustive review.
- In the United States, on surface mining sites, [5] recorded an average of 1.5 deaths per year between 2003 and 2017. In underground mines, [6] recorded an average of 1.6 deaths per year between 2003 and 2015.

Poor visibility for the operator, whether due to blind spots (e.g., machine design), obstacles (e.g., stacked materials, blind turns, separation curtains) or lighting conditions (e.g., glare, darkness), is a major cause according to several studies [2][4][6]. The presence of PWs near operating machinery is another contributing factor, whether due to poor planning (traffic management/signage), non-compliance with instructions (prohibited areas), or lack of communication/training. Therefore, the addition of proximity detection and warning devices has long been seen as a promising solution (since the mid-2000s) in both the construction and mining sectors [2][4][7-8]. These are targeted alarms unlike standard backup alarms.
Depending on the technology, proximity detection systems may work with a tag on the PW (e.g., RFID or magnetic) or without a tag (e.g., ultrasonic, radar, laser, image processing with artificial intelligence [AI]). These systems vary in performance. For example, only systems with tags or image processing can distinguish between a person and an object. Research trends are progressing towards integrating multi-sensor platforms that combine several detection technologies to overcome the limitations of each. Additionally, AI-enhanced camera is a rapidly developing field [9].
Beyond targeted warnings to the operator and PW, proximity detection devices can also control the ME by linking the detection signal to the vehicle's transmission. In emergencies, the signal can trigger a slowdown, a deviation, or even inhibit the engine's start. As of 2024, this type of system is available on some new equipment. Nonetheless, these systems are considered driver aids, not safety devices, as the reliability of detection is not quantified in the same way as optical curtains or scanners with dedicated standards (e.g.,[10]).

According to [4], proximity detection device could have been useful in 60% of ME-PW collisions in their study. This figure rises to 78% in underground mines according to [6]. Cases of close collaboration between the ME operator and the PW were generally excluded. The authors suggest that these devices should provide an additional layer of prevention and complement the effective implementation of regulatory requirements, such as traffic management plans, designated reversing areas and spotters, training, communication methods, high-visibility personal protective equipment, and lighting management in the area.

1 Objectives

The objectives of this work were: 1) to review all investigation reports involving a fatal collision between a PW and a ME from 2013 to 2023 in the province of Quebec (our jurisdiction), 2) to categorize the information provided by inspectors, and 3) to discuss the potential usefulness of vision assistance and proximity detection devices. This exercise is not limited to reversing manoeuvres or a specific industry, as in some studies (e.g., [3]). Furthermore, the aim of this exercise is not to conduct a statistical analysis of fatal accidents, as is often done, but rather to offer a database of real-life situations detailing the conditions, stakeholders, and circumstances at the time of the accident. The details from the investigation reports allowed us to achieve this.

2 Methodology

2.1 Investigation reports and selection criteria

The investigation reports were extracted from the database of the organization responsible for labour inspection in the province of Quebec (i.e. CNESST) [11]. This organization makes the investigation reports public for prevention purposes. The investigations are conducted by two inspectors who perform a structured data collection (e.g., interviews, equipment expertise) and an analysis based on the creation of a cause tree to minimize the inherent biases of this type of investigation [12]. The anonymized investigation reports range from 20 to 40 pages, allowing for the inclusion of numerous details, illustrations and reconstructions.

The investigation reports included in this study were selected by reviewing the summary. In case of doubt, the report was read in its entirety, and the decision was made jointly. The specific inclusion/exclusion criteria for the reports in the sample were as follows:

- Only fatal accidents occurring between 2013 and 2023.
- A ME includes equipment used for work whose movement is land-based and motorized [13].
- The ME was in normal use. A ME undergoing maintenance was not included.
- A PW is a person on foot working as part of their job. The person may be mobile or stationary, standing or not, at the time of the accident.

- By collision, it is understood that a part of the ME strikes or crushes the PW. The collision may involve the movement of the entire ME or a part of it (e.g., turret rotation). All ME movements are included.
- Road accidents (e.g., a private vehicle hitting a road flagman) are not included.

2.2 Selected sample

The database from the labour inspection was last consulted on August 9, 2024. A total of 420 investigation reports were available for the period from 2013 to 2023 (date of the accident), 171 of which involved a ME (41%). Based on the selection criteria, 34 reports were related to a fatal collision between a PW and a ME. This figure represents 8% of all available cases or 20% of the cases involving a ME. These 34 reports were analyzed and are presented below.

2.3 Analysis and Categorization of Information

A database was developed to systematically compile the information presented in the investigation reports, facilitating subsequent sorting and analysis. Part of the database is more descriptive, covering the context, time, locations, causes established by the inspectors, the ME, the PW, their respective work activities, as well as elements related to regulatory obligations regarding risk reduction. The second part of the database includes some inferences to describe the dynamics of the accident, the awareness of both the ME operator and the PW regarding each other before and at the time of the accident, and the potential usefulness of a proximity detection and warning device. Table 1 outlines the main variables collected (non-exhaustive). The classification was improved through an iterative process. Data analysis was conducted using pivot tables.

Theme	**Variable**	**Value**
Time of the accident	Year. Month. Day	2013-2023. January-December. Monday-Sunday
	Time. Shift	Morning (6am-12pm); Afternoon (12pm-6pm); Evening (6pm-12am); Night (12am-6am)
Location of the accident	Location category	Building; Forest road; Yard/Parking lot; Road; Vacant land
		Indoor; Outdoor
	Industry sector	*Classification used by the labour inspection*
Machine mobile	ME type	Loader; Forklift; Excavator; Dump truck…
	ME use	Moving without work; Product delivery; Earthmoving operations…
	Driving assistance	Rearview mirror, rear camera, proximity detection device…

PW (victim)	Number of deaths. Gender	0-10 / Male; Female
	Victim's job	*Free text*
	Activity during the accident	*Free text* (e.g., various tasks, walking, assistance)
	Subcontracting (ME operator, PW)	None; PW only; ME operator only; PW and ME operator (same employer); PW and ME operator (different employers)
Accident dynamics	Type of accident	Crushed/struck by the ME; Crushed/struck by an ME component
	ME movement	Moving forward; Moving backward; ME component movement
	Dynamics of the movement	Starting/initiation phase; ME already in motion
	PW position relative to the danger zone before the accident	PW already present; PW not present (ME enters stationary PW's zone; trajectory convergence)
	ME speed	*Free text* (in km/h)
	Impact area on the ME	*Free text* (e.g. rear right wheel)
Awareness of shared space	General awareness of ME-PW shared space (extended perimeter and time)	ME operator: Yes; No PW: Yes; No
	Awareness of ME-PW shared space just before the accident	ME operator: Yes; No PW: Yes; No
	PW in a blind spot	Yes (specify area); No
Backup alarm	Backup alarm mandatory	Yes; No; Not applicable
	Functional backup alarm	Functional; Not functional; Absent; Not applicable
Traffic plan	Requirements (traffic plan)	*Variable based on accident location, number of workers…*
	Compliance (traffic plan)	Yes; No
High-visibility vest	High-visibility vest mandatory	Yes; No
	Compliance (vest use)	Yes; No
Inspector conclusions	Identified causes	*Free text (2 to 3 causes)*
	Corrective measures	*Free text*

Driving assistance	Usefulness of driving assistance	No; Yes – vision assistance only; Yes – detection/warning only; Yes – vision assistance and detection/warning

Table 1 - Database variables (non-exhaustive) and classification

3 Results

In summary, the review and analysis of fatal occupational accidents related to ME-PW collisions in Quebec led to the following findings:

- The number of deaths per year due to a ME-PW collision is stable throughout the period (3/year). There is no downward trend.
- The accidents occurred outdoors (32/34; 94%), mostly during the summer/fall period (22/34; 65%). More than 50% of the deaths occurred on a construction site as defined by Quebec's law (19/34), with the other accidents occurring in the forestry sector (4/34), the service sector (4/34), and the commerce sector (3/34). The mining sector was not represented in the sample.
- The PWs were typically men (32/34) holding positions as ME operators, surveyors, flaggers, or day labourers.
- The MEs involved were trucks (14/34; 41%), earth-moving machinery (14/34; 41%), forklifts (3/34; 9%), and forestry machinery (3/34, 9%) (Table 2). Specifically, we can note dump trucks for earthwork delivery (8/34; 24%), excavators for earthworks (8/34; 24%), loaders for snow removal and other tasks (4/34, 12%), forklifts in transit without load (3/34; 9%), and skidders in forests (3/34, 9%). These results are consistent with the literature, which highlights the predominance of dump trucks and earth-moving equipment [2].
- Reverse collisions are the most frequent, accounting for 62% of cases (21/34), which is also consistent with the literature [4]. Thus, accidents occurred following other movements of the ME in 38% of the cases, including (i) forward movements (6/34), (ii) turret rotations (4/34), and (iii) other component movements (3/34) (Table 3). This aspect must be considered in prevention efforts, where the emphasis is often placed on reversing manoeuvres.

	Use at the time of the accident							
ME	Earthwork	Earthwork delivery	Movement without work	Positioning	Load handling	Loading/ unloading	Other	**Total**
Truck	**0**	**7**	**0**	**4**	**0**	**2**	**1**	**14**
Dump truck	-	6	-	1	-	1	-	8
Ampliroll	-	-	-	1	-	1	-	2
Box	-	-	-	2	-	-	-	2
Semi-trailer	-	1	-	-	-	-	-	1

Flatbed	-		-	-	-	-	1	1
Earthmoving	**9**	**0**	**2**	**2**	**1**	**0**	**0**	**14**
Excavator	6	-	-	1	1	-	-	8
Loader	2	-	2	-	-	-	-	4
Bulldozer	1	-	-	-	-	-	-	1
Paver	-	-	-	1	-	-	-	1
Forklift	**0**	**0**	**2**	**0**	**1**	**0**	**0**	**3**
Forestry	**0**	**0**	**1**	**0**	**1**	**0**	**1**	**3**
Skidder	-	-	1	-	1	-	1	3
Total	**9**	**7**	**5**	**6**	**3**	**2**	**2**	**34**

Table 2 - Distribution of deaths by type of ME and its use at the time of the accident

Dynamics of the movement	**Movement of the ME during the accident**				**Total**
	Reverse	Forward	Turret rotation	Component movement	
Starting phase	11	3	4	3	**21**
Continuous movement	10	3	0	0	**13**
Total	**21**	**6**	**4**	**3**	**34**

Table 3 - Distribution of deaths by the movement of the ME during the accident and the dynamics of the movement

- Regarding the dynamics of the ME movement, more than 60% of the accidents occurred during the starting phase of the ME (21/34), and the remaining 40% occurred during continuous movement (Table 3). In connection with this point, in two thirds of the cases (22 cases), the PW was already present around the ME at the start of the movement.
- In more than 80% of cases (28/34), the ME operator and the PW were generally aware of each other's presence at some point before the accident. Therefore, this may not be the most effective lever for prevention. However, in the remaining six accidents where general awareness was lacking, four occurred in the context of subcontracting (involving different employers).
- Logically, the ME operator was unaware of the PW's presence just before the accident in 88% of cases (30 cases) (Table 4). The various events that lead to a dangerous movement of the ME or one of its components toward the PW include:
    - The ME operator does not perceive the PW (91%):
        - PW never visible (76%): PW positioned in a blind spot throughout the movement (70%); PW emerging from behind an obstacle or a pedestrian exit of a building (6%).
        - PW potentially visible but not noticed (15%): PW poorly visible or not identified through visual aids before starting or during

movement (e.g., poor scanning, insufficient lighting, dark clothing at night, poor-quality or small monitor image) (6%); ME operator focused on the ME's tool or task rather than on the surrounding environment (9%).

- The PW is perceived by the operator, but there is a false manoeuvre due to a coordination issue, whether in signal interpretation or other factors (9%). No accidents were reported due to an unexpected movement caused by a problem with the operation of controls.

On the side of the PW, they were unaware of the ME just before the accident in only 13 cases (38%) (e.g., facing away or at a three-quarter angle, wearing a hood, or looking down) (Table 4). In reverse movement cases, the backup alarm did not suffice to alert the PW, even in instances where the alarm was properly positioned. In the 21 other cases where the PW was aware of the ME's presence, they were either in direct collaboration or had entered the zone voluntarily without the operator noticing (50%; 17/34).

Thus, regarding the level of awareness just before the accident, the prevention levers to work on are, for the operator, (i) the visibility of the PW (76%) or (ii) their actual location (15%), and for the PW, (i) the lack of awareness of the ME (38%) or (ii) entering the zone knowingly without notifying the operator (50%).

Specific awareness of the PW	**Specific awareness of the ME operator**		**Total**
	No	Yes	
No	13	0	13
Yes	17	4	21
Total	**30**	**4**	**34**

Table 4 - Distribution of deaths according to the awareness of the ME operator and the PW regarding their presence just before the accident

- Regarding the risk reduction measures in place, backup alarms were present and functional in almost all cases. The issue with backup alarms seems to be their lack of impact in certain situations. This is partly because it is not a selective warning [14-15]. The wearing of a high-visibility safety vest was noted in 12 cases, but in 10 cases, the PW was in the ME's blind spot at the time of the accident, highlighting a limitation of this type of measure. The presence of a rearview camera was not sufficient to prevent the accident in five cases, either because the PW was out of view at the start or during the reversing movement, or because they were hard to detect on the monitor due to lighting, dark clothing, or the operator's focus on the task rather than on the monitor. The detection zone, lighting, and the size and quality of the image on the screen are factors to consider when using a camera [16]. Traffic management and reversing manoeuvre regulations were rarely followed at the accident sites.

This represents an important prevention lever to consider, even before proximity detection devices.

4 Discussion

Despite the use of certain risk reduction measures, the residual risks of ME-PW collisions remain high in some circumstances. In this context, proximity detection devices are increasingly appearing in construction sites, for example. In our sample of fatal accidents, it can be argued that in 88% of cases (30/34), such a device could have been useful since the ME operator is unaware or no longer aware of the PW's presence just before the accident. This includes 25 cases where the PW is in a blind spot (20 behind and 5 in front) and 5 cases where the PW is not in a blind spot, but the operator is looking elsewhere (e.g., focused on their task, high cognitive load) (Table 5). If we go beyond warning with a control system connected to the ME, inhibiting movement of the ME when detecting the PW in the zone would have been effective in the 19 cases during the startup phase. Braking would be required in the other cases, which is more difficult to implement without additional risk (e.g., braking with a load).

(Just before the accident)	**PW is not the blind spot**	**PW is in the blind spot**
ME operator knows that the PW is present	3 cases - Assistance device unnecessary	1 case - Vision aid only
ME operator does not know that the PW is present	5 cases – Proximity detection and warning device only	25 cases – Proximity detection and warning device + vision aid

Table 5 - Usefulness of a proximity detection and warning device and vision aid in the 34 cases

However, despite the announced performances, [17] expressed reservations regarding proximity detection devices: “the diversity and complexity of collision risk situations related to the movements of machinery, along with the inherent limitations of detection devices, mean that their implementation can be very disappointing.” Moreover, user-centred feedback is still rare outside the mining sector. Based on the context of the fatal accidents, preliminary field visits and a review of the literature, certain difficulties with the use of proximity detection devices can be anticipated, such as:

- Being able to cover the actual hazardous area depending on the various movements (i.e., forward, backward, rotation) and the blind spots of the ME as well as obstacles in the environment. Without multiplying sensors, only technologies with tags (e.g., RFID, UWB) allow simple detection over 360° and through certain obstacles. However, managing effective tags wear for all PW

and the context of subcontracting limits possible applications. The installation of four AI-enhanced cameras for reconstructed 360° detection has recently emerged on the market.

- Providing the most targeted and personalized warnings so that the ME operator and the PW remain attentive (e.g., unlike backup alarms). The operational principles surrounding the determination of the detection zone in real contexts and the best ways to alert the individuals involved are not clearly identified [9]. The recent standard [18] attempts to address the issue of detection distance.
- Being adapted to environmental conditions (e.g., dust, rain/snow, mud) since MEs are used outdoors, particularly on construction sites. The real-world performance of devices recently brought to market is still poorly documented (e.g., modes of degradation of detection, operational limits).
- The use of AI in safety applications is a topic under discussion in standardization [19]. The reliability level cannot be defined in the same way as for proven safety devices [10]. For the moment, proximity detection devices are considered as driver assistance devices and not safety devices. Nevertheless, these devices add a layer of risk reduction, but the key for the operator lies in identifying and integrating their limitations for the current application. These limitations may vary from one site to another.
- The acceptability factors of this technology by workers have not been documented [20].

These points highlight the need for research regarding the implementation and actual use of proximity detection devices to guide future integrators and users. This is what we plan to do in the continuation of our work, focusing on construction sites in Quebec.

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On the move: safety and health in global transportation chains

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Abstract

Connecting the dots

In our interconnected world, global supply chains are the backbone of daily life, powered by transportation across land, sea and air. Transportation is the lifeblood of commerce, linking producers to consumers and sustaining industries. Robust Occupational Safety and Health (OSH) standards are vital not only for workers but also for the resilience of global supply networks.

Transport workers – drivers, seafarers, pilots and deliverers – enable the movement of raw materials, supplies and products, keeping international production and assembly networks functional. Yet, the sector faces significant challenges, including high accident rates, non-stationary workplaces, tight deadlines and varying safety standards across borders and across sub-segments like aviation, shipping and road haulage.

Hazards are compounded at logistics hubs and other interfaces, where diverse workers and subcontractors collaborate, often with inconsistent training. Addressing risks like poor packaging, inadequate labeling and load securing is essential to prevent shared and propagated dangers in the supply chain. A strong culture of prevention is crucial to protect workers and ensure the seamless functioning of global supply networks.

Ensuring the safety, health and well-being of workers in the global transport industry is challenging due to the large number of parties involved and the many interfaces between transport modes. The high incidence of accidents and health hazards during the loading, transporting and unloading of goods vehicles, seagoing vessels and aircrafts are largely due to inadequate communication at interfaces as well as varying occupational safety and health standards between the different parties of transport services. An effective prevention culture throughout the whole transportation chain requires a clear identification of hazards and areas for action as well as an agreement upon minimum safety and health standards in order to provide a solid basis for effective cooperation and communication for the safety, health and well-being of workers.

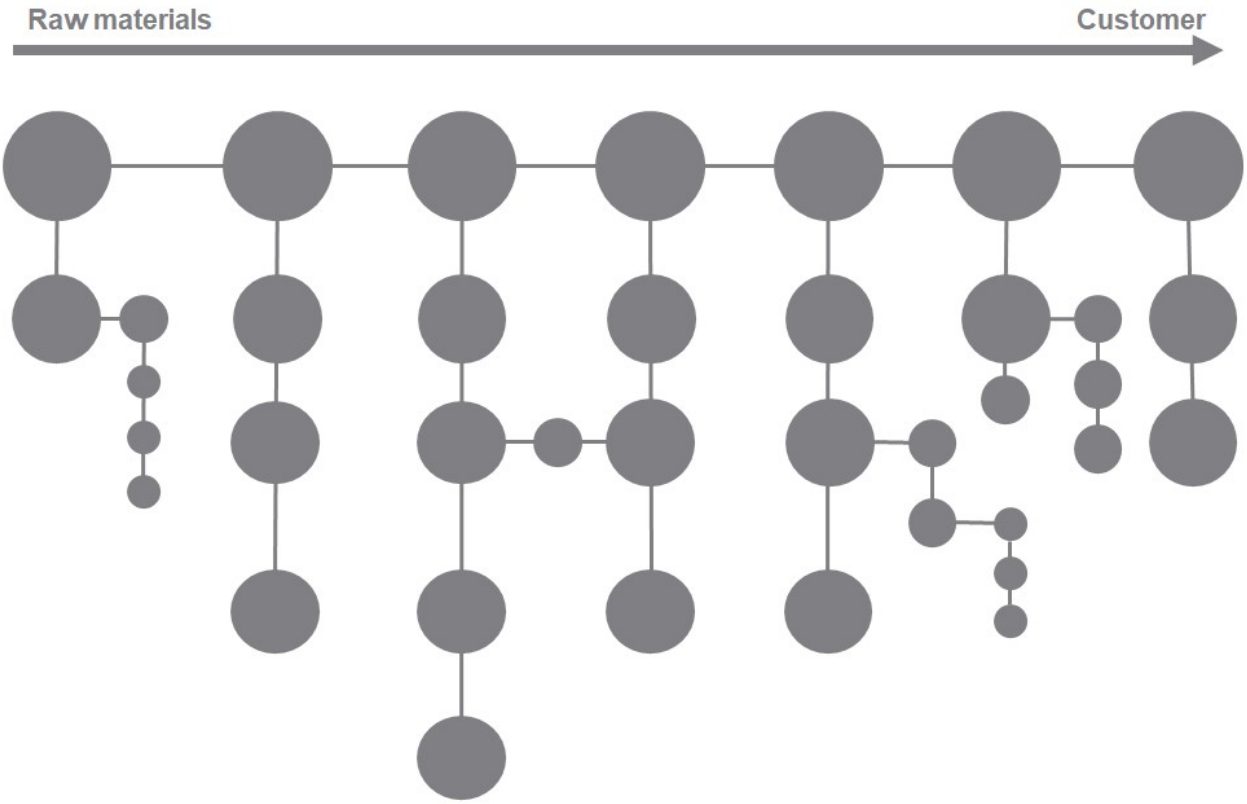

Fig. 1: Exemplified global supply network illustrating the many transports necessary to connect the dots, adopted from [1] ©ISSA

1 Road haulage

1.1 Transporting goods and its challenges

Road transport is a critical part of global transport chains. Truck drivers often work long hours, which can lead to fatigue, sleep deprivation and unhealthy eating. Apart from traffic conditions, one of the biggest sources of danger is the loading and unloading of trucks, especially when it comes to securing the load. Incorrect securing can lead to serious accidents, both during transportation and unloading. Correct load securing techniques and regular vehicle safety checks are key to preventing these types of accidents. Special equipment, such as anti-slip mats and lashing straps, and proper training are essential to ensure driver safety. Another important safety challenge is the safe access to and exit from the cabin and superstructures of goods vehicles.

To prevent these types of incidents, routine training and proper instruction are emphasized. Mistakes, such as failing to park vehicles correctly or following incorrect sequences, often lead to rolling vehicles or trailers, posing significant risks. To address these issues, an interactive game has been developed to test and reinforce knowledge of safe procedures. This game, available as an online tool or card deck, encourages players to arrange steps in the correct order, with immediate feedback provided on both safe and unsafe actions. Supplementing these efforts, a leaflet and

an instructional video have been created, summarizing key procedures during coupling, such as applying parking brakes, using wheel chocks and correctly connecting brake lines to ensure safety throughout the supply chain.
The occupational safety, health and well-being of drivers begins with the provision of safe work equipment by employers, ensuring vehicles are not only roadworthy but also safe to use at logistics hubs and conducive to a healthy workplace. This requires a thorough risk assessment during vehicle procurement to ensure that appropriate safety features are included. Features such as safe access to superstructures and secure entry and exit from the driver's cab are crucial for minimizing risks. Guidelines for purchasing safe and healthy commercial vehicles, including recommended safety features, are outlined in a dedicated brochure.
Each year, nearly 4,000 drivers insured by the accident insurance institution experience fall-related accidents while working with commercial vehicles. Common causes include slipping, stepping into voids, or stumbling, often resulting in broken bones, twisted ankles, or sprains. These incidents frequently lead to extended absences from work and some even result in fatalities. Vision Zero initiatives aim to address and reduce these fall incidents, with specific strategies detailed in the latest ISSA Vision Zero practice volume.

2 Aviation

2.1 Safety above the clouds and on the ground

Safety standards are particularly high in the aviation industry. However, this does not automatically mean that working in air freight is without risks. When goods need to be made available around the world as quickly as possible, air transport is the preferred option. The loading and unloading of cargo, in particular, poses safety hazards due to the many interfaces at the airports and the high demands placed on the handling of goods. Air cargo handling involves handling a great variety of goods, often in confined spaces and under time pressure. Especially in logistics hubs and airports, coordination between different teams and transport modalities is crucial. Clear communication channels, structured procedures and established safety protocols play a key role in preventing incidents and protecting the health of all employees.
In air cargo handling, diverse means of transportation and load carriers are utilized, with cargo varying significantly in dimensions, weight, shape and material. As a result, ground staff are subjected to heavy physical demands and heightened risks of incidents caused by improperly secured cargo. Air freight containers and pallets are transported between aircraft and freight centers using specialized trailers, such as dollies. Despite the availability of organizational and technical measures, manual handling remains unavoidable during activities such as lifting, carrying, pulling and pushing heavy loads. These tasks often contribute to long-term health issues among workers.

Efforts to address these challenges have included the implementation of a training concept, which improved the physical fitness of ground handling teams and reduced workload-related stress. Conducted close to the workplace during working hours, the training was tailored to specific apron tasks and led to notable outcomes, including fewer sick days, increased employee engagement and resource savings for the company.
Additional measures are required to mitigate risks associated with manual handling, such as regular inspections of work equipment to ensure safe operation. The potential for crushing or shearing injuries while handling transport units underscores the need for proper positioning, alignment and securing of cargo. Comprehensive guidelines, like those provided in the Aviation Safety Information, support the regular inspection of equipment, contributing to improved safety in air cargo handling.

3 Maritime shipping: Risks at high seas and in ports

Maritime transport is an integral part of global supply chains and presents its own set of challenges. There are particular risks in handling dangerous goods, lifting heavy loads and securing cargo during port operations. Cargo in containers must to be properly secured to minimize the risk of cargo shifting and containers must be properly lashed by the port workers in accordance with the ship's cargo securing plan to prevent containers from falling overboard in adverse weather and sea conditions. When dangerous goods are being shipped, it is of paramount importance that the shipper accurately declares these goods so that they can be safely stowed and segregated on board of the ship. This is critical not only for the safety of the crew, but also for the protection of the environment, as spills or chemical reactions of hazardous materials can have catastrophic consequences. In ports where containers are handled, clear work instructions and safety precautions are necessary to prevent accidents caused by improper handling or the inhalation of toxic fumes from fumigated containers.
Seagoing vessels function as self-contained systems, resembling a small town where electrical energy is generated, drinking water is produced, wastewater is treated, waste is processed, food is prepared, leisure activities are conducted and medical facilities are operated. For seafarers, the separation of workplace and private space is not feasible, giving work-life balance a unique context on board. To address the wide range of occupational hazards present in this environment – unparalleled in any other industry – the *Handbook of Safe Working Practices* was developed.This comprehensive manual, comprising 28 chapters, outlines the primary hazards and corresponding preventive measures for occupational health and safety in merchant shipping and fisheries. It aids executives and crew members in recognizing dangerous situations during daily operations and provides workflows to mitigate risks.

In this context, the German flag state administration also offers very good resources for OSH standards with a wide variety of information and advice to seafarers and shipping companies.

4 The last mile: Speed and security in harmony

Last-mile delivery services play a central role in the modern supply chain. Drivers are often under enormous time pressure and are responsible for getting parcels to their destination safely and on time. One of the main risks in this area is road safety. Courier drivers are particularly vulnerable to road accidents due to the challenges of urban traffic, such as high traffic volumes, the inability to find a good place to stop, the density of the road network with complex intersections and so on. They are also exposed to risks due to unsuitable or non-ergonomic working conditions and heavy lifting, which can lead to physical complaints. In addition, they often work for or are themselves subcontractors and sub-subcontractors, which poses additional challenges to their safety and health at work. Measures such as regular safety training, ergonomic vehicle equipment, the use of technical aids, such as a hand truck, mandatory labeling of heavy packages and the awareness of safe behavior on the road are crucial to minimizing these risks.

Despite increasing automation in many processes, manual labor remains essential in tasks such as loading and unloading transport vehicles, lifting and carrying and repackaging damaged packages. Deliverers, like most workers in the transportation sector, are frequently exposed to challenging weather conditions, including extreme temperatures, rain and high UV radiation. Combined with the pressures of strict deadlines, these factors necessitate tailored concepts to ensure the safety, health and well-being of delivery personnel. To support these efforts, a media package for courier, express and postal services has been developed [11]. It includes a guide for entrepreneurs, a handbook for delivery personnel, a leaflet with safety rules and an occupational safety film for training purposes. Additional resources focus on topics such as safe lifting and carrying techniques and sun protection [12,13].

In the transportation sector, where occupational and road safety are closely intertwined, nearly three-quarters of all fatal accidents reported to BG Verkehr are road-related. While external factors like traffic density, road conditions and weather cannot be controlled, measures such as optimizing route planning, equipping vehicles with driver assistance systems and providing regular driver safety training can significantly enhance safety. These training sessions focus on building awareness, recognizing traffic hazards and promoting safe driving behavior, ultimately reducing accident-related costs. Financial support for these trainings is provided by BG Verkehr for its members for vehicles including trucks, buses, vans, cars and bikes.

5 Interfaces in logistics centres, ports and airports: Seamless security?

The interfaces between the different modes of transportation – on land, water and in the air - are particularly critical points in supply chains. In logistic centers, ports and

airports, smooth cooperation and communication between the various parties involved is essential. This could also include a jointly coordinated and agreed risk assessment. Errors at these interfaces, whether due to inadequate safety precautions or insufficient coordination, can lead to relevant delays and even accidents. For example, inadequate load securing in the truck sector can lead to problems when loading goods onto an aircraft or ship, so the risks are passed on as the goods are passed on. The handling of dangerous goods requires even more precise coordination and clear communication to ensure the safety of all parties involved.

Fig. 2: Exemplified interfaces between transportation modes. ©BG Verkehr

6 Conclusion

A holistic approach for safe transportation chains

Health, safety and well-being in global transport chains is of paramount importance and requires a holistic approach. This includes ensuring safe working conditions for everyone involved, from courier and truck drivers to airline and ground staff as well as ship and port crews. Many hazards can be avoided through standardized reporting of cargo-related properties as well as improved communication and cooperation between companies working at interfaces along the supply chain. Preventive measures, regular training and awareness of potential risks are essential to creating a safe and healthy working environment. In order to ensure the smooth and safe global movement of goods, it is the responsibility of every company involved to ensure the safety not only of its own employees, but to also care for the safety of workers temporarily working on its premises and of workers further along the transportation chain. Ultimately, it is not just a matter of passing on goods, it is a matter of passing on the care for each other.

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Rapid Vulnerability Management for Networked Machinery and Safety critical Remote Control Systems

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Abstract
Industrial systems reliant on radio frequency remote controls face significant vulnerabilities, including replay attacks, command injection, and emergency stop (E-STOP) abuse. Replay attacks, allowing malicious command execution, and E-STOP abuse, halting operations by disrupting signals, are particularly concerning. A survey of 98 occupational safety specialists highlighted that 43% of companies possess networked controls capable of causing harm if exploited. Testing of industrial controls, including cranes and automated guided vehicles, confirmed vulnerabilities exploitable in minutes. To address these risks rapidly, standardized reporting frameworks like CSAF and machine-readable contacts for vulnerability reporting enhance security and response efficiency.

1 Vulnerabilities of Safety related Remote Controls

Radio frequency remote controls are also used in industrial environments for safety-critical applications. A common application is the radio remote control of industrial cranes. In this case, both the emergency stop and the commands for moving the load are transmitted by radio.
In 2019 TrendMicro Research published a report on vulnerabilities of industrial remote controls. The report splits the vulnerabilities of cranes with radio frequency remote controls in five major attack classes: Replay attack, command injection, E-STOP abuse, malicious re-pairing and malicious reprogramming. The E-STOP abuse and the very dangerous replay attack take a special place here because they are trivial to carry out.
The emergency stop of a radio remote control typically uses the closed-circuit current principle. An emergency stop abuse is simplified by the fact that you now only have to disrupt the radio signal to force an emergency stop.
In a replay attack, the attacker simply records the legitimate signals and then sends the same signals again at a later time.
While the emergency stop abuse initiates the safe state and typically only comes to a halt, a replay attack can completely take over control and deliberately execute life-threatening commands.

2 Survey on the prevalence of networked work equipment that can injure employees

The initial step was to ascertain the existing degree of networking and the potential risks within companies. To achieve this, the Institut für Arbeitsschutz der DGUV (IFA) conducted a survey of 98 occupational safety specialist from a variety of German companies. The objective of the survey was to determine whether individuals could be adversely affected if an IT attack were to maliciously enable remote control of all the functions of the networked devices. The survey did not consider protective measures that were already in place.

In the survey on the current degree of networking and the potential hazards in industry, 98 occupational safety specialists from various companies were interviewed (Figure 1). Of these, 20% stated that their own company does not yet have any networked controls. 34% of those surveyed stated that there is a network, but that the machines and systems are inherently safe and that no injury to employees is possible even if the control system is corrupted. 43% of those surveyed have networked controls in their company that could injure people if security vulnerabilities are exploited.

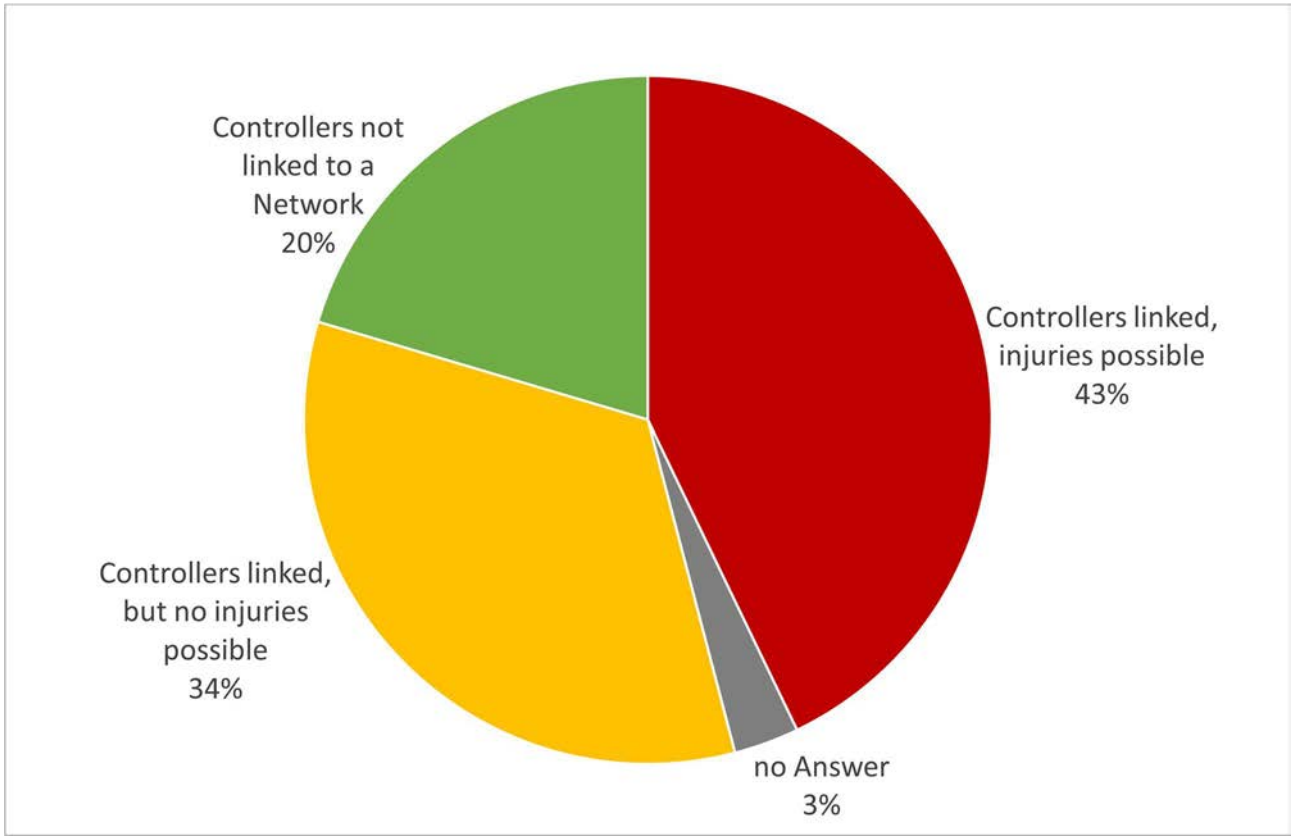

Fig. 1: The interviewed occupational safety specialists stated in 43% of the companies that controls in the company are networked and that employees could be injured in the event of an attack on the company network.

These results revealed the high prevalence of dangerously vulnerable controls, leading to further investigations being carried out in the IFA's Industrial Security Testing Laboratory.

3 Examination of further safety-critical work equipment

The IFA investigated safety-related controls of cranes, automated guided vehicles (AGVs) and ignition controllers for artificial firework with a radio frequency remote control to determine whether a significant number of vulnerable controls are available on the European market. It was possible to conduct a replay attack on the tested controllers within 5 minutes.

4 New communication techniques as key to manage vulnerabilities

Vulnerabilities in machines, caused by design and programming flaws, threaten a wide range of systems. Traditional contact methods, such as website forms, are often ineffective for quickly and securely reporting discovered vulnerabilities. In addition, legal uncertainties such as the "Hacker Paragraph" (§ 202c StGB in German law) make it difficult to report such vulnerabilities responsibly (Responsible Disclosure).
The security.txt specification as described in RFC 9116 provides a solution [3]. It is a standardized text file containing contact and encryption information. This file is stored in the.well-known/ directory on web servers and is accessible worldwide via a fixed URL. This allows security researchers and companies to communicate with confidence.
The benefits for both sides are that security researchers can be honored and recognition can be published. Companies can also attract qualified specialists. The use of security.txt will be mandatory in the future under a new EU regulation to ensure accessibility and avoid fines [5].

The IFA has therefore set up an internet platform that provides tools and information on emergency contact free of charge [6]. It contains short films on emergency contact for decision-makers in German, English, Dutch, Japanese, Polish, Czech and Chinese.

5 Solution for efficiently reporting and denying vulnerabilities

In new European regulations, manufacturers of digital products are being held more accountable. The Cyber Resilience Act (CRA) for instance requires in Article 14 “Reporting obligations of manufacturers” under paragraph 8.
“After becoming aware of an actively exploited vulnerability or a severe incident having an impact on the security of the product with digital elements, the manufacturer shall inform the impacted users of the product with digital elements, and where appropriate all users, of that vulnerability or incident and, where necessary, of any risk mitigation and corrective measures that the users can deploy to mitigate the impact of that vulnerability or incident, where appropriate in a structured, machine-readable format that is easily automatically processable. Where the manufacturer fails to inform the users of the product with digital

elements in a timely manner, the notified CSIRTs designated as coordinators may provide such information to the users when considered to be proportionate and necessary for preventing or mitigating the impact of that vulnerability or incident." [2]

Manufacturers, operators, and regulatory authorities face the critical challenge of converting vulnerability data into structured, machine-readable formats that can be seamlessly processed and automated. A key enabler of this capability lies within the Common Security Advisory Framework (CSAF) [4], an open standard that standardizes the dissemination of vulnerability-related information.

CSAF offers an open, standardized framework for delivering machine-readable information on software vulnerabilities. Built on the JavaScript Object Notation (JSON) data format, it enables the automated generation, publication, and dissemination of security advisories by manufacturers. These advisories provide comprehensive details on specific vulnerabilities, including their severity levels and recommended mitigation measures for affected products.

6 Evaluating the Potential of the Common Security Advisory Framework (CSAF)

CSAF improves the efficiency of security advisories by providing a machine-readable format that enables automated systems to assess vulnerabilities and recommend actions. This enhances response speed and ensures manufacturers can convey precise details, such as immunity to specific threats.

During the 2021 log4j crisis, widespread uncertainty delayed mitigation efforts. CSAF, particularly its Vulnerability Exploitability eXchange (VEX) profile, could have reduced this uncertainty by enabling manufacturers to clarify product impact.

CSAF ensures consistency by standardizing vulnerability representation, scalability by automating large-scale assessments, and efficiency in collaboration by facilitating seamless information exchange. It fosters transparent communication between manufacturers and operators, allowing direct integration of security data and bidirectional feedback.

By streamlining vulnerability management, CSAF minimizes manual effort, reduces economic disruption, and strengthens cybersecurity resilience across diverse infrastructures.

The adoption of CSAF represents a transformative step in vulnerability management, enabling automation, consistency, scalability, and collaborative efficiency. By standardizing the way vulnerabilities are communicated and processed, CSAF reduces response times, enhances operational clarity, and strengthens the resilience of critical systems against emerging security threats.

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Towards an Ontology for Safe Gender-Aware Business Process Management

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Abstract
This paper introduces an ontology for safe gender-aware business process management, addressing the need to incorporate gender equity within business processes in alignment with the principles of Industry 5.0 and Safety-II. Traditional business process management (BPM) has predominantly focused on optimizing performance metrics such as cost, time, and error reduction. However, with the advent of Industry 5.0, a paradigm shift is occurring where social, environmental and safety factors are becoming equally important alongside technological advancements. In this context, gender equity emerges as a critical component of social sustainability yet remains largely unexplored in BPM research and practice. To bridge this gap, we propose an ontology that defines key concepts, relationships, and principles for developing safe gender-aware business processes. Drawing inspiration from the Gender Innovation Approach and recommendations from the European Institute for Gender Equality (EIGE), the ontology includes concepts describing foundational principles for safe gender-aware BPM. These principles aim to ensure that business processes integrate gender equity, justice, and safety while maintaining efficiency and effectiveness. A safe gender-aware business process not only acknowledges gender diversity but leverages it to enhance process innovation, performance, and safety. Our ontology further identifies the phases of the BPM lifecycle modeling, design, analysis, and reengineering, where gendered assessments can be applied. Additionally, it includes concepts to represent indicators to assess whether a business process is gender-aware and safe or requires reengineering to meet gender equity and safety-II standards. Ultimately, this ontology provides a basis for businesses to assess their processes and initiate necessary changes, fostering inclusive safety participation and aligning with Industry 5.0's goals of accessibility, sustainability, and efficiency.

1 Introduction

Throughout history, women have faced systemic discrimination, even in today's supposedly progressive societies. Despite their essential contributions, women continue to encounter barriers in various fields, including STEM and work environment. Historically, these fields were male-dominated, with women facing significant challenges and prejudice. Even by looking at simple statistical data, it is easy to see that female employment rates are lower than male ones. This was partly due to gender stereotypes, such as the persistent belief that men and women have inherent differences in abilities and aptitudes, making certain fields more suitable for one gender than the other. Indeed, labor data clearly shows a gender gap, with women overrepresented in care and education and men dominating fields like politics, science, and technology [1].

Such a gender gap is reflected by industrial processes that do not consider the peculiarities of being a woman. Let us consider a simple example. Sara is a process engineer working in a semiconductor company. Her job takes her to a clean room where she works on production machines. The clean room is a safe environment but can always be prone to gas leaks or possible fires. She has been pregnant for three months and wants to minimize any risk to the unborn child. Unfortunately, enterprise policies do not allow any exemptions for Sara, who is therefore forced to work in the clean room. During her shift, a fire occurs, and Sara is transported to the hospital for a fetal health check. Considering such a case, it is evident that the work regulations applied should have differed between men and women. In particular, the company should have taken pregnancy into account and implemented all necessary safety measures to protect the fetus [2].

In this context, our aim is to address the gender gap in workplace safety as in different work environments, safety and well-being regulations and rules do not usually consider the physical differences between genders. As the first step to this goal, we aim to create a conceptual model to be used to analyze whether business processes are aware of gender diversity and, if needed, to support their reengineering.

Hence, our goal is to construct an ontology that can be applied to various work sectors. An ontology is a conceptual model of a fragment of an observed reality consisting of interlinked concepts [3]. The envisaged ontology addresses business process management in all its phases (i.e., identification, discovery, analysis, redesign, implementation, monitoring) to determine whether they are gender-blind or gender-aware [2]. Indeed, the ontology aims to support the analysis of BPM phases both in terms of work opportunities, such as gender pay gap, held positions, responsibilities, and policies that allow for work-life balance, and safety. A process is considered gender-blind if its sole objective is to minimize costs and maximize profits without considering gender inequalities among workers. Conversely, a process is gender-aware if it allocates resources and attention to reducing these inequalities, offering equal opportunities to both genders and

contributing to a more equitable society, in line with the Industry 5.0 paradigm which seeks to reconcile development and sustainability [4]. A society that provides equal opportunities for all fosters an environment brimming with diverse perspectives and inputs, which in turn facilitates breakthroughs and problem-solving. This paper aims at proposing a conceptual instrument to assess the extent to which gender equity is present in the field of safety and to raise awareness of the challenges faced by women in industrial work. By addressing gender awareness in safety, this paper seeks to inform policy-makers and advocate for the implementation of effective measures to address gender disparities.

The core premise of our work is that safety and gender-awareness are emergent properties of business processes, stemming from the entire business process management (BPM) lifecycle. Therefore, innovations aimed at enhancing these properties must address all phases of the BPM lifecycle.

The paper is structured as follows. Section 2 reviews related work. Section 3 outlines the core of the ontology for safe gender-aware business process management, and Section 4 concludes with the main achievements of this work and some future research directions.

2 Related Work

Numerous studies over time have addressed the issue of women's underrepresentation in the workplace and the safety measures implemented to ensure the well-being of workers. One of the reasons for this gap is the presence of a gender stereotype. The harmful stereotype that women are ill-suited for the workplace has far-reaching consequences. It not only reinforces outdated gender roles but also undermines the value of traditionally feminine traits like empathy and emotional intelligence. These traits, often essential for effective leadership, are frequently overlooked in favor of more assertive and dominant behaviors typically associated with men. As a result, women are often pressured to conform to a narrow leadership style, limiting their potential to foster innovation and inspire their teams [5].

The belief that men and women have different skills can explain why women and men are concentrated in different fields, women prevail in care and instruction fields, while men prevail in fields such as engineering, science that generally are highly paid. Men generally have more opportunities for promotion. Women are paid 16% less than men. Women are more likely to self-select out of job applications if they don't meet all the qualifications, while men often apply even if they meet only 60%. While this has been attributed to women's lower confidence, research suggests it's more likely due to societal expectations that women follow rules and adhere strictly to criteria. Moreover, women receive less feedback respect man, even if both asked them [6].

In some work environments, there is a lack of safety equipment designed for women. Personal protective equipment (PPE) is more important in some jobs such as construction and manufacturing. In fact, several accidents occur in workplaces every

year and PPE could make a difference. Women have a higher risk of having an injury, because there are not fitted PPE items. In fact, for example in the job construction field in the U.S., men are approximately 93,8%. Essential safety gear like harnesses, gloves, helmets, and boots can be difficult to find in women's sizes. However, thanks to recent awareness campaigns, this issue is being addressed. Ensuring all employees have access to properly fitting PPE is a crucial responsibility of employers. Ignoring recent advancements in women's PPE can create a more dangerous workplace for female employees, potentially leading to decreased confidence, increased stress, and reduced performance [7].

A recent study in TUC's guide [8] shows that women and men are always treated equally in terms of safety and health, without considering gender differences. Historically, more attention has been given to risks in traditionally male-dominated fields like construction and mining, while injuries and illnesses common in female-dominated jobs, such as stress and musculoskeletal disorders, have been largely overlooked. Moreover, work equipment is generally designed for male population. According to the International Labour Office [9], women usually have more psychosocial-risk. Women's dual roles as paid workers and unpaid caregivers often lead to higher stress levels. Ignoring gender differences in workplace policies can inadvertently exacerbate existing inequalities. Occupational Safety and Health (OSH) is crucial for promoting gender equality [10].

3 Ontology for Safe Gender-Aware Business Process Management

The proposed ontology for safe gender-aware business process management consists of a core ontology which could be extended according to the specific industrial application or, more in general, safety context. The ontology is visually presented as a UML class diagram in Figure 1.

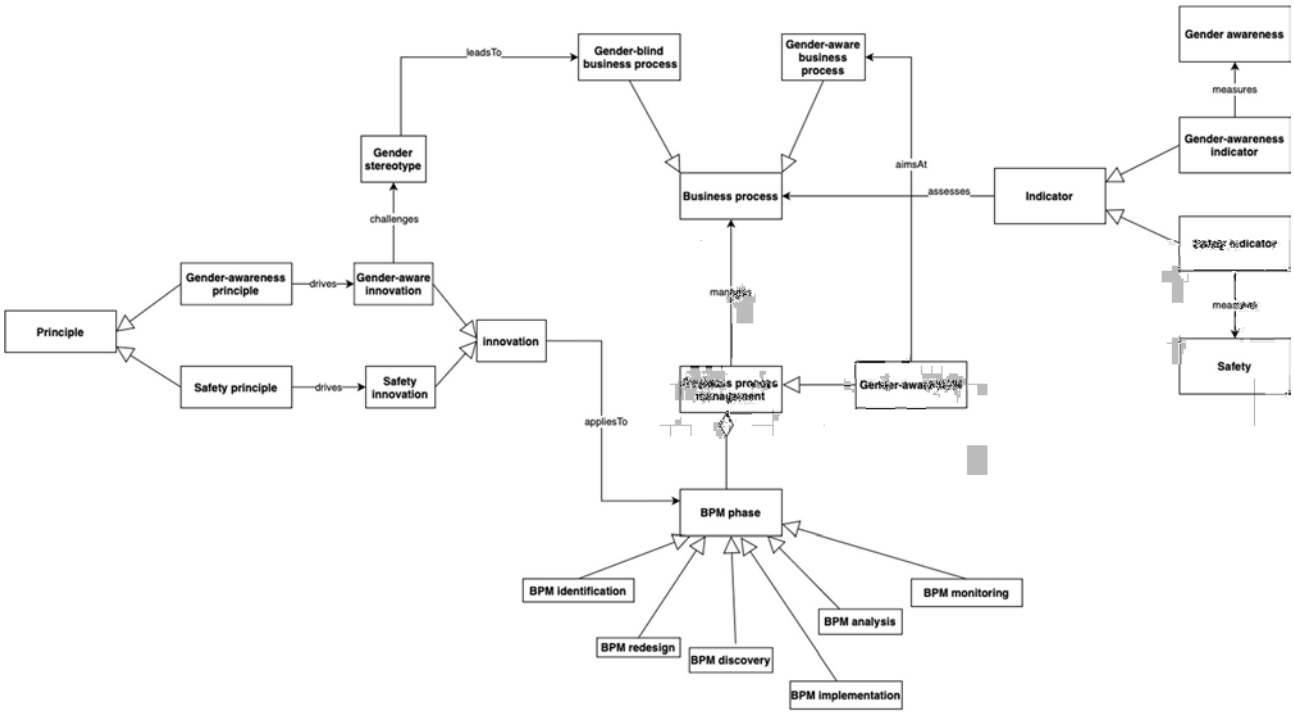

Fig. 1. Concepts of the Ontology for Safe Gender-Aware Business Process Management and their relationships

The ontology concerns business processes and their management. To describe the main concepts, we refer to [11]. In the center of the diagram, we observe the *business process* concept that is defined as a series of steps or activities that an organization performs to achieve a specific goal. It is a structured set of tasks that, when executed in a particular order, produces a desired output or service. Business process management is a systematic approach to improving and managing an organization's process to enhance efficiency, effectiveness, and adaptability. It involves the identification, design, execution, monitoring and optimization of business processes to achieve specific business goals and respond effectively to changing market conditions The *BPM phase* is part of BPM, and we define it as a key stage within the BPM lifecycle that focuses on systematically managing, improving, and optimizing organizational processes to achieve better efficiency, effectiveness, and adaptability. Each BPM phase encompasses a specific set of activities designed to evaluate, transform, or oversee processes to meet business goals. The main BPM phases include: *(i) process identification*, *(ii) process discovery*, *(iii) process analysis*, *(iv) process redesign*, *(v) process implementation*, and *(vi) process monitoring*. Process identification *(i)* is a phase that aims to define the specific business problem and identify, scope, and link relevant processes related to it. The result of process identification is a newly created or revised process architecture, offering a comprehensive view of the organization's processes and how they interconnect. This architecture serves as a foundation for selecting the processes to manage throughout the subsequent phases of the lifecycle. Often, process identification is conducted alongside the identification

of performance metrics. Process discovery *(ii)* is a phase that aims at documenting the current state of each relevant process, usually by creating one or more as-is process models. Process analysis *(iii)* is a phase where challenges and inefficiencies within the as-is process are identified, documented, and, where possible, quantified using performance metrics. Process redesign *(iv)* is the phase that aims to identify and implement changes that address the issues highlighted in the analysis phase, helping the organization achieve its performance goals. Various change options are evaluated and compared based on selected performance metrics. Process redesign and analysis work closely together: as new change options are proposed, they are assessed using analytical techniques. Ultimately, the most effective options are selected and integrated into a redesigned process, resulting in a to-be process model. Process implementation *(v)* is the phase where the transition from the as-is process to the to-be process is prepared and executed. Process implementation involves two main aspects: organizational change management and automation. Organizational change management includes activities designed to help all process participants adapt to new ways of working. Process automation, on the other hand, involves developing and deploying IT systems (or upgrading existing systems) to support the to-be process. Process monitoring *(vi)* is the phase when once the redesigned process is in operation, relevant data is collected and analyzed to assess its performance against established metrics and objectives. This phase helps identify bottlenecks and areas for further improvement.

The second part of the ontology deals with safety and gender awareness in business processes. A *gender-blind business process* [2] is a process that prioritizes process efficiency while disregarding principles of gender equity and justice. A *gender-aware business process* [2] is a business process that incorporates the principles of gender equity and justice while ensuring its own efficiency. Inspired by the Gender Innovation Approach [12] [13], a gender-aware business process harnesses the creative power of sex, gender and intersectional analysis for improving management, and both are part of business process class. *Gender aware BPM* is a framework that incorporates gender analysis and perspectives into the design, implementation, and evaluation of organizational processes and aims to reach gender-aware business processes. A *gender stereotype* is a generalized view or preconception about attributes or characteristics, or the roles that are or ought to be possessed by, or performed by, women and men. A gender stereotype is harmful when it limits women's and men's capacity to develop their personal abilities, pursue their professional careers and/or make choices about their lives, and it leads to gender-blind business processes.

Then, an *indicator* is something that shows or reveals information about a particular condition or situation. It can be a fact, measurement, signal, or device that provides insights into what is happening or what is likely to happen. A *safety indicator* is a measurable value or metric that provides information about the safety performance of a system, process, or organization. A *gender-awareness indicator* is a measurable criterion used to assess the extent to which gender considerations are integrated into

business process management lifecycle. Then, *innovation* is the process of introducing new ideas, methods, or products. It involves taking a creative idea and turning it into something tangible and valuable [14]. *Gender-awareness innovation* refers to the development and implementation of new ideas, strategies, or practices that actively consider and address gender differences and inequalities. This concept integrates gender perspectives into innovation processes to create solutions that promote gender equity, enhance inclusivity, and respond effectively to the needs of diverse genders. *Safety innovation* refers to the creation and implementation of new ideas, technologies, or processes that enhance safety and reduce risks in various settings. It involves a proactive approach to identifying and addressing potential hazards, improving safety performance, and preventing accidents and injuries. Innovation applies to a BPM phase. *Principle* is a fundamental truth, law, or assumption that serves as the foundation for a system of beliefs, behaviors, or reasoning. Principles are guiding rules or standards that help shape actions, decisions, and judgments in various contexts, including ethics, law, science, and personal conduct. *Gender-awareness principles* are guidelines that promote understanding and awareness of gender roles, stereotypes, and inequalities. They encourage the recognition of the diverse experiences and needs of individuals, regardless of their gender identity. *Safety principles* are fundamental guidelines that help ensuring a safe environment. These principles are applied across various industries and settings, including workplaces, homes, and public spaces. Gender-awareness principles and safety principles respectively drive gender-aware innovation and safety innovation.

4 Conclusion

The ontology developed in this study offers the opportunity to design and develop valuable applications for addressing gender stereotypes and discrimination within industrial processes, especially those with potential safety implications for workers. By organizing knowledge related to gender bias in workplace processes, this ontology enables a structured approach to identifying and understanding the influence of these biases on operational safety.

Additionally, the ontology facilitates the analysis of industrial processes to assess whether they are gender-aware or gender-blind, allowing for a proactive evaluation of potential safety risks arising from gender insensitivity. This approach aids in recognizing processes that may unintentionally compromise worker safety due to overlooked gender-specific factors.

Finally, the ontology supports the reengineering of gender-blind processes to integrate gender-awareness, promoting safer and more inclusive industrial practices. Through its application, this work contributes to a safer work environment by aligning process design with both safety and gender inclusivity goals, setting a foundation for further advancements in gender-responsive safety measures within industry.

As future work, we intend to further develop the ontology by extending it with more specific concepts and by integrating it with some upper models, such as the Basic Formal Ontology [15] and the WAx ontology [16] [17] [18].

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How can cultural diversity at work contribute to a culture of prevention?

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Abstract
In the current debate on labor shortage, migration is often discussed as one of the solutions to filling the vacancies. Having a multicultural workforce though, comes with the challenge of keeping all workers safe and healthy despite linguistic and cultural barriers. Many employers are already implementing practical solutions to deal with this challenge. How successful are these solutions and could they even serve as a crystallization point for improving the culture of prevention in general?
The interaction between cultural diversity and occupational safety and health is often seen as a challenge, raising questions like: How can workplaces be safe and healthy despite communication barriers? But what if we shifted our perspective and regarded this challenge as an opportunity to innovate and strengthen the culture of prevention in the workplace? If we take a closer look at the pillars of a culture of prevention and compare them with the recommendations for managing occupational safety and health in a multicultural environment, we see some interesting overlap.
In 2023 and 2024 the ISSA Sections on Prevention in Transportation and on Prevention in Health Services organized two international symposia on the topic of cultural diversity at work in the context of occupational safety and health [1,2]. The present paper is the result of a qualitative analysis of the content of these two symposia. It presents a deep dive into the results of these two symposia and offers the main lessons learned.

Fig. 1. Impressions from the Symposium "Cultural Diversity at Work: Safe and Healthy Integration of Skilled Workers." Dresden, Germany, 27-29 May 2024.
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1 Growing cultural diversity in the workplace

A migrant worker is an individual who moves from their home region or country to another, often in search of employment opportunities that may not be available locally. This term typically refers to workers engaged in temporary, seasonal, or long-term jobs across various sectors, such as agriculture, construction, or manufacturing and may involve crossing national or international borders. Migrant workers are often driven by economic needs, but their migration can also be influenced by other factors such as political instability, climate change, or family reunification.

In 2023, migration to OECD countries reached record levels for the second year in a row. Not only have 6.5 million permanent migrants arrived in 2023, but also the number of temporary migrants and asylum seekers has skyrocketed. Growing labor demand in host countries has been a key driver of migration over the past two years [3]. When analyzing the working conditions of these migrant workers in their new host countries, it is good to differentiate between the different backgrounds and reasons for migration. For instance, there is huge difference between highly skilled migrants and poor dispossessed migrants such as illegal immigrants.

Although not all migrant workers are at risk regarding their occupational safety and health, for instance when migration results in new career opportunities or a general enhancement of well-being, on average, the less skilled migrant workers are often engaged in jobs that are potentially hazardous to their health. They often work for less pay, for longer hours and under worse conditions than do non-migrants. Worldwide, migrant workers have higher rates of adverse occupational exposures and working conditions, which can lead to poor health outcomes, workplace injuries and occupational fatalities [4].

2 Onboarding migrant newcomers

Beyond the challenges migrant workers face in the workplace, they often grapple with adjusting to a new social environment, which can be overwhelming and multifaceted. Learning a new language is frequently one of the first hurdles, as effective communication is essential not only for work but also for navigating everyday life. Finding appropriate housing is another significant obstacle, often complicated by unfamiliar rental systems, high demand, or discrimination. Moreover, dealing with bureaucratic processes in a foreign country can be exhausting and confusing. This may include tasks like getting official qualifications recognized—such as diplomas, certifications, or a driver's license—or setting up a bank account, each of which can involve complex procedures and delays. These logistical barriers can create a sense of frustration and helplessness.

On a deeper level, many migrant workers experience a profound sense of loss. Leaving behind family, friends and the familiarity of their home environment takes an emotional toll, compounded by the pressures of adapting to a new culture. Initially, the excitement of starting a new job and the warm reception from colleagues often help mitigate these feelings. However, as this initial phase wanes – usually after about three months – a sense of emptiness, often described as a "culture shock" may set in. This phase can involve feelings of alienation, homesickness and even self-doubt as workers struggle to reconcile the realities of their new life with the expectations they had before arriving.

For employers striving to integrate migrant workers safely and healthily, it is vital to recognize these challenges and the cumulative impact they can have on mental well-being. Supporting migrant workers requires a long-term, proactive approach that prioritizes mental health alongside practical assistance. This might include providing access to counseling services, fostering a supportive workplace culture and maintaining regular check-ins to ensure that workers feel valued, connected and supported throughout their adjustment period. Addressing these needs holistically not only benefits the workers but also strengthens the organization by building a resilient and engaged workforce.

3 Intercultural awareness

Intercultural awareness is a critical component of creating a robust culture of prevention because cultural differences often lie beneath the surface, influencing behavior in ways we may not immediately recognize.

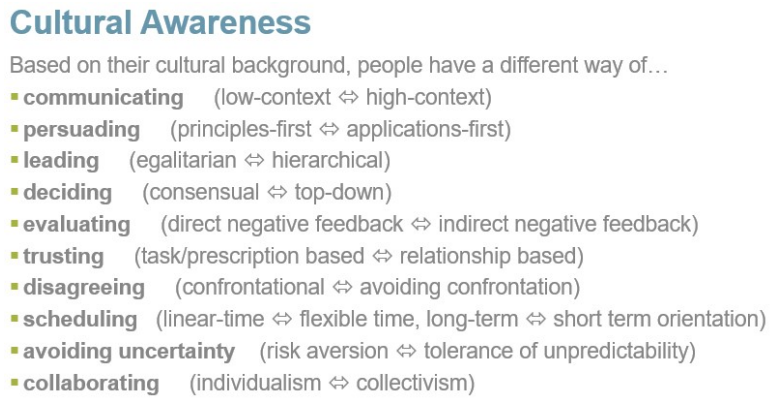

Fig. 2. Cultural awareness. Adopted from [5, 6]
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- For example, people from high-context cultures often rely on implicit communication, assuming shared understanding, whereas those from low-context cultures prefer explicit, detailed instructions.
- When it comes to persuasion, some individuals prioritize logical principles and theoretical foundations, while others focus on practical applications and concrete examples.
- Leadership styles also vary significantly, with some cultures favoring egalitarian approaches where all voices are heard, and others leaning towards hierarchical structures with clear authority.
- Decision-making processes can range from consensual, involving broad consultation, to top-down, emphasizing swift, individual leadership.
- Feedback styles also differ – direct and straightforward in some contexts but indirect and softened in others to maintain harmony.
- Trust-building further illustrates these differences. In task-oriented cultures, trust develops through competence and reliability, while in relationship-oriented cultures, personal connections and rapport take precedence.
- Disagreements may be openly debated in confrontational cultures, whereas they might be delicately avoided to preserve relationships in others.
- Approaches to scheduling range from linear and strictly timed to flexible, where priorities shift dynamically.
- Collaboration can also differ, with some groups prioritizing individual achievement and autonomy, while others emphasize collective goals and interdependence [5].
- Likewise, attitudes towards uncertainty vary; some cultures exhibit strong risk aversion and prefer detailed planning, while others embrace unpredictability with greater flexibility [6].

However, it is crucial to approach this knowledge with nuance. These patterns should not be treated as rigid rules or applied as a cultural “manual” for specific countries. Nor should individuals be pigeonholed based on assumed group characteristics. The key to

fostering intercultural awareness is recognizing the rich diversity beneath the surface and treating each person as a unique individual. This mindset not only enhances our ability to navigate differences but also strengthens mutual respect and understanding in the workplace.

4 Onboarding migrant workers safe and healthily

From an employer's perspective, integrating migrant workers is both a necessity driven by labor shortages and an investment requiring time and resources. While it is often cheaper and more convenient to recruit locally, the current labor market makes it essential to focus on welcoming workers from diverse backgrounds effectively [7].

Cultural Diversity: Challenges & Recommendations

Challenges	Recommendations
Language	courses, translators, pictograms, videos without words, buddy program, technical devices (ear piece translator)
Different values, ethics, customs, different perception on safety	cultural awareness, incentivize communication, have clear expectations, praise correct behavior, trustful error culture
Migrant: culture shock, existential uncertainty & bureaucracy	have patience, show respect, thoughtfulness, mental health awareness, improve social climate, support with paperwork
Not enough time to learn procedures and systems	redesign onboarding processes, patience, buddy program
What about the existing team?	incentivize communication, participation, leadership, team building, cultural awareness, mutual respect, social climate
Failing appreciation for the translators and buddies	show respect and appreciation, praise

Fig. 3. Cultural diversity: challenges and recommendations.
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Integrating migrant workers successfully comes with a number of challenges that go beyond the usual difficulties of recruiting and onboarding new employees. It is important to keep these in mind and develop appropriate strategies to deal with them. Here is an overview of the most common challenges and ways to approach them.

- The language barrier is a key challenge, but this can be mitigated with practical solutions such as language courses, the use of translators, pictograms, wordless instructional videos, buddy and mentoring programs, or technical devices like earpiece translators.
- Differences in values, ethics, customs and perceptions of safety also require attention. Employers can address these issues by fostering cultural awareness, encouraging open communication, setting clear expectations, praising correct behavior and cultivating a trust-based error culture.
- Migrant workers often face personal challenges, including culture shock, existential uncertainty and the complexities of bureaucracy. Employers can support them by showing patience, respect and thoughtfulness, promoting mental health awareness, improving the workplace social climate and assisting with paperwork.

- Another common issue is insufficient time for migrant workers to learn new systems and procedures. Redesigning onboarding processes, providing structured support through buddy programs and demonstrating patience can help ease this transition.
- Additionally, the integration process affects the existing local team. Encouraging communication, participation and leadership, while fostering team-building activities, cultural awareness and mutual respect, is vital for a harmonious work environment.
- One thing that is easily overlooked is the failing appreciation for the extra efforts of colleagues who serve as translators, buddies or mentors. Employers should recognize and value their contributions by showing respect, expressing gratitude and offering regular praise.

5 Culture of Prevention

The above-mentioned recommendations for successfully integrating migrant workers align closely with the key elements of a strong prevention culture. A prevention culture reflects the value an organization places on safety, health and well-being in everyday work. When these priorities are deeply ingrained, everyone understands the importance of identifying risks and continuously seeking improvements. In such a culture, topics are openly discussed by all members of the organization, regardless of their role or background, within a social climate of respect, belonging and appreciation. Essential elements include leadership that sets the tone, effective communication that ensures clarity, active participation from all team members, a trust-based error culture, a supportive social climate and a continuous commitment to safety and health.

Interestingly, these same elements underpin the successful integration of migrant workers. Leadership fosters inclusivity and sets clear expectations. Communication bridges language and cultural gaps, while participation engages all workers, creating shared ownership of processes. A healthy error culture encourages open dialogue about mistakes and solutions and a positive social climate supports belonging and trust. Combining these principles shows that cultural diversity can strengthen the organization’s prevention culture. The integration of migrant workers not only addresses immediate labor needs but also presents an opportunity to enhance workplace safety, health and well-being for everyone.

Culturally aware OSH leadership

Culturally aware leadership in the field of occupational safety and health begins with incentivizing communication, ensuring that essential topics are openly discussed rather than assumed to be self-evident. Leaders must articulate clear expectations, recognizing that behaviors, such as punctuality, may hold varying levels of importance across cultures. Explicitly discussing these expectations helps bridge potential misunderstandings. Timely praise is another critical component. Acknowledging correct behavior rather than solely focusing on outcomes reinforces the desired practices that underpin long-term success, such as fostering an open dialogue about errors.

An open and trustful error culture is essential for safety, requiring leaders to address the cultural nuances of shame and guilt. By fostering communication that avoids blame,

they create an environment where mistakes are seen as opportunities to learn rather than failures to conceal. Safety training should not exist in isolation but be embedded within a broader prevention culture. This requires leaders to ensure that training is supported before, during and after implementation, with supervisors and colleagues taking the content seriously. Finally, culturally aware leadership emphasizes continuity, demonstrating a clear and consistent commitment to occupational safety as a long-term priority for the organization and its people.

6 Culturally aware OSH communication

Culturally aware communication in the field of occupational safety and health starts with recognizing that assumptions about what is "normal" may not apply universally. While it is not about mastering the specifics of every culture, it is crucial to develop a broad sense of intercultural awareness—an understanding that differences in values, behaviors and perceptions exist at deeper levels than we often realize. This mindset underscores the importance of explicit communication: everything that matters, from seemingly small details like office climate preferences to critical issues of safety and health, must be openly discussed.

Adopting a basic attitude of non-assumption and learning to communicate preferences and wishes clearly, for instance, by using first-person expressions, helps avoid the pitfalls of blaming or shaming. These skills become even more essential in multicultural settings, where trust and mutual understanding are vital. Building a culturally aware prevention culture is not just a matter of ethical responsibility; it is also a business necessity. Without it, the investment in recruiting and onboarding a diverse workforce risks being wasted. As workplaces become increasingly diverse, culturally aware communication is no longer optional—it is a cornerstone of sustaining safe, healthy and effective operations.

7 Conclusion

Regardless of whether the aim is to improve the culture of prevention or to integrate migrant workers, it is worth keeping in mind that the reality of our own lives is not necessarily that of the person next to us. Actively embracing inclusivity and intercultural awareness both serve as strong pillars to improve the culture of prevention in the workplace.

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Human Machine Interaction (HMI) - Visual coding for inclusion

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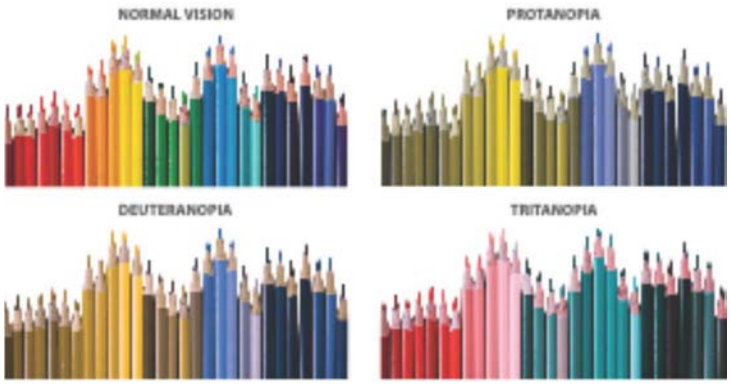
Abstract
Disability is a reduced capacity of interaction with the social-cultural-physical environment compared to what is considered “normal” and it is a condition that everyone can experience in life. A properly designed physical environment, as well as inclusive products and technologies, are factors that can ‘scale down’ disability and encourage participation and autonomy in carrying out activities. In the workplace, an inclusive and accessible environment is a prerequisite to assure the right to work on an equal basis in safe, healthy and well-being conditions.
Statistical data indicate that in Europe about 8% of males and 1% of females are affected by partial colour blindness, commonly known as Daltonism. These values suggest not to overlook such “group of workers", and highlight the need to evaluate work contexts where these persons might be exposed to risks or find themselves in unfavourable conditions compared to “normal” people. This paper contains the main reference standards and measures that can improve inclusion and safety of color-blind people when operating a human-machine interface. Moreover, it gives color-design guidelines that can help reduce the risk that can occur in industrial workplaces, where workers interface with machine control devices equipped with visual, color-based, emergency or operating signals.

1 Introduction

Dyschromatopsia is one of the color-vision deficiency that can compromise safety at work, as, altering the visual capabilities of a worker, it could origin errors during the task performance. Dyschromatopsia, commonly also known as Daltonism, is a color-vision deficiency due to impairment or absence of one of the three color-vision receptors (cones). There are three types of cones, depending on the wavelength to which they are sensitive: there are cones called S (short), which are most sensitive to short wavelengths; M (medium) cones with greater sensitivity on medium wavelengths, and L (long) cones which are sensitive to long wavelengths [1]. Anomalous Trichromacy (Protanomaly, Deuteranomaly, and Tritanomaly) is characterized by the presence of all cones, but with an altered visual function (Fig. 1A).
Dichromia (Protanopia, Deuteranopia, Tritanopia) is characterized by the absence of one cone, which makes red, green, blue and yellow recognition difficult or even

impossible (Fig.1B). Visual coding of Human-Machine-Interface (HMI) control devices are usually based on these colours.

A



B

Fig. 1. A: comparison between the vision of a normal subject and subjects affected by Anomalous Trichromacy.B: comparison between the vision of a normal subject and subjects affected by Dichromia.

2 Control devices

Control devices constitute the element through which the operator activates or deactivates machine functions. They can be located on the machine itself or far from it (remote commands), being connected, for example, via wire, radio, optical, or sound signals. Control devices must be clearly visible and identifiable using, where appropriate, pictograms; they must be designed to allow the unambiguous identification of the actions that are performed by their activation. They can be "associated" with indicators, with or without specific visual and/or audible warnings, which provide operators with information about machine operating parameters such as speed, load, temperature or pressure. Furthermore, they can give operators warnings about safety values exceeding relevant parameters. In all cases, the comprehensibility of the signal must be guaranteed [2].

3 The visual code in control devices

Establishing rules to attribute a specific meaning to some visual, acoustic and tactile indications is functional for a rapid recognition of the machine state and the actuators position. The choice of coding depends on the tasks that the operator must perform, and the associated surrounding conditions in which these must be performed.
Among type B International technical standards containing directions related to the codes for control device indicators [2] - [7], CEI EN 60073-1 defines the principles of visual, acoustic and tactile coding. The visual code is one of the identified means, both together with and as an alternative to acoustic and tactile codes, and it can be expressed with color, shape, position and change of characteristics over time (intermittency). The use of color and intermittency are the most effective visual means to attract attention. Precisely for this reason, they are used for specific meanings: color (hue) to give priority, intermittency to attract attention. The color hue is, therefore, considered the most effective means of visual coding, because it can be decoded most quickly. In fact, it is used, as a priority choice, for safety messages (Fig. 2).

Colour	*Meaning*		
	Safety of persons or environment	Condition of process	State of equipment
RED	*Danger*	*Emergency*	*Faulty*
YELLOW	*Warning/Caution*	*Abnormal*	*Abnormal*
GREEN	*Safe*	*Normal*	*Normal*
BLUE	*Mandatory significance*		
WHITE	*No specific meaning assigned*		

Fig.2. Table 2 - CEI EN 60073:2003-04 Meaning of colours for coding – general principles

The possible visual deficiency of the user makes the measure ineffective: not being able to distinguish red may mean not recognizing Danger. The technical standard [3] requires, when people who cannot distinguish colors are employed, to use additional coding (Fig. 3).

Supplementary means	Elements
Shape	Figure (alphanumeric, pictographs, graphical symbols, lines) Form (character font, size, line width) Texture (line type, shading, dotting)
Position	Location (absolute, relative) Orientation (with or without reference system)

Time	Changing over time (flashing): - Brightness - Colour - Shape - Position

Fig. 3. Coding by supplementary means to colour (visual code) – CEI EN 61310-1:2008-10

The indication of the standard is limited to cases in which the sensorial abilities of all operators are known. However, it is possible that visual abilities are not known, especially in the milder cases of color blindness (Protoanomaly and Deuteroanomaly). It is therefore desirable that adequate information and indications are always provided, to allow the people who must read, interpret and respond to such codes to receive adequate instructions [5].

3.1 Color in the visual code

Technical standards only give indications on color hue for control devices; conversely, they lack guidelines on saturation, brightness or contrast, which are indeed necessary for precise color identification. Specifically, for the exact definitions of surface colors, one should refer to ISO 3864-1, in turn referred to by UNI 7543-2. Both refer to the CIE 15.2:1996 colorimetric system and provide the chromatic and luminance coordinates admitted for the colors of safety signs for different materials. It's possible to find the unique indication on contrast in the provision of the standard EN ISO 13850: it requires that the actuator of the emergency stop device must be RED. As far as a background exists behind the actuator, and as far as it is practicable, the background shall be coloured YELLOW [6]. This specification is very useful in general but even more in the presence of "color-blind" workers who are always able to perceive yellow.

3.2 Chroma

Chroma is a very important aspect: it allows color-blind operators, except in rare cases of dichromacy (e.g. protanopia), to discriminate hues. It has been shown [8] that buttons made in ordinary material with saturated hues (i.e., with higher Chroma) can be better discriminated compared to the case in which less saturated hues are used, even by subjects affected by chromatic anomaly. The discrimination between the two colours improves as chroma increases. Fig. 4 shows two high chroma colors (left), and two low chroma colors (right), under normal, protanomaly, protanopia, deuteranomaly and deuteranopia conditions. It can be easily seen that high chroma colors can be more easily distinguished, in particular under non-normal color vision conditions.

Fig. 4. Left: Two high-chroma colors under normal, protanomaly, protanopia, deuteranomaly and deuteranopia.
Right: two low-chroma colors under normal, protanomaly, protanopia, deuteranomaly and deuteranopia.

It should be noted, however, that colour saturation also depends on the surface finishing of the button. Matte surfaces appear less saturated than glossy ones. The problem of the relationship between color perception and chroma is less important when using yellow and blue, since just a small percentage of people suffers of genetic visual anomaly for these colours (tritanopes; protans and deuteranopes perceive them correctly).

3.3 Luminance and Lightness

Luminance is not represented in the two-dimensional CIE diagram. However, the technical standard UNI 7543-2 provides the minimum usable values of the luminance factor[1]. Luminance, in fact, can help color discrimination. When two different hues (e.g. red and green) are placed side by side, discrimination can be difficult for the color blind [1],[8]. An example is shown in Fig.5, where two greens with different Luminance factors are shown close to the same red, under normal, protanomaly, and

1 The Luminance factor is the ratio between the luminance of the surface and that of a perfect diffuser illuminated in the same way. The Luminance factor Y of a color sample is a function of solely the sample Lightness (“Value”, in the Munsell color system).

protanopia visual conditions (on the left); under normal, deuteranomaly and deuteranopia conditions (on the right). The two greens have Luminance factor Y=14 and Y=35, respectively; the red has Luminance factor Y=14. It can be seen that under protanomaly and protanopia conditions, as well as under deuteranomaly and deuteranopia conditions, the red and the green are still discernible when the Luminance factors are different. Conversely, they appear very similar when they have the same Luminance factor.

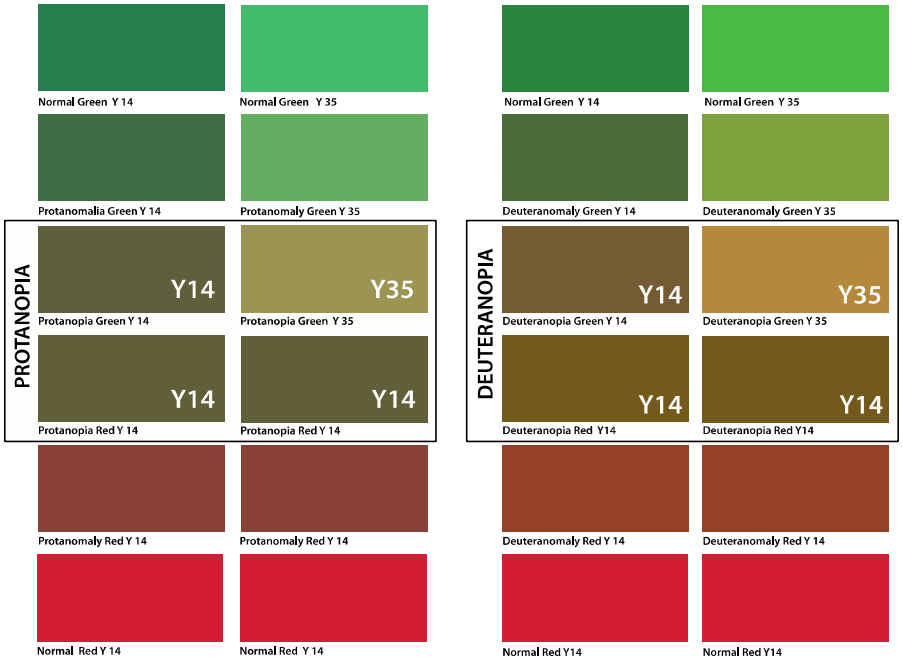


Fig. 5. Comparison under normal conditions, protanomaly, protanopia (left) deuteranomaly and deuteranopia (right) of one red and one green with the same luminance factor (Y=14) and of the same red with a second green with different luminance factor (Y=35).

4 Color vision anomalies and filtering lenses

According to scientific analyses the filter lenses commercially available cannot give a good perception of colours to colour-blind- people. Anyhow, they could be useful if a colour-blind operator needs to recognise only a specific signal. In this case, in fact, using a filter lens may brighten one signal and darken another one, making them distinguishable. For example, if a blue stimulus must be distinguished from a red one, the filter lens may leave the brightness of red stimulus unchanged, while making darker the blue stimulus.

It is therefore possible to manage in this way the possible risk connected with the use of a machine by colour-blinded people: it can be assumed that the assigned tasks are so diverse that it is impossible or uncomfortable for the worker to use the filter lens only when the red signal is expected.

5 Conclusions

HMI takes place also through color coding, which is considered a priority visual signal to communicate safety (information and warnings). At the same time, considering the significant impact of colour vision deficiency on the population, it is not possible to ensure safety at work excluding both colour-blind people (and elderly people too!) from many jobs; especially those that involve the use of machinery, sometimes even used in non-professional activities.

Although the standards consider generically “colour-blind people”, this definition refers to different situation and different levels of severity. Some colours vision tests promote this too generic interpretation. Consequently, it is possible that many persons with mild diseases that do not impair their operating capabilities are excluded from work. On the other hand, in such cases, an inclusive design could defeat the possible disadvantage beforehand. Technical standards, the adoption of which is voluntary, don’t give complete specific indications in this regard. For example, when a signal is primarily a colour signal, technical standards suggest including additional coding when it can be assumed there will be a colour-blind operator. It doesn’t give, e.g., indications of preference between the different codes. Considering that workers reaction time to the signal/alarm given by the machine is a function of the time they spend to perceive and decode it, it would be appropriate to evaluate the quality and quantity of various codes based on the time it takes to identify, recognise and interpret the coding.

It is desirable, in the future, to study this topic with tests designed specifically. Similarly, tests are useful for evaluating persons that could become job/task oriented i.e. linked to the specific task they must perform.

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Amusement parks: inclusion and safety through technological innovation

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Abstract

Addressing social inclusion across all areas of life and work is of paramount importance, ensuring that all segments of the population are considered, regardless of gender, age, ability, social status, occupation, or other factors. Inclusion means recognizing differences and developing the ability to respond effectively to the different needs they present by adapting our concept of sociality. Consequently, the concept of inclusion can be regarded as a fundamental entitlement that is not contingent on individual attributes or capabilities. To this end, an integrated methodology is essential to identify the technological solutions that can facilitate inclusiveness, both in training and in the execution of activities in daily and professional life.

It can be argued that the issue of inclusiveness is a significant concern for amusement park designers and managers for several reasons, both technical and psychosocial. The amusement park, a place of entertainment and recreation, can also serve as an opportunity to test individual abilities and limits, as well as to manage emotions and reactions in “extreme” scenarios that exceed the usual parameters. Moreover, participation in recreational activities can help socialization as well as social reintegration of people injured at work whose abilities have been affected. The exclusion of individuals from amusement parks may lead to feelings of frustration and marginalization. Furthermore, a proactive approach to the design of the park equipment and games could focus on educating and training children, adolescents and adults (including workers) in the appropriate handling of hazardous situations, both at work and in private life, to foster a culture of safety.

Guaranteeing the safety of all amusement park users, regardless of their differences, is crucial and shall consider that the equipment operating parameters are often set to subject users to stresses that approach human tolerance limits. Therefore, ensuring safety in this “extreme” setting also can help explore technical solutions that could be applied in work-related contexts.

This article presents case studies analysing technological solutions for inclusive and secure amusement park design, while also considering the potential of innovative approaches.

1 Introduction

The analysis of risks is linked to interactions between equipment and users, where these are not only operators and maintenance workers, but also people who to use them for leisure, is the objective of a project and research path in collaboration with ride manufacturers and amusement park operators.

In this context, it is of extreme interest to consider the issue of accessibility from the perspective of inclusiveness, to understand which constructive choices and which operational attentions - in the ordinary as well as in emergencies - are necessary for a place of life such as an amusement park to be truly accessible and inclusive for all.

Worldwide, there are thousands of amusement parks, ranging from small regional parks to large international destinations. The top 10 amusement park operators globally including Disney, Merlin Entertainments, and Universal, reported a combined attendance of 512.3 million visitors in 2023, showcasing the popularity of these attractions.

Amusement and water parks offer more than just entertainment: these recreational spaces offer the opportunity to socialize, testing individual limits, exploring emotional resilience, and fostering social inclusion. Amusement parks are a location for leisure, education, inclusion and cultural change.

Moreover, amusement parks provide employment opportunities for people with disabilities. Companies increasingly recognize the value of inclusive hiring practices, offering adaptive roles that match employees' abilities while enhancing workplace diversity.

27% of people over the age of 16 living in the European Union have some form of disability: considering that the EU has 448.4 million inhabitants, people with disabilities living within European borders are over 101 million: really many people who have the right to have fun like everyone else, whenever possible.

Excluding individuals from amusement park activities can generate feelings of frustration and marginalization, particularly for those with disabilities. Accessibility and inclusion should therefore be central to park design and operation, ensuring that all visitors—regardless of physical or cognitive abilities—can participate adequately. Engaging in recreational activities can help build confidence, strengthen social bonds, and foster a sense of belonging.

Participation in group activities at amusement parks can significantly improve socialization skills. For individuals with limited mobility or other types of disabilities, these shared experiences can rebuild bonds with friends, family and community. For individuals with limited mobility or other kind of disabilities these shared experiences can improve relationships with friends, family, and the community.

By embracing universal design principles and integrating educational components into their attractions, these venues can promote a culture of safety, resilience, and social integration. In doing so, amusement parks can transform into inclusive spaces that not only entertain but also empower and educate, ensuring that no one is left on the sidelines of joy and discovery.

While progress in accessibility is commendable, challenges remain. Many traditional rides still lack accommodations for individuals with physical disabilities, and the cost of implementing inclusive designs can be a barrier for smaller parks. However, these investments benefit not just guests but also the reputation of the parks themselves, attracting broader audiences and promoting a culture of equity that values the corporate social responsibility (CRS).

2 Equality and inclusion: living and working environments

In European policies the topic of inclusion has been the subject of great attention. On the EU Commission website [1] it is written: “A truly inclusive society empowers and uses everyone's potential. This is why the Commission has put equality at the heart of its agenda, striving to build a Union of Equality where all people can live free from discrimination.

In 2020 and 2021, the Commission adopted five strategies to create the conditions for everyone to live, thrive and lead regardless of differences based on gender, racial or ethnic origin, religion or belief, disability, age or sexual orientation”. Among them, “The Strategy for the Rights of Persons with Disabilities 2021-2030” which “aims to improve the lives of people with disabilities and ensure that they can enjoy their rights and participate fully in society and in the economy on an equal basis with others”.

Also in recent years, several regulations have been adopted to make the EU more accessible to people with disabilities, including for example

- the European Accessibility Act for Certain Products and Services [2],
- the Web Accessibility Directive [3],

and recommendations on accessible and assisted accommodation for people with disabilities.

Specifically, the European accessibility act “is a directive that aims to improve the functioning of the internal market for accessible products and services, by removing barriers created by divergent rules in Member States”: as well as having the aim of free movement of products within the EU, it has the aim of benefiting the persons with disabilities and elderly people. This directive defines the ‘persons with disabilities’ as “persons who have long-term physical, mental, intellectual or sensory impairments which in interaction with various barriers may hinder their full and effective participation in society on an equal basis with others” and applies only to certain products and services, considered among the most essential for the autonomy and inclusion of people with disabilities (computers and operating systems, ATMs, ticketing and check-in machines, smartphones, TV equipment related to digital television services, telephony services and related equipment, access to audio-visual media services such as television broadcast and related consumer equipment, services related to air, bus, rail and waterborne passenger transport, banking services, e-books, e-commerce).

However, despite these efforts and the progress made in recent years, persons with disabilities still face considerable barriers in our society. Confirming this, from a survey correlated to the adoption of the aforementioned “Strategy for the Rights of Persons

with Disabilities 2021-2030" [4], it emerged that "101 million people in the EU have a disability", of which 42.8 million are of working age and only half of them is employed; moreover, more than "50% people with disability feel discriminated against".
The concept of inclusion has developed from the UN convention on the rights of persons with disabilities and has helped to broaden the perspective of the 'simpler' integration: it concerns all human persons, regardless of their abilities or disabilities, which is also completely in line with the perspective of the ICF - International Classification of Functioning, Disability and Health [5] - which puts the person at the centre and fully opposes the concept of 'exclusion'.
Therefore the concept of inclusion, while not denying differences between people, shifts the focus of analysis and intervention from the individual to the context, with the aim of identifying and removing barriers. This is not always easy, as the extent to which an element can be a barrier to movement varies from person to person.
Thanks also to regulatory interventions, many accessibility problems in public and private places have been solved over time, such as those related to stairs, doors, slopes, lifting equipment, small spaces, suitable materials for a path or floor, orientation signs, dimensions of certain furniture components, development of appropriate signage, dedicated and adequate parking and toilet facilities, etc.

3 Amusement parks: recreational and working places for all

The perspective of inclusion described in the previous point is particularly interesting when applied to the amusement park environment, which presents additional difficulties in relation to the built environment alone, also due to the scarce regulation of the sector and the limited data on the accessibility of attractions.
A place dedicated to recreation and well-being, the right of everyone to enjoy in peace and safety, to improve the quality of life of everyone, regardless of disability or age, and where children can not only access and enjoy the entire park in complete freedom, but also use the games and attractions installed, even better if they are independent. Hence the need to design and develop inclusive parks, where the attractions are complex machines that must guarantee very high safety standards and, at the same time, universal accessibility.
This necessarily requires greater attention and a multidisciplinary approach to understand the best strategy to minimize risks and reach benefits for all.

3.1 The amusement

Over the years, numerous scientific studies have investigated how much amusement positively influences human well-being and play, pleasure and fun are important in any cultural construct: for a good quality of life, 'positive emotion' and fun experiences are essential because - by bringing benefits to the conditions of stress, anxiety, depression - they provide people with greater emotional stability and therefore more resources to face daily life [Figure 1].

If we relate the concept of inclusivity to the benefits of positive emotions and fun, we can see how maximum inclusivity coincides with high levels of wellbeing, and how the amusement park can therefore also fulfil an important social function.

3.2 Inclusion, Accessibility and Security

However, working from an inclusion perspective does not mean ignoring potential risk situations associated with structurally complex environments such as parks: accessibility means the ability to ensure a safe and appropriate physical space, while respecting differences and diversity. Within a park, these perspectives must be placed in a dynamic relationship with each other, creating paths (not only 'physical' ones) that allow everyone to enjoy their rights without taking unnecessary risks, and to accept their limitations.

The main barriers to accessibility are often mental barriers, which see disability as a "lack" that prevents people from "doing". But if we repeat the argument from the point of view of the abilities that people retain, it is easy to see how it becomes much less limiting. On the other hand, people with disabilities must also be willing to recognize their limitations (as we all must) and accept that there are situations that cannot be overcome. Accessibility must not be seen as 'at any cost', but as a potential to be developed as much as possible, always bearing in mind the possible risks. Access is a right, but managers also have a duty not to create unnecessary risk situations and to protect their work and their role.

Fig. 1: fun experiences as a right for

It is certainly a difficult balance to strike, as each actor tends to dominate the process, whereas the solution probably lies in finding a compromise, a meeting point that is reasonable and satisfactory for all.

The risk assessment of attractions, through the analysis of the different operational phases and the skills needed to manage them, seems to offer a concrete perspective to tackle the

problem, even in its most complex aspects, and to propose solutions that can be easily implemented.

3.3 Mental barriers

Cultural and mental barriers also play an important role in inclusive approaches and the 'regulation' of different accessibility options.
Widespread prejudices prevent different health conditions and needs from being seen for what they really are and instead place them in a space where the first reaction is rejection and fear, exclusion, the opposite of what is intended.
For example: one of the most common misconceptions is that Down syndrome is a disease, when it is rather a genetic condition that does not prevent a person from leading a 'normal' life. Or that people with mental health problems are "dangerous" and should therefore be kept away a priori. Or that autistic children can have uncontrolled and uncontrollable reactions on rides. All categorizations that refer to a concept where diversity is basically seen as a sign of 'illness': a 'sick person' who is 'unable to...'. But behind the diagnostic labels, we must remember that there are people, that each person is different, and that we must look at the people with their needs and requirements.
A great deal of cultural training is therefore needed, especially for park operators who deal directly with guests, and for management who define the criteria for accessibility and safety. Only with a thorough knowledge of the different conditions in which everyone can find themselves can the best solutions be assessed from a truly inclusive perspective.
This aspect also concerns guests with special but not obvious conditions, who therefore must choose between making their problems known or pretending that they do not have them. In this case, accessibility and inclusion are also based on a relationship of sharing and trust: "if I clearly indicate my condition, I enable the operators to offer me the best possible situation in this particular context", i.e. to take the most effective protective measures and to make any rescue intervention by the operators quicker and timelier. If no one knows anything, the potential risks multiply and the possibility of prevention is reduced.

4 The regulatory context

The use of attractions in amusement parks is certainly first and foremost an 'experience'; the sensations and effects on the body and mind are many, on different levels, in combination with each other.
They range from biomechanical effects to psycho-emotional ones, with sensations that could go so far as to make one perceive a dangerous situation. Fortunately, this is not the case, as the risks are assessed at the design stage and then during operation, based on international technical standards that include requirements derived from dozens of years of experience and billions of people who have safely used attractions around the world. This is a fact and can be seen in the safety statistics.

However, when we talk about 'accessibility and inclusion' in amusement park attractions, we must consider the almost infinite human diversity. This human diversity, combined with the many types of attractions, with levels of biomechanical effects from the mildest to the most extreme, with scenic effects and special effects that complement and combine with physical effects, makes 'design for all' technically very complex to achieve, and the goal at this stage can hardly be to allow 'all people on all attractions'.

The technical and safety challenge is therefore no longer focused on people with disabilities or special needs, but on 'all people' with their diversity and abilities.

Unlike the built environment, where there is a wealth of data and standards, there is little medical/scientific data on accessibility in attractions, because the situations are really special, outside the everyday experience. This is the very purpose of attractions, to provide unique, fun, exciting, extreme experiences.

Currently, the design and choices to ensure maximum accessibility and inclusiveness, without unacceptable risks, are referenced to the approach contained in the technical standards for the safety of attractions, the EN 13814 series at European level and the ISO 17842 series at international level, the only references available being specific equipment for use in fairgrounds and/or amusement parks, which are excluded from the scope of the Machinery Directive 2006/42/EC.

According to these standards, the starting point for proper design is a risk assessment, it called a DRA (Design Risk Assessment) and developed by the attraction manufacturer. The park then develops an operational risk assessment called the OURA (Operation and Use Risk Assessment). In terms of accessibility and inclusion, the manufacturer's aim is to identify the essential skills required for safe use of the attraction, including emergency situations and possible evacuation. The park develops appropriate procedures, information and training to complete the risk mitigation framework.

According to the technical standards, all phases to use of the attraction, from entry to exit, should be analysed: hazards identified, risks assessed, hazards eliminated or reduced where possible, risks mitigated, as should always be done in a risk assessment. But this is a special risk assessment because it involves people, with all their diversity and consequent abilities.

Specifically, the two international technical standards EN 13814-1:2019 and ISO 17842-1:2023 include an informative appendix entitled "Limited accessibility to amusement devices", which provides information and data useful to developing DRA and OURA risk assessments from an accessibility perspective.

Unfortunately, the lack of data and specific studies makes this analysis difficult and complicated. The 2012 Italian study "A Ride for All" [6] on the accessibility of attractions for people with Down syndrome produced important results and defined a scientific and technical method to evaluating the results of tests carried out on attractions. This study is often cited in international publications on the subject and was the preparation for another study in 2022 on the accessibility of attractions for blind and visually impaired people, in collaboration between Italy and Germany, with tests carried out in

Italian amusement parks using the methodology of the mentioned project "A Ride for All".

5 Strategies and technologies for improving the state of the art

Currently, WG1 of the international technical committee ISO/TC 254 "Safety of amusement rides and amusement devices" is drafting the standard “Safety of amusement rides. Effects of amusement rides on passengers. Identification of potential biomechanical risks of amusement ride”. If the work on this draft standard, which is expected to be long and complex, is successful, several important and useful accessibility data will be available.

In the US, the ASTM technical standards also address the issue of "patron eligibility", i.e. the accessibility of people's attractions; Europe and the US are working together on this content to adopt a common technical strategy based on shared data and content.

Anyway, there is still a lot of research to be done to improve accessibility and inclusion in attractions.

88It is clear that there is a great deal of attention and sensitivity in the world of amusement parks to the issue of accessibility for people with special needs, and this concerns all stakeholders - from manufacturers to park managers, from consumer associations to those of families of people with disabilities, to lawyers, certifying bodies and the authorities involved, such as the fire service - even if the solution does not appear to be simple or immediate.

Considering the range of disabilities and the different types of attractions and situations, the problem becomes extremely complex and needs to be tackled step by step; this is one of the reasons why the "A Ride for All" project was started with people with Down syndrome and physical disabilities [Figure 2]. Indeed, the complexity highlighted requires consideration of several areas:

- medical and psychological,
- safety,
- accountability,
- management and business.

From a psychological point of view, there is no doubt that attractions evoke emotions and sensations in the passengers, which can be generated by physical parameters such as speed, acceleration, height, or related to theming and special effects, or by a combination of the two - they are designed and

Fig. 2: 'A ride for All' project

built for this very purpose - but the fact is that each passenger reacts in his or her own way, and this is true for every type of person.
However, there may also be limitations due to physical characteristics, age, pathologies linked to a particular syndrome, etc. In these cases, it is necessary to take a series of precautions, which may even lead to the restriction or even the strong discouragement of the use of the attraction.
Safety must always be a fundamental factor in any activity, and even more so in amusement parks, because the public perception is that there is not the slightest risk in amusement parks, even if sometimes, in the carefree nature of entertainment, guests often behave in a "careless" or inappropriate manner, thinking that nothing can happen anyway. The level of safety in amusement parks must therefore be particularly high, even if not all possible misbehavior is always reasonably foreseeable.
The problem is further complicated when it is necessary to tailor safety criteria and precautions for guests with special needs. The starting point is correct and prior information from the park, which the guest must make an effort to fully understand. If this understanding is limited by factors related to the guest's medical condition, then there needs to be someone who can assist with full understanding and subsequent decisions. This is the scenario of the carer of the person with special needs. An issue that is being discussed all over the world, our world of amusement parks.
It is not possible for the Park or park staff, however well trained, to understand a person's potential and limitations simply by looking at them and meeting them for a few minutes.
It requires the contribution of someone who knows the person well, including their limitations and potential (i.e. the knowledgeable accompanying person); this is particularly true for children and other people with special needs. As far as the involvement of the carer is concerned, there are already procedures in place in different parks that are very similar, even though they were developed separately and at different times. This gives hope that we can achieve good international practice in a reasonably short time.
Then there is the big issue of emergency situations, including evacuation. Under normal conditions, some guests with special needs may not require an escort, but if there is a situation where the attraction is blocked and evacuation is necessary, is there any certainty that the guest with special needs will be able to leave the attraction easily? In some cases, could their condition increase the risk to other passengers? And could their pathology cause them to hinder rather than cooperate at the evacuation? These are all simple and logical questions, but to date there are no 'codified' answers.
There is also much debate about liability. The jurisprudence is far from clear and in many ways the legislation is contradictory. That is why a legal board with a large group of lawyers and judges is working on the ‘One ride for all’ project and analysing the situation, not only at national level. It is clear that park builders and managers cannot be responsible for situations that are not under their actual control and, in relation to this, a problem arises because, while on the one hand one would like to avoid restricting

access to people with special needs, on the other hand there may be objective safety conditions that could make these restrictions unavoidable.

6 Case studies

Considering what we have discussed, here are some real case studies that illustrate how some of the largest and most famous parks are currently approaching the issue of inclusion and accessibility.

6.1 Disneyland Paris and accessibility for guests with disabilities

Disneyland Paris is widely recognized as a pioneer in promoting inclusion and accessibility for guests with disabilities. With over 30 years of commitment to creating a welcoming environment, it receives approximately 125,000 guests with disabilities each year. This commitment includes a comprehensive approach to accessibility that ensures equal opportunities for enjoyment and engagement in the Disney Parks experience. Guests with disabilities can benefit from Priority Access Cards which allow them to access attractions, shows and facilities with minimal waiting times. Furthermore, an autonomy-based accessibility program allows them to self-assess their ability to participate in attractions without classifying disabilities. This approach promotes independence and personalization of the experience.

Visual and auditory assistance has been adopted: services include French sign language interpretation for shows, auditory circuits in theatres and innovative tools such as 3D maps and audio guidance systems for blind guests.

Cast Members receive regular training on inclusivity and assisting guests with diverse needs. The park actively hires employees with disabilities, who make up nearly 6% of its workforce, promoting representation and understanding.

Disneyland Paris demonstrates how amusement parks can transcend recreation to become centres of inclusion, empowerment and accessibility support, offering magical experiences for all individuals, regardless of ability.

6.2 Gardaland and accessibility for guests with disabilities

Gardaland is the bigger Italy's amusement parks. It has implemented significant actions to encourage inclusion and accessibility for guests with disabilities and – as Disneyland Paris - offers a variety of services tailored to the needs of people with physical, sensory or cognitive disabilities ensuring they have a safe and enjoyable visit.

Gardaland provides specific guides for people with disabilities which include detailed information on which attractions are accessible, tailored for guests with physical, visual or cognitive difficulties. Special signage helps visitors identify rides and attractions suited to different needs, such as epilepsy or claustrophobia.

Visitors with mobility problems are accompanied by staff to assess whether the safety features of the rides are compatible with their needs. Specific rides and areas have been adapted to accommodate guests with visual impairments, including access for guide dogs where possible.

Gardaland collaborates with accessibility experts to design comprehensive planning for the safety and comfort of guests: specific rides and areas have been adapted to accommodate guests with visual impairments, including access for guide dogs where possible. An Easy Rider service allows guests with disabilities to book a guide to help them navigate the park and prioritize attractions. Staff members are trained to assist with the specific needs of disabled visitors, ensuring a seamless experience.
However, while most attractions are accessible, some remain unavailable due to safety and evacuation complexities.

7 Conclusions

In recent years there has been a great increase in interest in these issues, however the operational solutions actually put into practice are still partial and insufficient. On the other hand, finding and formulating operational proposals is not easy: to do so, objective starting data would be needed which, at the moment, are very scarce given the particularity and vastness of the attractions.
In analogy to what has been implemented for work equipment, it is believed that to guarantee the safety of equipment intended to be used by people of extremely different ages, training and psychosomatic characteristics and, in emergency cases, in conditions of serious emotional stress (panic), it is essential to create a risk analysis tool (possibly digital) that guides the manufacturer and the amusement park in the concrete implementation of what is foreseen at a legislative and technical level. The basis for the implementation is research and in-depth analysis of European and national legislation and international technical reference standards that provide answers to safety requirements, bringing everything back to the state of the art.
Only through collaboration between experts willing to really delve into the problem will it be possible to arrive at concrete, sustainable (also economically), non-discriminating and realistic proposals. With the common final aim that amusement parks could be an opportunity of aggregation, integration, fun for all guests and their families, respecting the rights and safety of all.

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Extended reality in primary education: potential and challenges for the inclusion of schoolchildren with different abilities

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Abstract

In technologically advanced countries, the use of extended reality technologies (XR) as an educational technology in primary schools is expected to increase. XR technologies include virtual reality (VR), mixed reality (MR) and augmented reality (AR). XR technologies can be a useful aid in the teaching of history, geography, and science in primary schools. For history, simulations can be produced in which the pupil directly participates in a historical event of particular importance. For geography, XR conditions can be created that allow students to virtually visit remote regions of the world. Finally, for science, virtual trips inside the human organism can be prepared, as is often already the case, illustrating the functions of organs and apparatuses or into the infinitely small to learn about the structure of atoms and molecules. Since these innovative technologies risk weakening or reducing interactions between pupils, particular attention must be paid to developing opportunities for social interaction and collaboration. Furthermore, special attention has to be paid to integrating digital technologies with traditional teaching systems. For example, it is recommended to start from the paper or digital text to build links with XR systems. One of the main challenges of this technology is to fit it into the Universal Design perspective to enable its use regardless of the functional level of the pupil with disabilities. Immersive experiences can represent, for schoolchildren with cognitive disabilities, a more satisfying learning experience. On the other hand, motor and sensory disabilities (particularly visual and auditory) are a possible cause of exclusion of pupils with different abilities. However, the development of technologies makes it possible to find solutions that facilitate inclusion from the perspective of Universal Design. The study aims to present the potential and challenges of introducing XR technologies in primary schools for the inclusion of pupils with different abilities.

1 Introduction:

The rapid advancement of new technology in schools is playing a significant role in supporting students. Integrating technology in primary schools can provide substantial benefits for students to enhance learning and interaction. The introduction of Extended Reality (XR) technology in education fields must consider the rights of people with disabilities, otherwise, there is a risk that it will increase the gap between people. It is essential to use these technologies in a way that supports equal participation and avoids existing inequalities.

XR (Extended Reality) technologies refer to a set of immersive technologies that blend and enhance the physical and digital worlds, creating interactive and engaging experiences. XR includes various forms of digital reality:

- Virtual Reality (VR) creates a fully immersive, digital environment that replaces the real world, where users can interact with 3D objects and situations using devices like VR headsets and controllers.
- Augmented Reality (AR) overlaps digital elements (such as images, sounds, and information) into the physical world, enhancing the user's perception of their real environment. Users can see and interact with both digital and real elements simultaneously, such as smartphones, tablets, or AR glasses.
- Mixed Reality (MR) combines elements of both VR and AR, enabling more interaction between physical and digital objects. In an MR environment, virtual objects can interact with the real world in real time and vice versa. MR is used in fields like architecture, design, and healthcare.

These technologies have the potential to address a wide range of learning needs and to providing tailored experiences for students with physical or sensory disabilities. For example, VR can provide students whit physical disability to explore locations they might not be able to visit while AR can help children with learning disabilities understand complex concepts, easily.

At the same times , XR technologies also presents challenges. Accessibility is a key point, as not all XR systems are designed to the students with disabilities needs. Also there is the potential risk to extend the gap between students with and without disabilities.

Therefore, the study aims to present the potential and challenges of introducing XR technologies in primary schools for the inclusion of pupils with different abilities.

2 Methodology

A multidisciplinary team from the Central Medical Department of INAIL (National Institute for Insurance against Accidents at Work) has examined the potential of (XR) technologies in education field. This team collaborated with various stakeholders, including ergonomic specialists, to assess both the opportunities and obstacles associated with the use of XR technologies in primary schools.

3 Results

3.1 Opportunities

XR can offer highly personalized learning experiences. For students with disabilities, XR can adapt content to meet individual needs, enabling students with disabilities to engage in tailored lessons to their specific learning styles and abilities.

XR technologies significantly increase student engagement to provide immersive, interactive experiences. This is particularly important for students with learning difficulties who may find traditional classroom settings challenging. Students learn

more enjoyable and stimulating thanks to game-like elements, storytelling, and interactive scenarios.

XR can offer immense benefits for students with physical disabilities to access experiences and environments that might be physically inaccessible. For example, VR can transport students to virtual field trips all without leaving the classroom.

XR can break down social barriers for those who may feel socially isolated. Through collaborative VR activities, students can work together on projects, practice communication skills, and engage in group learning experiences, fostering a sense of community and improving social skills. Many XR platforms are capable of providing real-time feedback and adaptive learning for example, XR systems can track a student's progress and adjust the level of difficulty or can offer hints to ensure that each student receives the support they needed.

3.2. Obstacles

XR systems are not designed for accessibility. For example, VR systems often require high levels of physical interaction, such as moving around a space or using hand controllers. Also many XR applications do not have built-in features like text-to-speech, voice recognition, or adjustable visual settings that would make them more accessible to students with visual impairments or hearing loss etc.

The high cost of XR hardware, such as VR headsets, AR devices, and the software, can be a significant barrier, especially for schools with limited budgets. In addition to the initial investment, maintaining and updating XR systems requires a lot of resources.

Also, many educators may not be familiar with XR tools or how to use them to support students with disabilities and they may fight to integrate XR into their teaching practices without proper training. Another risk is the underline the digital divide. If some students have access to cutting-edge technologies while others do not, it could widen the gap between the stuedents.

Amon other things, prolonged exposure to immersive VR environments particularly VR, can cause discomfort or health issues, such as eye problem, headaches, or motion sickness, disorientation and fatigue. For students with certain physical or cognitive disabilities, these health concerns may be pronounced, even more.

4 Conclusion

There is no doubt that XR technologies offer holds tremendous potential for enhancing inclusion, creating personalized learning experiences, and providing equal access to educational opportunities for all students, including those with disabilities. At the same times it is essential to address the obstacles related to accessibility, cost, teacher training, technological infrastructure and equity. Considering and overcoming these challenges, XR can become a tool to promote a more inclusive and educational environment for students of all abilities.

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Sustainable, innovative, and compliant paints to protect health and the environment, beautifying the world

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Abstract

The automotive industry is evolving towards sustainability, efficiency, and regulatory compliance. A key focus is the development of innovative paints that enhance vehicle aesthetics while meeting stringent standards. The Automotive Coatings described in this article are advancing solutions to ensure compliance with the latest Classification, Labelling and Packaging (CLP) Regulation and other Environmental Health and Safety (EHS) laws by reducing hazardous substances like MEKO (Methylethyl ketone oxime), GMA (Glycidyl methacrylate), monomeric isocyanates, MIBK (Methyl isobutyl ketone), naphthalene, and cumene.

The industry presented has shifted from traditional solvent-based formulations to modern innovative paints, including:

1. **Waterborne Paints**: utilize water as a solvent, significantly lowering Volatile Organic Compounds (VOC) emissions, while providing excellent performance and durability.
2. **High-Solid Coatings**: contain a higher percentage of solids, which reduces solvent use and VOC emissions, improving coverage.
3. **Powder Coatings**: applied as a dry powder and cured with heat, eliminating solvents entirely while enhancing durability.

It has made substantial efforts to eliminate hazardous substances from automotive paints:

- **MEKO:** once an anti-skinning agent, it poses serious health risks. This industry has fully replaced it with safer alternatives.
- **GMA:** as a monomer used in epoxy resins, it causes sensitization. They have minimized its use by developing low-GMA resins compatible with existing formulations.
- **Isocyanates:** commonly used hardeners that pose health risks; this industry now offers low monomeric concentration alternatives that comply with EU regulations.
- **MIBK:** a traditional solvent now replaced with safer mixtures that maintain product performance while reducing safety risks.
- **Naphthalene and Cumene**: both are hazardous air pollutants. This industry has moved towards low-cumene solvents and reduced naphthalene content by adopting safer alternatives.

The illustrated industry is committed to developing innovative, compliant paints that minimize environmental impact, reduce health risk and advance sustainability in the automotive sector.

1 Innovative Paints for Automotive Compliance

The illustrated approach to developing safe and sustainably advantaged products is built upon more than 140 years of expertise. The result is a broad portfolio of paints, coatings and specialty materials that transform everything from the places we work to the vehicles we drive.

The Automotive coating team has come a long way from traditional solvent-based formulations. Modern innovations include waterborne paints, high-solid coatings, and powder coatings, each offering unique benefits:

1.1 Waterborne Paints

The customers are facing growing demands to reduce their environmental impacts across their operations. This industry collaborates closely with its customers to incorporate sustainably advantaged solutions from the early design phase of their product lifecycles.

Waterborne coatings can have lower environmental and human health impacts for the workers that apply its products, without compromising on quality.

These paints use water as a solvent, significantly reducing volatile organic compounds (VOCs) emissions. They provide excellent performance and durability while being environmentally friendly.

Waterborne base coats have become the main base coat technology for all new paint shops built after the year 2000. This success is driven partly by the environmental benefits, and partly by their superior performance and robust application properties. The main binder is typically a partially cross-linked core shell emulsion polymer based on acrylics and/or polyester. The melamine reacts with the binder during the clear coat baking step and introduces some cross-linking into the base coat film.

Auxiliary resins are either waterborne polyesters or polyurethane dispersions. These co binders are introduced mainly to improve chipping performance, flow, and appearance.

1.2 High-Solid Coatings

These coatings contain a higher percentage of solid components, reducing the amount of solvent needed. This results in lower VOC emissions and improved coverage.

With low solids paint type, which are largely made up of solvents, most of the paint evaporates when drying, but high-solids paint types were made to be used without the help of as many solvents.

1.3 Powder Coatings

Applied as a dry powder and then cured under heat, these coatings eliminate the need for solvents altogether. They offer superior durability and resistance to chipping,

scratching, and fading. Powder Coatings are comprised of the same types of components as liquid paints except the most of raw materials are solids, and Powder Coatings contain no solvents or water. They have a Resin/Binder system that will react with a Crosslinker. They sometimes have a Catalyst that will catalyze the reaction between the binder and the crosslinker. Very important ingredients in powder coatings are the Flow Modifiers. Since powder coatings use no solvents, they rely on these flow modifiers to get the system to flow and level while they are in the molten or melted stage before the crosslinking begins to take place.

1.4 New E-Coat technologies with expanded baking window

This new advanced E-coating technology offers exceptional corrosion resistance and environmental sustainability with the following benefits:

- Corrosion Resistance: highly durable and protective barrier on metal surfaces, offering excellent resistance against corrosion, rust, and other environmental factors. This helps to extend the lifespan of coated products and reduce maintenance costs.
- Uniform Coverage on complex-shaped parts, ensuring consistent protection across the entire surface. This is achieved through an electrochemical process where the coating is deposited evenly on the substrate, including hard-to-reach areas and recesses.
- Environmental Sustainability: water-based coating system that significantly reduces volatile organic compound (VOC) emissions compared to solvent-based coatings. This makes it an environmentally friendly choice for manufacturers seeking to minimize their carbon footprint.
- Cost Efficiency due to its high transfer efficiency and ability to coat complex parts with minimal material waste.
- Enhanced Appearance: smooth and consistent finish, enhancing the appearance of coated products. It can be used as a standalone coating or as a base for additional layers of paint or powder coatings, allowing for customization and aesthetic flexibility.
-

2 Reducing Hazardous Substances

Efforts to reduce hazardous substances in automotive paints in the last years have been focused on several key chemicals:

- MEKO (Methyl Ethyl Ketoxime):

This substance is a chemical compound commonly used in Alkyd-based paints as an anti-skinning agent and to prevents the formations of a skin on the surface of the paint when exposed to air by inhibiting the oxidation process that leads to skin formation. When added to paint, MEKO reacts with oxygen more readily than the components of the paint, thus preventing premature drying. [1]
Here's a simplified chemical reaction illustrating how MEKO works:

$MEKO + O_2 \rightarrow MEKO\text{-}Oxidized$

Despite its effectiveness its usage poses significant health risks including being a Category 1B carcinogen, toxic if swallowed, and causing damage to organs. MEKO is subject to strict regulations in the EU, and products containing MEKO at concentrations of 0.1% or higher must be labeled appropriately and are restricted to professional use only. [2]

Quite often alkyd coatings are based on cobalt catalysts in combination with MEKO anti-skinning agents. These coatings indeed dry via autoxidation when oxygen reacts with points of unsaturation based on fatty acids in the resin. This process can be prolonged if unaided, so Cobalt is utilized as an oxidative catalyst to speed the curing of alkyd resins.

Since Cobalt catalysts are reactive to oxygen, an anti-skinning agent such as MEKO is required to prevent the paint surface from forming a film (called “skin”). Therefore, many alkyd-based paint formulations are dependent on cobalt for adequate curing and on MEKO for storage stability. [3]

MEKO and cobalt catalysts have been replaced with safer alternatives to minimize health risks.

High-performance catalysts are the next-generation driers that have been selected because superior in sustainability and performance compared to metal carboxylates like Cobalt. These sustainable solutions are based on organo-metallic ligand technologies both in waterborne and solvent borne systems.

This industry has been in the past a significant user of MEKO (methyl ethyl ketoxime) in their products, particularly for painting industrial engines and trucks axles and the replacement of both MEKO anti-skinning agents and cobalt catalysts with environmentally friendly and safer alternatives have permitted to provide sustainable formulations from a product stewardship standpoint and enhance overall performance in alkyd paint.

- GMA (Glycidyl Methacrylate):

Glycidyl Methacrylate (GMA) is a widely used monomer in the paint industry. Its unique chemical structure, featuring both methacrylate and epoxy functional groups, allows it to enhance various properties of paints, making it a valuable component in several paint technologies.

The use of GMAIL in paint product formulas is linked to the following chemical properties and benefits:

- Adhesion Improvement: GMA’s epoxy group can react with various substrates, improving the adhesion of the paint to surfaces such as metals, glass, and ceramics. This is particularly beneficial in industrial applications where strong adhesion is crucial. [4]
- Crosslinking Ability: The epoxy group in GMA can undergo crosslinking reactions, which enhances the mechanical properties of the paint, such as hardness and durability. This makes the paint more resistant to wear and tear. [4]

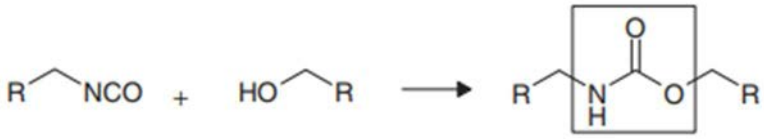
- Chemical Resistance: Paints formulated with GMA exhibit improved resistance to chemicals and solvents. This is due to the formation of a dense, crosslinked network that prevents the penetration of aggressive substances. [5]
- Weatherability: GMA-modified paints show better resistance to UV radiation and weathering, which helps in maintaining the appearance and performance of the paint over time. [6]

Thanks to various R&D projects, they have been capable to develop alternative resins with lower content of free GMA. The development and usage of these alternative resins, fully compatible with the existing formulation, helped to minimize health risks for workers handling these products.

- Isocyanates with low monomeric level:

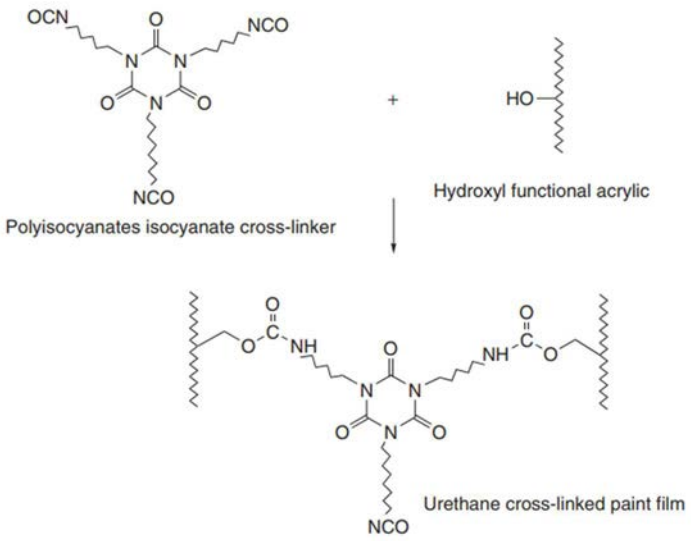
Isocyanates are essential components in many paint formulations, providing durability and chemical resistance. However, monomeric isocyanates pose significant health risks and contribute to environmental pollution.

Polyisocyanates, which are generally used for formulating two-component paints, react with hydroxy-functional polymers to form urethane groups:

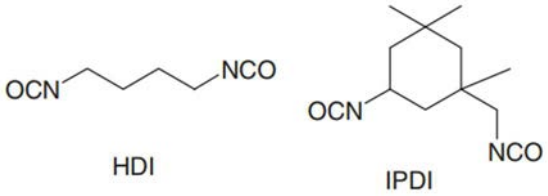


With the widespread use of effect pigments – aluminum flakes, micas, and all other types of interference pigments – color design capabilities have become unlimited. To protect these pigments from the environment, a clear coat is applied over the colored base coat. These clear coats offer protection from extensive sunlight, scratches, and all types of chemical attack.

The chemical reaction by which the coating cures involves reaction of the polyisocyanate with the hydroxyl group of a polyol to form a urethane cross-link as illustrated in the following figure.



Coatings based on such urethane group-functional networks are of excellent quality – for example, in terms of UV stability, elasticity, and resistance to chemical exposure. This is, of course, only possible where the appropriate cross-linking agents and binders are specifically chosen. Aliphatic polyisocyanates are used for this purpose. [7]
The term polyisocyanate covers a broad spectrum of polymers. At the basis of this broad spectrum are, on the one hand, different diisocyanates from which the polyisocyanates are formed in oligomerization processes. The most used polyisocyanates are based on HDI (hexamethylene diisocyanate), followed by IPDI (isophorone diisocyanate).



This industry has introduced products with low monomeric concentration, equivalent in technical performance to previous formulations but with improved environmental, health, and safety aspects. This shift towards low monomeric isocyanates represents a significant advancement in the polyurethane industry. By reducing health risks and improving environmental compliance, these innovative chemicals ensure safer working conditions and contribute to sustainable manufacturing practices.

- MIBK (Methyl Isobutyl Ketone):

Methyl Isobutyl Ketone (MIBK) is a versatile solvent used in various industries, including paints, coatings, adhesives, and pharmaceuticals. In the paint industry, MIBK is valued for its ability to dissolve resins, oils, and waxes, making it an effective solvent for nitrocellulose, vinyl resins, and acrylic resins. Despite its benefits, MIBK poses significant health risks and environmental concerns, prompting the need for safer alternatives. [8]
MIBK is classified as a hazardous air pollutant (HAP) and has been identified as a potential carcinogen by the International Agency for Research on Cancer (IARC). Exposure to MIBK can cause respiratory and skin irritation, and long-term exposure may lead to more severe health effects. Additionally, MIBK contributes to volatile organic compound (VOC) emissions, which are harmful to the environment. [9]
Reformulating products has involved several efforts aimed to identify safer alternatives and maintaining performance characteristics such as drying time, adhesion, and durability without MIBK.
Moreover, it has been fundamental to ensure that new formulations comply with evolving environmental and safety regulations was however crucial. [10]
Research and development teams has tested safer solvents mixture that permitted to replace MIBK without compromising product performance. Solvents with lower VOC content, such as propylene glycol ethers, have been adopted to replace MIBK. [11]
In the last years most of the products have been reformulated to eliminate the usage of MIBK, identifying safer alternatives that maintain performance characteristics without compromising product quality.

- Naphthalene and Cumene:

Naphthalene and Cumene are both chemicals commonly found in paint. Both are hazardous air pollutants and classified and regulated under the European Union's Classification, Labeling, and Packaging (CLP) with Acute Toxicity. [12]
Reformulating paints to eliminate cumene has been a complex process that required careful testing and adjustments to ensure that the final product meets performance and regulatory standards. Once potential alternatives were identified, extensive testing and evaluation were necessary to assess their effectiveness. This included evaluating the solvents' ability to dissolve pigments, binders, and other additives, as well as their impact on the paint's drying time, adhesion, durability, and other performance characteristics.
Based on the testing results, adjustments and optimization were required to fine-tune the formulations.
The successful reduction of cumene and naphthalene content in paint formulations through the new solvent composition offers significant benefits; it minimizes the health risks associated with paint application and reduces the release of cumene into the environment.

3 Conclusion

The illustrated industry is committed to sustainability in the development and production of its products. The company offers low-VOC and VOC-free formulations, invests in waterborne technology, develops energy-efficient coatings, promotes sustainable packaging, conducts life cycle assessments, and collaborates with industry partners and regulatory bodies.
The dedication to sustainability extends to its manufacturing processes, aiming to reduce energy consumption, water usage, and waste generation. By integrating sustainability into its operations and product development, its aim is to create a more sustainable future for its customers, employees, and the communities it serves.
The development of innovative paints that comply with environmental regulations and reduce the use of hazardous substances supports a sustainable future with minimal environmental impact in the automotive industry.

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The consideration of the human-machine interface in the prevention of the operator error in the safety management system

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Abstract
The Seveso III Directive 2012/18/EU imposes an obligation to consider the human factors and the interfaces between operators, processes, and plants, with the correct workspace design, as part of implementing the Safety Management System. It is fundamental that in the risk analysis the human factor and the conditions in which significant activities for the safety of the establishment must be carried out, for achieving specific objectives for the prevention of major accidents.
A well-designed man-machine interface and the distribution of workspaces allow you to minimize the possibility of operator error in the control room, both during normal operating conditions and emergencies. The prevention of human error cannot ignore the knowledge of the potential negative consequences deriving from non-compliance with procedures. The assessment of human error must be used to verify if the procedures adopted to improve the behaviour of the operator, or the instrumental controls give the best contribution to safety. A fundamental role is represented by training activities and emergency drills, which must be carried out from design to critical analysis of results, preparing any corrective actions.
The consideration of the Human-Machine Interface in the correct implementation of a safety management system must start from a good design of the work system and be based on: detecting any problems at the interfaces thanks to the feedback from operators; monitoring the status of systems, through maintenance activities, and ensuring a good house-keeping; using proper labeling of equipment and alarm annunciators; improving the reliability of operators' performance; implementing an effective system of operational controls, that allows preventing any human errors; the functionality of the operator/process and operator/equipment interfaces to monitor the process, identify any anomalies or emergencies and implement the planned intervention procedures.

1 Introduction

The Seveso III Directive 2012/18/EU [1], implemented in Italy by a legislative decree issued in 2015 - D.Lgs. 105/2015 [2], is aimed at the prevention of major accidents involving dangerous substances. The D.Lgs. 105/2015 covers establishments where dangerous substances may be present (e.g. during processing or storage) in

quantities exceeding certain thresholds. Operators of the establishments are obliged to take all necessary measures to prevent major accidents and to limit their consequences for human health and the environment. Depending on the amount of dangerous substances present, establishments are categorized in lower and upper tiers, with different obligations. The requirements include, among others: notification of all concerned establishments; deploying a Major Accident Prevention Policy (MAPP) through the implementation of a Safety Management System for Prevention of Major Accidents (SMS-PMA); producing a Safety Report (SR) for upper-tier establishments; producing an Internal Emergency Plan (IEP) for upper tier establishments; providing information in case of accidents. As part of the implementation of the Safety Management System, the D.Lgs. 105/2015 imposes an obligation to take into due consideration the human factors and the interfaces between operators, processes, and plants, with the correct workspace design. During the control activities, it is necessary to verify that training programs and emergency drills are implemented to improve operator behaviour. It is therefore fundamental that in the risk analysis the human factor and the conditions in which significant activities for the safety of the establishment must be carried out, giving particular attention to the interfaces between operators and processes in the phase of operational control of the plants.

2 The control activities: human factors and HMI

2.1 Human factors in the control activities

In Italy, the SMS inspections are conducted to verify the suitability of the operator MAPP carrying out a planned and systematic examination of the systems being employed at the establishment, whether of a technical, organisational or managerial nature. The human factors and the interfaces between operators, processes, and plants are specific items of interest during the SMS control activity [3]. In fact, the commission must: Verify that training and drill programs exist and are implemented to improve the behaviour of the operator; Verify that the work shifts, and the distribution of tasks have been established considering the psycho-physical stress to which the workers are subjected and that mechanisms are put in place to verify that the appropriate psycho-physical conditions are maintained. Among the tools available to the inspection commission during the documentary verification, it is possible to verify directly, also by consulting the documentation relating to the health and safety at work analysis, the compliance with the indications relating to the maintenance suitable psycho-physical conditions of the workers. During the “on-site” visit, the possible insights concern interviews with the employees both on the management methods of ordinary and extraordinary management, maintenance, emergency interventions, and on their involvement in the drafting and/or revision of the operating instructions.

2.2 The consideration of the HMI and the human error

The national technical standard UNI 10616:2022 (Establishments with major-accident hazard-Safety management systems-Guidelines on implementation of UNI 10617) [4] provides guidelines for implementing a safety management system, describing the procedures and technical tools useful for achieving specific objectives for the prevention of major accidents in industrial establishments (national technical standard UNI 10617:2019) [5]. It deals with most of the hazards and major accident risks present both in simple installations and in more complex installations where the process risks can be preponderant compared to those connected to the simple loss of containment. The application of the contents of the standard must be commensurate with the specificities of the major accident hazards present in the establishment. In the standard, specific attention is paid to the human-machine interface (HMI), meaning the system that separates the operator, who is using a machine (i.e. the control panel located in the control room in the case of the process industry), from the machine itself, while ensuring a constant connection. Among the objectives for the continuous improvement of the SMS-PMA, which arise from the results of the identification of the hazards and the assessment of the risks of a major accident, the improvement of the quality of the interface between the operator and the plant/process can also be included (i.e. promptness, accuracy and punctuality in reporting anomalies). In close connection with the HMI, it is considered the prevention and assessment of human error, a fundamental aspect of process safety management. To strengthen and disseminate the culture of safety, the site manager should also operate through the implementation of a company policy which clearly and transparently identifies the criteria for distinguishing acceptable behaviour from that which cannot be considered as such, distinguishing situations involving intentional misconduct from human errors attributable to organizational causes. The awareness of the people who carry out a work activity in the plant, involved in activities relevant to safety, can in fact be verified through knowledge of the potential negative consequences deriving from a failure to comply with the specified procedures, with consequent human error, and the possibility of even a major accident. The need to verify the system procedures, on the other hand, may derive from the possible analysis of the accidents and/or near misses connected to the ascertained human error.

3 Design and schemes to prevent human error

3.1 Design of the man-machine interface

The functionality of the interfaces between operators, process and systems, consisting of the instrumentation located in the control room with related switchboards/monitors/buttons/optical and acoustic signalling panels, including wireless devices, must be ensured through the periodic check program of the active safety systems, consisting of toxic and/or flammable gas detectors, fire

detectors, alarms and blocks for critical operating parameters. The displays must report process variables, alarms, automatic blocks, recordings, as well as actuators for control actions on the process, such as starting/stopping pumps and compressors, opening/closing valves, changing the regulation and operating parameters set. The main functions of an interface are: Presentation of process information; Immediate implementation of control actions; Support for diagnosis, decision making or planning. Important elements of an interface are usability, to make the HMI easy to use (reducing the possibility of errors), and accessibility by the panel operator. A correct design of the control, alarm and automatic blocking systems must consider the analysis of the operator's tasks at the switchboard and the optimal ergonomic and specific environmental factors for correct operation of the systems and plants. A good, designed man-machine interface, in the control room of a process plant, and the distribution of workspaces, allows you to minimize the possibility of operator error on the panel, both during normal operating conditions and during emergencies, throughout the process life cycle, and in case of plant or process changes. These interfaces must be considered throughout the life cycle of the process and during plant or process changes. Control provisions must be adopted to manage any modifications/changes made, in conditions of necessity and under specific responsibility, to the switchboards or control equipment. These changes must not reduce the ergonomic design characteristics as well as they must consider other project requirements, such as accessibility for maintenance or periodic checks.

3.2 Practical schemes of control rooms

To represent some practical examples of a control room [6], with the relative representation of process parameters and data on the screen of a DCS (Distributed Control System), the case of a typical process industry was investigated. In the following, schemes of correct design and distribution of spaces in a control room, with the relative minimum requirements are presented [7]: Figure 1: Illustrations of definitions associated with workstation visual display; Figure 2: Visibility of large screens and the widths of corridors; Figure 3: Travel routes and collaborative operation among units.

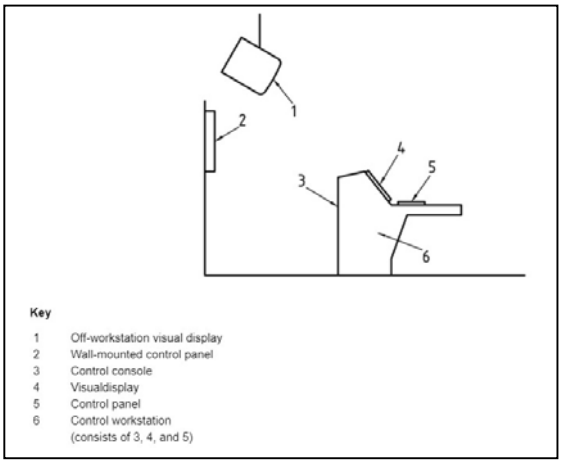

Fig. 1. Illustrations of definitions associated with workstation visual display (Source: T. Naito et al, 2011)

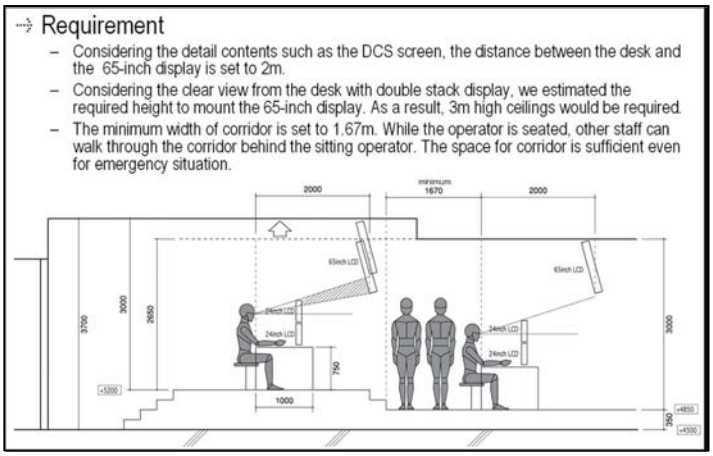

Fig. 2. Visibility of large screens and the widths of corridors (Source: T. Naito et al, 2011)

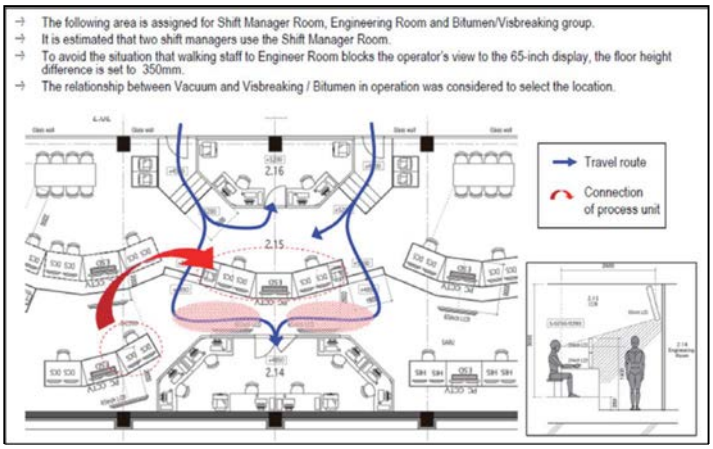

Fig. 3. Travel routes and collaborative operation among units (Source: T. Naito et al, 2011)

The key points for the adequate representation of data and information on a screen, to improve the man-machine graphic interfaces [8], are: Colour graphic

representation (Figure 4); Device status display (Figure 5); Representation of data values (Figure 6).

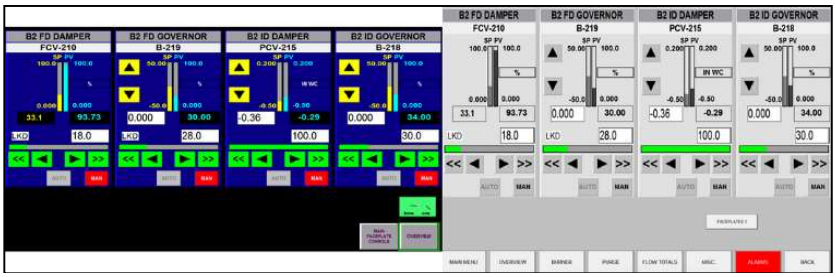

Fig. 4. Colour graphic representation (Source: R. Kowalski et al, 2017)

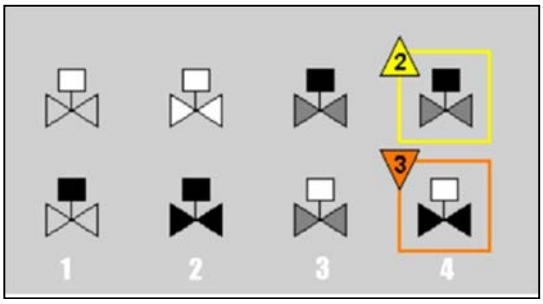

Fig. 5. Device status display (Source: R. Kowalski et al, 2017)

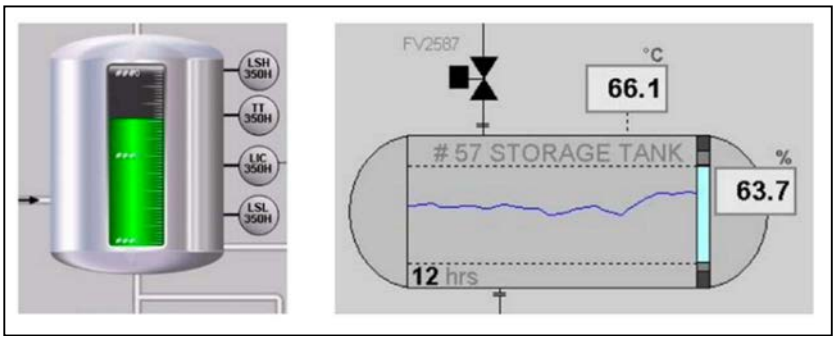

Fig. 6. Representation of data values (Source: R. Kowalski et al, 2017)

Typical examples of control panels are finally given in the following, as taken from the DCS (Distributed Control System) in the control room [9]: Figure 7: Plant overview; Figure 8: Process Air Unit.

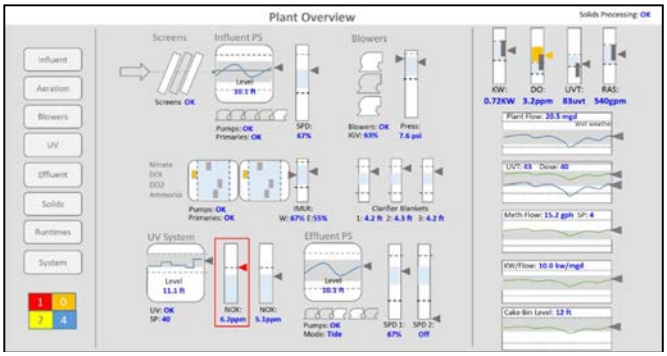

Fig. 7. Plant overview (Source: ANSI/ISA, 2015)

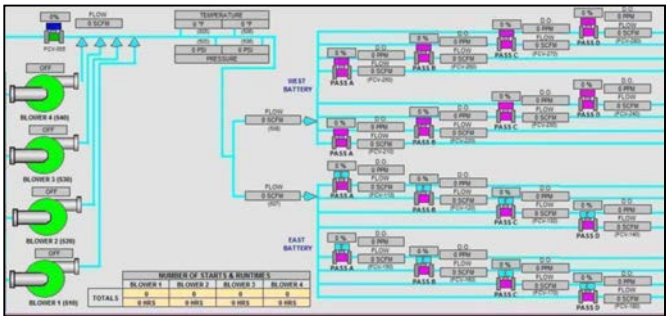

Fig. 8. Process Air Unit (Source: ANSI/ISA, 2015)

3.3 The prevention of human error in a process plant

The prevention of human error cannot ignore the knowledge of the potential negative consequences deriving from non-compliance with system procedures, with the possibility of a major accident. The assessment of the possibility of human error must be used in the reliability analysis to verify if the procedures and operational controls adopted to improve the behavior of the operator or the instrumental controls give the best contribution to the safety of the system. The management by the workers of operating anomalies and/or emergencies must be verified both in the actual conditions of occurrence of the events and in the simulations, to highlight any deficiencies connected to the human factor. The analysis of non-conformities relating to procedures, regulations, and operating instructions, detected because of inspections and/or accidents/near-accidents, generally linked to human error, can highlight deficiencies related to the behaviour of people, the organization, and the work environment. Such deficiencies must be subject to appropriate corrective actions. Emergency drills are an important element of evaluation. They must be carried out according to a specific path that goes from planning to the critical analysis of the results, to prepare any corrective actions, also in terms of response times and emergency management of the operators to reduce the possibility of accidents related to human error.

4 The consideration of the human factor in the SMS

Based on the experience coming from the control activities conducted on some Seveso Italian establishments, in the following the discussion about examples and indications of particular or recurring situations are given about the consideration of the human factor in the SMS. The inspections must mainly be aimed at evaluating how much the company policy, and therefore the management system, require that human factors are taken into consideration in the conduct of the plant's activities, identifying any deficiencies. The aspects that must be taken into consideration are the organizational elements, the policy and standards followed in the design and modification phases of the plants, the operating conditions, including problems related to process management, and the working environments. As regards the design phases of new processes or operating systems, it must be evident that the company policy or the standards adopted foresee the consideration of human

factors. Indicative of the fact that human factors have been considered is, for example, the evidence of the analysis of the aspects related to the spaces available to the operators, the accessibility of the equipment, the correct construction and location of the control panels and the use of prototypes and pilot plants also for the analysis and revision of the operator-plant interface. At an operational level, information on work shifts must be acquired, for example by verifying that the available resources are distributed in a homogeneous manner, or in any case congruent with the workload, that the responsibilities have been clearly identified and are commensurate with the experience and ability of the employee to identify the cause of an error which may also cause a major accident. In fact, it must be considered that stress and fatigue can be the result of incorrect personnel management. To identify a possible deficiency in this sense, one could, for example, analyse the criteria for allocating resources within the various operational areas, verifying whether both the physical and aptitude characteristics and the degree of experience, which must be possessed by the person responsible for the critical tasks of the plant, have been specified. Regarding the operating procedures available to operators, the main aspects to consider are that these are clear and complete, written in a language that operators can understand, that their involvement in drafting and revision has been envisaged and, most importantly, that these procedures provide employees with all the elements that enable them to identify and manage unforeseen situations. It should be remembered that the conditions of the working environment (lighting, temperature, exposure to noise, vibrations or chemical agents, etc.) also play a fundamental role in the employee's ability to interact with the systems and equipment. In this regard, it will be important to verify not so much that the values of these parameters are compatible with the activity carried out, but rather that national and international standards have been considered in the organization of the activity for the definition of optimal conditions in the workplace, providing, in the procedures, the analyses to establish what are the levels that allow to guarantee efficiency and safety. Finally, it should be considered that the system must provide for the periodic measurement of these parameters, to verify that the pre-established limits are respected, adopting compensatory measures in case it is not possible to respect the limit.

5 Conclusions

The consideration of the human factors and the interfaces between operators, processes, and plants, with the correct design and the distribution of workspaces, in the implementation of a safety management system must be based on: 1) The detection of any problems at the interfaces, thanks to the feedback information coming from both the operators and the maintenance technicians; 2) Monitoring the status of equipment and systems. It is important that equipment is visually inspected throughout the work shift. Reading the instruments placed on the equipment makes it possible to verify the reliability of the parameters reported by the remote-control

systems in the control room. Furthermore, only through visual inspections anomalous situations can be promptly identified. The information found must be recorded on special checklists which must be reviewed on a periodic basis by the supervisors so that what is reported is consistent with other data and that any anomalous situations are promptly resolved. In addition, it is good practice to have equipment checks integrated with normal operations; 3) An adequate maintenance of work tools and equipment, including maintaining good conditions of cleanliness and order in the workplace (s.c. housekeeping); 4) The use of correct labelling and signalling of containers, pipes, equipment, etc., also through appropriate colour codes, to allow immediate knowledge of the risks and the identification of systems and components. Of specific importance, for example, are the methods for signalling automatic blocks to the switchboard, especially in the event of a bypass due to contingent plant requirements, with the relative operating management procedure; 5) The maintenance of good lighting conditions, essential for identifying the equipment, reading the instruments and identifying possible problems; 6) The improvement of the reliability of the operators' performances. Particular attention should be paid to the procedures for handing over deliveries between shift managers and/or switchboard operators during shift changes in the plant and in the control room, keeping adequate traces in the system documentation; 7) The implementation of an effective system of operational controls based on procedures, permits, inspections, etc., that allows to prevent or promptly identify any human errors before they cause accidents; 8) The functionality of the operator/process and operator/equipment interfaces to make it easier for the operator to monitor the process, identify any anomalies or emergencies and implement the foreseen intervention methods. Consider, for example, the problem of managing a maximum number of alarms on screen in the event of a generalized emergency, or the problem of assessing reliability/redundancy for critical alarms (in the event of a power failure).

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Vulnerability factors in PMCS (Polymer-Matrix Composites) wet lay-up products in temporary structural repairs of equipment and pressure pipes

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Abstract
A temporary wet hand lay-up repair using two-component fibre-matrix composite materials is characterised by three distinct phases: the deposition phase of the dry reinforcement, the vacuum impregnation phase of the reinforcement with thermoplastic or thermosetting resins, and the catalysis or polymerisation phase of the resin at room temperature [1]. If, on the other hand, prepreg reinforcement fabrics are used, the fibres pre-impregnated and pre-catalysed with thermosetting epoxy resin are then subjected to a thermal vacuum cycle. For continuous-cycle plants or those with a public utility character, especially in sites with a high operational criticality (e.g. refineries, chemical and petrochemical plants), the temporary 'wet lay-up' repair techniques for rapid safety restoration often do not include vacuum impregnation of dry fabrics, nor dedicated curing cycles in the case of the use of pre-impregnated fabrics, even though they are regulated by international standards and technical specifications. Manual deposition and impregnation procedures used by the operator with the aid of brushes or rollers, without the application of vacuum or a curing cycle, can compromise the elastic behaviour, mechanical strength, time limit and containment of any losses [2], [3].
Other fundamental parameters of a correct repair procedure using composites are: the conditions of the working and storage environment of the products, the expiry date, the resin/hardener mixing ratio, the fibre/resin volumetric ratio, the time of use, the types of reinforcement fabrics, the post-curing CnDs. Starting from the representation of the elastic behaviour of an orthotropic and transversely isotropic foil, along the longitudinal and transverse directions, the present work analyses some important process factors of 'Wet Lay-Up' with PMCs (Polymer-Matrix Composites), with the aim of improving and integrating some standards in the processes of temporary structural repair of equipments and pressure pipes.

1 Elastic behaviour and mechanical strength of the sheet

The characterisation of a composite material from a technological point of view is carried out by considering its macrostructure, evaluated as continuous and homogeneous throughout its volume. The micromechanical study of composites, on the other hand, is concerned with the inhomogeneous nature of the different phases, the interactions between the constituent materials, and makes it possible to estimate

the main engineering quantities from the individual constituents. In order to be able to define the global elastic and mechanical behaviour of the laminates, it is useful to consider the simplified scheme of a single ply, layer with unidirectional reinforcement, consisting of parallel and equi-spaced circular fibres, embedded in a continuous collaborating matrix. The anisotropic behaviour of such a fibre-matrix system depends on the properties of the individual constituents, on chemical and physical interactions, on numerous other general, product and process requirements [1], [4].

Assuming perfect fibre-matrix adhesion and equal deformations in both fibres and matrix, the elastic behaviour of an orthotropic and transversely isotropic film is completely defined by the 5 engineering elastic constants (stiffnesses), such as

- Young's modulus in the longitudinal direction $\boldsymbol{E_1}$
- Young's modulus in the transverse direction $\boldsymbol{E_2}$
- The shear or tangential modulus of elasticity in the plane of the plate $\boldsymbol{G_{12}}$
- "Major" Poisson's coefficient in the longitudinal direction $\boldsymbol{\nu_{12}}$
- "Minor" Poisson's coefficient in the transverse plane ν_21 $\boldsymbol{\nu_{21}}$

The mechanical strength of the sheet is identified by five independent parameters

- the tensile strength in the longitudinal direction $\boldsymbol{\sigma_{1L}}$
- the compressive strength in the longitudinal direction $\boldsymbol{\sigma_{1L}^{c}}$
- the tensile strength in transverse direction $\boldsymbol{\sigma_{2T}}$
- the compressive strength in the transverse direction $\boldsymbol{\sigma_{2T}^{c}}$
- the shear strength in the plane of the sheet $\boldsymbol{\tau_{12}}$

In general, the continuous matrix phase gives the composite deformability and compressive strength along the transverse direction, and interlaminar shear strength. The reinforcing fibres, on the other hand, results in an increase in tensile strength along their longitudinal direction.

The lamina in Figure 1, considered transversally isotropic in the plane 2-3 transverse to the direction of the fibres, presents along the longitudinal direction of the reinforcement, mechanical characteristics (stiffness, strength) superior to those exhibited in the other directions (Fig. 4).

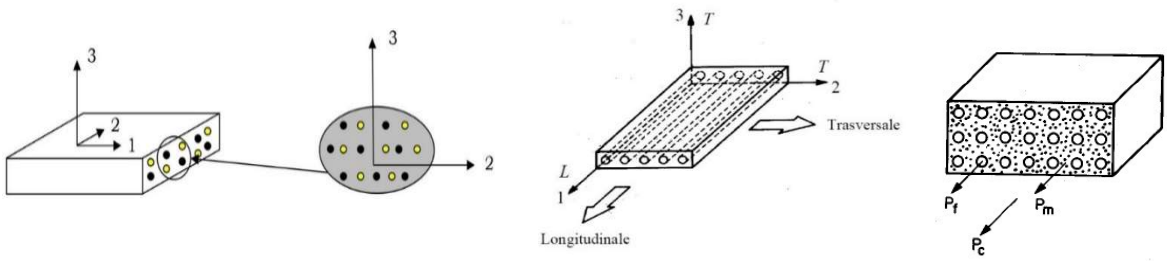


Fig. 1 – Simplified diagram of sheet with unidirectional reinforcement.
Source: Materiali compositi – I. Crivelli Visconti; Progettazione meccanica con materiali compositi – B. Zuccarello

1.1 Longitudinal tensile strength σ_{1L}

An accurate determination of the mechanical properties of a composite can be performed experimentally by means of mechanical tests. In good agreement with the experimental evidence, however, the strength and stiffness can be estimated theoretically from the characteristics and concentration of the constituents. The unit normal stress (ratio between the applied axial load P and initial section A) is obtained, under the assumption of Hookean behaviour, i.e. under isodeformation conditions, neglecting the effects due to the different lateral contractions of the fibres and the matrix, and considering the load acting on the fibre and collaborating matrix [1], [4], [5]

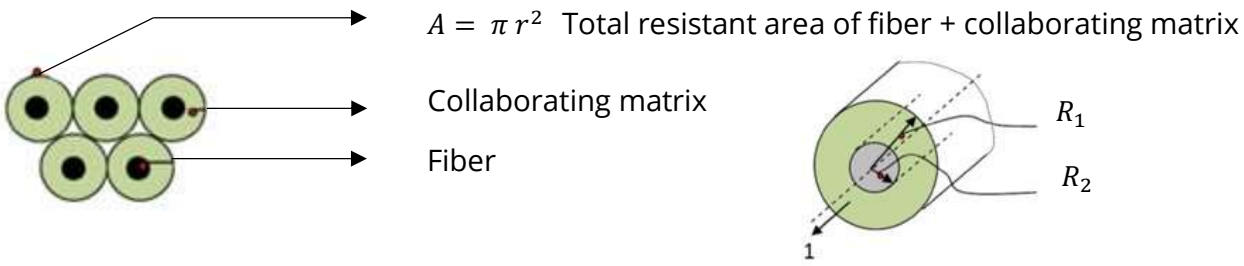


Fig. 2 – Unidirectional sheet scheme used for determining longitudinal characteristics

With reference to Figure 2, the total tensile load P_{1C} applied to the lamina results from the sum of the P_f e P_m load, borne by the fibres and matrix respectively:

$$P_{1c} = P_f + P_m$$

In terms of stresses, this translates into the average stress on the sheet (rule of mixtures), averaged over the stresses present on the fibres and matrix, weighted according to their respective volume percentages:

$$\sigma_{1L} = \sigma_f V_f + \sigma_m V_m$$

Generally, since the matrix is characterised by a higher, compressive deformability and shear strength than the fibres and a low tensile strength, the fracture of the composite depends on the tensile strength of the fibres. The presence of reinforcing fibres therefore results in an increased breaking load [6], [7].

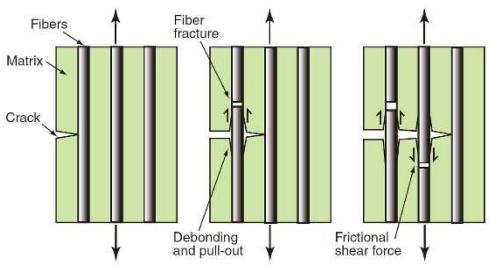


Fig. 3 – Failure modes of laminates as a function of the load applied along the longitudinal direction of the sheet
Source: Materials science and engeneering– Callister, Rethwisch;

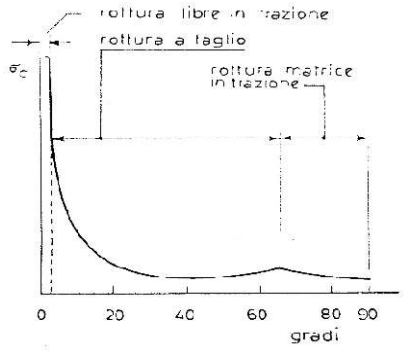


Fig. 4 – Resistance of a composite to variations in the fiber-load misalignment angle.
Source: Materiali compositi – I. Crivelli Visconti;

1.2 Longitudinal elastic modulus E_1

Under the assumption that fibre and matrix have linear elastic behaviour, the longitudinal Young's modulus of the lamina also obeys the "law of averages or rule of mixtures" as it is a function of the elastic moduli of the phases (fibre and matrix) and their volumetric percentage [1]. [5]:

$$E_1 = E_f V_f + E_m V_m \text{ (GPa)}$$

Where:

$$V_f + V_m = 1$$

The longitudinal elastic modulus E_1 obtained in iso-deformation conditions turns out to be a characteristic essentially dominated by the fibres, since a large part of the total tensile load P_c applied to the composite is discharged onto them. Assuming that $E_f > E_m$ and $\sigma_f > \sigma_m$, the action of reinforcement in terms of stiffness and strength depends on the value of V_f, i.e. the quantity of fibres present. Even though only a small part of the load is supported by the area of the collaborating matrix, technological limitations advise not to exceed V_f values of 60 ÷ 70% in practice. Above these percentages, in fact, the number of fibres in contact increases enormously, and they damage each other, not allowing a good fibre-matrix interface bond.

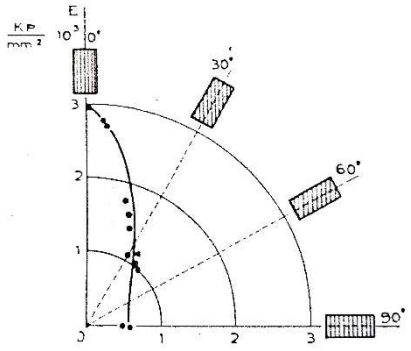
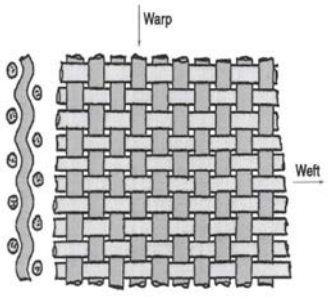


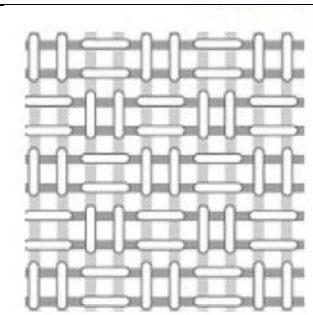
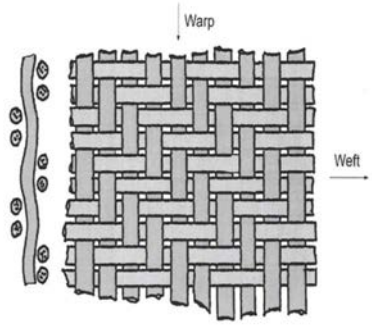
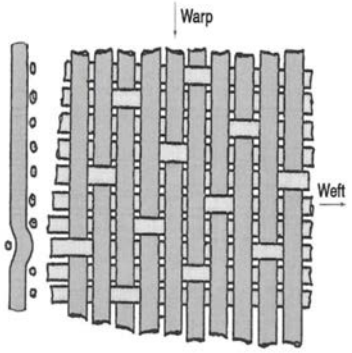
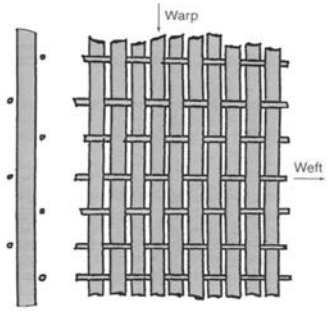
Fig. 5 – Value of Young's modulus of a composite as the angular angle of the fibres varies.
Fonte: Materiali compositi – I. Crivelli Visconti;

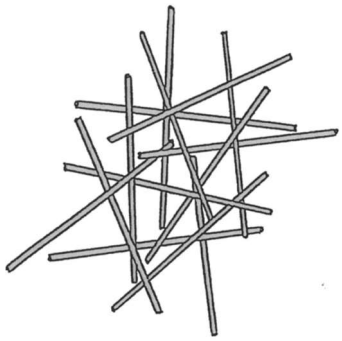
2 Elements of wet lay-up technology with epoxy resins and fabrics

PMCs, reinforced with glass fibre (GFRP), carbon fibre (CFRP) and aramid fibre (AFRP), are today widely used as structural materials in the mechanical engineering, marine, transport, civil, sports and even consumer goods sectors. The aim of a process technology specification for wet lay-up is to define the criteria for manufacturing or repairing components by impregnating glass, graphite or aramid fibre fabrics with epoxy resins mixed with hardeners. With the aim of improving and integrating certain standards in the temporary repair processes of equipment and pressure pipes, some general product and process requirements, which are essential in the drafting of a technical-application specification, are analysed below [2], [3], [4]:

- The control of the environmental conditions of the processing area: temperature 10÷18 °C, humidity ≤ 75% R.H., clean work area, free of dust, fumes, grease, lubricants or other contaminants;
- Checking the expiry date of resins and hardeners to ensure that they retain all the manufacturing properties;
- Controlling the storage life in the warehouse and processing area of resins and hardeners so that they retain their properties;
- The resins and hardeners for wet lay-up (low viscosity and high penetrating power);
- Preparation and mixing ratio of the resin/hardener components (hardener, accelerator). The quantity of resin and hardener must be accurately weighed in the proportion indicated by the mixing ratio (100:15 ÷ 100:38). Before use, the two components must be homogeneously mixed, taking care not to incorporate air bubbles;
- Use time of resin/hardener mixture (for EA956NA/ EA 956 ≤ 30 minutes);
- Fibre/resin volume ratio: glass fibre 1:1.2; carbon fibre 1:1; kevlar fibre 1:1.8
- Procedures for the impregnation of dry reinforcement fabrics, by brush dabbing: avoid brushing actions that could create misalignments, alter the equidistance and parallelism of the fibres along the direction of loading, the coalescence of contact points between the fibres that negatively affect the physical-mechanical characteristics of the composite;
- The different types of fabrics for wet lay-up, shown in fig. 6-11.

	Fig. 6 – The most common pattern is the 2D plain-weave known as canvas, characterised by weft and warp threads interfaced in a regular and periodic manner with unit spacing. The fabric is characterised by moderate fibre crimp (curvature or warp generated by the high number of overlapping weft and warp threads, which limits the stiffness and strength of the composite). It is generally less drapable than other

	fabrics. Source: SR Technics, Basic Maintenance Training Manual.
	Fig. 7 - More drapable and durable than plain-weave is the 2D basket weave, which differs by having two or more fibres woven on top of each other. Source: SR Technics, Basic Maintenance Training Manual
	Fig. 8 – In 2D twill-weave weaving, each weft is interfaced with the warp with double periodicity, producing a visual effect of a diagonal along the fabric. Compared to plain weaving, it is more drapable and wettable, due to the reduction in fibre crimp. This results in higher values of mechanical properties in the laminate plane (along the main warp and weft directions). Source: SR Technics, Basic Maintenance
	Fig. 9 – With **2D n-satin weaves**, a family with fewer and fewer interlacing points between the fibres is identified (each weft passes over all but one warp). The main characteristic of such a fabric with a smooth surface is its marked anisotropy with high strength in the two main plane directions and better drapability than plain weave, allowing the covering of complex warps. Source: SR Technics, Basic Maintenance Training Manual.
	Fig. 10 – With **1D unidirectional weave** type fabrics, a weave with greater weft spacing than the warp is identified. The marked anisotropy gives very high mechanical properties along the warp direction, low strength along the weft direction, occasional added. Source: SR Technics, Basic Maintenance Training Manual.

	Fig. 11 – With mat or felt type fabrics, **chopped strand mat**, the fibre bundles are cut with a length of approximately 5 cm. The random spacing of the fibres gives greater isotropy with similar mechanical properties in all directions but significantly lower than with woven fabrics. Good interlaminar cut resistance. Source: SR Technics, Basic Maintenance Training Manual.

- The monomer-to-polymer transformation process (polymerisation) of a thermosetting resin with a catalyst, can be achieved cold, if it refers to a slow curing process at room temperature (about 30 minutes). Hot curing, polyaddition curing process, takes place by heating the resin between 80 and 200 °C. The hot curing procedure used in lamination with prepreg fabrics consists of 3 distinct steps [1], [3], [4]
  1. gelitification at room temperature (polymerisation of approximately 70 per cent of the matrix is achieved)
  2. curing: the polymer is subjected to controlled temperature application (air circulation oven, heat blankets, infrared lamps) and cross-linked under vacuum (vacuum bag); it improves mechanical properties, compaction, fibre-matrix bonding, minimises local defects and residual stresses formed in the previous step, removes any gas inclusions, voids, air bubbles or solvents trapped in the matrix,
  3. post-curing: the polymer is heated to a higher temperature than before in order to further harden the matrix and release residual stresses. The post-curing temperature is conditioned by the critical temperature (glass transition)

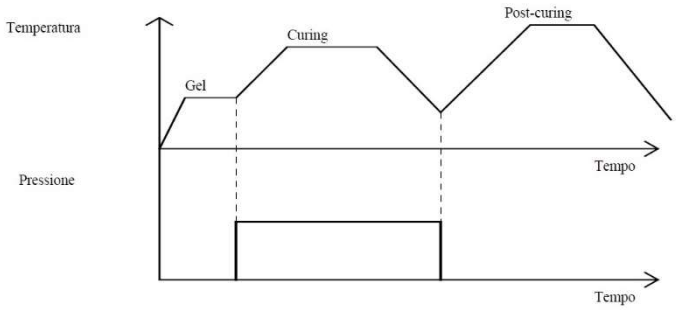


Fig. 12 –thermal and pressure cycle in a polyaddition process
Source: Progettazione meccanica con materiali compositi – B. Zuccarello

In a good composite, the volume ratio V_v between the void volume v_v and the effective volume of the composite $v_{c,e}$ must be $V_v = v_v/v_{c,e} \leq 1\%$. On the other hand, composites of low quality may have up to 5% microporosity.

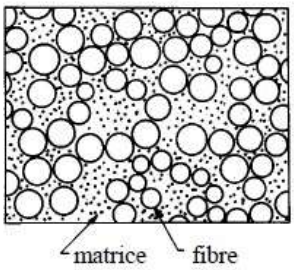


Fig. 13 – Cross-section of sheet with unidirectional reinforcement, with the presence of voids.
Source: Progettazione meccanica con materiali compositi – B. Zuccarello

- Non destructive testings (NDT)

In composite structures used for temporary wet lay-up hand repair, it is necessary to perform NDT to verify their structural integrity by detecting typical construction defects such as:

1. non-uniformity of fibre/matrix ratio;
2. non-uniformity of matrix characteristics;
3. surface defects;
4. lay-up defects (errors in foil or fibre orientation, gaps between planes, etc.);
5. inclusions of foreign bodies etc;

On the other hand, checks during operation of the components are aimed at identifying damage typical of operation, such as:

a) environmental degradation (hygroscopic, thermal, etc.) of the matrix;
b) debonding;
c) matrix fracture or damage, etc;
d) delamination;
e) creep etc.

Currently, the most commonly used testing techniques are: Visual Testing), Tap Test Tool, Radiographic Testing), Ultrasonic Testing with C-scan technique, Thermografic Testing, Acoustic emission Testing, Computed Tomography, Microwave Non Destructive Testing, Shearography.

3 Conclusions

In this paper, the critical steps of a temporary wet lay-up hand repair using two-component fibre-matrix composite materials are presented.
Process specifications establish strict temperature and pressure control, to optimise mechanical properties, compaction, fibre-matrix interaction, reduce local defects and residual stresses.
The cold or hot curing process is carried out with the aid of vacuum bags, infrared lamps, or through specific polymerisation cycles in an autoclave. It would therefore be desirable for the technological specifications used in advanced industrial sectors,

where very high mechanical performances are required, to also be implemented in the traditional process industry, which generally uses manual deposition and impregnation procedures, without the application of the vacum bag or specific curing cycles.

'*Marble is like man, before you embark on something, you have to know him well and know everything he has inside. So if there are air bubbles in you, I am wasting my time*'. Michelangelo Buonarroti.

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Virtual reality in the training of workers in confined spaces: a concrete experience

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Abstract
Examination of several accidents involving operators working in confined spaces with or without pollution has shown that there may be various factors underlying accidents that occur in these environments and that it is not easy to train workers destined to work in there, because of these environments' particular characteristics. In the analysis of which factors can influence the effectiveness of an operation in these spaces, not negligible human factors also come into play, psychological and specific to the individual. Education and training, in this sense, can reduce the negative impact of these factors through experience and knowledge of the operating modes, in order to manage not only the ordinary activity in these spaces, but also the management of high-risks and emergency situations for the individual. For this reason, Inail researchers from the "Safety of processing and production plants" Laboratory, in a logic of prevention through innovation, designed and built a physical simulator to replicate in a protected and effective way all types of risks to workers operating in these environments. The simulator has been designed to alter the cognitive conditions of those who use it, making them experience situations of danger and consequent extremely realistic risks, typical of confined environments (poor visibility, cramped spaces, communication difficulties, poor ventilation and emergency rescue difficulties, etc.). To further minimize the risks workers may encounter in this type of environment, training workers on the actions to be performed, using virtual reality, can be very helpful. To this end, as part of a research project financed by Inail (Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro, i.e. National Institute for Insurance against Accidents at Work), in which the Department of Industrial Engineering of the University of Naples Federico II and the Department of Computer Engineering of the Sapienza University of Rome also participate, we are working on the virtual reconstruction of real confined spaces. The ambitious goal is to integrate physical activity on the field and virtual reality activities as much as possible, so that the two can coexist and support the worker both in

normal work activities and in training ones. To date, we have completed the reconstruction of an underground environment of a few square meters located near the runways of Fiumicino airport and we are working on the implementation of some training units intended for workers who enter that space and aimed at reproducing the actions they have to perform.

1 Introduction

A confined and/or suspected of pollution space is a place where maintenance, adjustments, mechanical parts installation, cleaning and other activities can be carried out, but it is not designed to carry out continuous working activity. Until recently, Italian legislation did not describe what is meant by a confined space.
Only recently, in November 2024, a new technical standard of the UNI (Italian National Unification Body) 11958:2024 - Confined and/or suspected pollution environments - Criteria for the identification of dangers and assessment was published in Italy of the risks, provide an initial description of a confined and/or suspected pollution environment. Although a technical standard is not as binding as a legal standard, the definition of a confined environment within it is an important step because it provides for the first time a reference for companies and workers who have to work in this type of environment. In this technical standard, the confined and/or suspected contaminated environment is defined as a "limited space, not designed and built for the continuous presence of a worker, but of such dimensions as to allow entry and performance of the assigned work performance" . ". , characterized by limited and/or difficult entry or exit routes, with possible unfavorable ventilation, within which the presence or development of dangerous conditions for the health or safety of workers cannot be ruled out". In summary, can state that a confined environment and/or an environment suspected of pollution has the following characteristics, which are not always necessarily satisfied:

- limited and not designed or built for the continuous presence of a worker;
- characterized by limited and/or difficult entry or exit routes;
- characterized by possible unfavourable ventilation and the potential presence of dangerous chemical agents (e.g. gases, vapours, dusts, mists) is to be expected.

The number of deaths in these environments is often higher than the number of accidents, because fatal events affect not only those who are directly involved in the primary accident, but also those who intervene in an attempt to rescue them. Therefore, the training of those who work in confined and/or suspected polluted environments is of fundamental importance.

2 Risk factors in confined spaces

The main risk factors for those who work in confined and/or suspected of pollution environments are the following:

- asphyxia due to lack of oxygen caused by fermentation processes (formation of

carbon dioxide, hydrogen sulphide, etc.) and/or formation/presence/introduction of gases that replace oxygen (nitrogen, carbon monoxide, etc.), entrapment in loose materials (cereals, granules plastics, catalysts, inert powdery supports);
- unfavourable microclimatic conditions due to high humidity, high or low temperatures, use of personal protective equipment (PPE) resulting in limited perspiration, type of work being performed, etc.;
- explosion/fire due to evaporation of flammable liquids[1], presence/formation of flammable gases, raising of flammable dust and presence of ignition sources of various kinds (electrostatic charges, use of tools and work equipment that produce sparks, electrical systems and appliances, operations of cutting and welding), etc.;
- intoxication due to the presence of residues, decomposition or biological reactions, ineffective insulation, etc;
- fall due to failure or incorrect preparation of provisional works, failure to use PPE, use of unsuitable equipment or improperly used (e.g. too short or unsecured ladders), etc.;
- electrocution due to systems/tools not suited to the classification of the area, not complying with applicable legislation or in poor condition, manoeuvring errors (lack of electrical insulation), failed coordination, failed electrical isolation, etc.;
- contact with organs in motion such as parts of the plant/machines not adequately protected, use of equipment unsuitable for the restricted environment, etc.;
- investment/crushing due to access from road areas, falling objects, manoeuvring errors by vehicles, lack of coordination during entry/exit.

3 The Inail model of education and training

Italian legislation currently does not define the contents of training for workers in confined and/or polluted environments. As part of this legislative vacuum, Inail designed and implemented a one-day training course consisting of a classroom part and a simulation part. It is worth underlining that in designing the structure of the course, the Inail researchers did not rely on any previous experience in this area, nor on already known guidelines or best practices: the conceptualisation and implementation of the classroom training and the training phase with the simulator arise from the awareness of Inail researchers of the need to train workers in a context that reproduces their real working conditions as faithfully as possible, with the aim of increasing the safety and awareness of those who work in such spaces. The lecture part focuses mainly on the qualification criteria for companies and self-employed workers who intend to work in confined and/or polluted environments, as currently provided for by Italian legislation, on a general overview of the types of risks that workers may encounter in these environments, on the development of an effective work and emergency procedure to deal with these risks, and on the main tools and individual protection devices that workers must use. The use of case studies and demonstration videos is also included in this phase of the training. However, the most

important phase of the training day, and the one most appreciated by workers, is the one that takes place using the simulator. The simulator training phase also includes the simulation of a rescue procedure for a worker for whom an accident is faked. The rescue is carried out by other workers. For this reason, all workers are provided with appropriate personal protective equipment, including a harness, restraint lanyards, protective helmet, gloves and safety shoes. To date 790 workers have been educated and 615 of them have been trained using the simulator. In some cases, an exercise was also carried out with the direct participation of the fire fighters and an emergency ambulance, with the implementation of a procedure involving the rescue of the fake victim by the fire fighters and the subsequent intervention of the emergency ambulance personnel to provide first aid. The training course is constantly improved taking into account all the data and feedback collected in each edition relating to the level of knowledge of workers on the topic of confined and/or suspected of pollution environments. Since the training course was provided to workers of companies of different production sectors (chemical, port, agricultural, wine, construction, etc.), this has made it possible to acquire a greater understanding of the actual level of knowledge as well as the risk perception that workers experience during activities, so as to modify the Inail training model by adapting it to the actual needs of workers operating in the various sectors mentioned above. During the course, the trainees filled out, in addition to the learning test, post-it notes at the entrance, before the start of the training phase, and at the exit, at the end of the training phase; the purpose of the entrance post-it was to find out whether the workers were aware of the risk factors in confined and/or suspected polluted environments and whether they had ever dealt with this type of environment during their normal work activity. At the end of the training day, two further post-its were administered to the workers to obtain feedback on the overall level of satisfaction with the course attended and suggestions for improving the training course. Since the purpose was to summarise the answers obtained through the post-its into statistical data that would allow us to have an overall picture of the workers‘ prior knowledge, as well as their suggestions on the training and didactic offer, the difficulty of obtaining homogeneous clusters of data from the post-its and the need to investigate the impact of psychological factors on the workers’ behaviour, advised us to use a pre- and post-training questionnaire, administered via QR code. In addition to the questionnaires, a digital check-list was prepared to detect and report in real time, by the trainers, the critical points and errors most frequently encountered during training. Some of the results of the 2024 education and training sessions of learners (data updated to September 2024) in confined and/or suspected of pollution environments, are reported below. The data refer to a sample of 370 workers who were administered the questionnaires via QR code.

4 Psychological factors in education and training

Operator performance and safety compliance are key factors when dealing with confined and/or suspected of pollution environments. In particular, the effectiveness of the operations in these environments must necessarily consider not negligible human factors of a psychological nature, such as motivation, personal and interpersonal qualities, and tolerance to the mission. Studies emerged in the 1970s which show that education and training can reduce the negative impact of psychological factors through experience and knowledge of operating practices, to ensure the proper management of both ordinary activities and high-risk emergency situations for the individual[1]. Nowadays, virtual reality (VR) and other new technologies have enabled immersive and interactive training experiences providing real-time physical feedback to enhance situational awareness and decrease risk in these spaces. In addition, new simulation techniques make it possible to practice repeatedly, thus enabling workers to become proficient in operating practices and to improve their memory. In more recent times, in fact, numerous studies have contributed explaining how immersive education and training experiences constitute an optimal methodology to improve the efficiency and validity of training. Due to these considerations, "experiential" training has become more and more necessary to have a positive and effective impact on the factors mentioned above to learn how to manage the psychological aspects in the most suitable way for safety. In fact, the results of the questionnaires administered via QR code to the 370 employees mentioned above show that psychological factors (inattention, distraction, physical and mental fatigue) affect performance: in particular, 16% of the sample states that they feel inattentive, distracted or tired while performing work activities, and more than half (53%) confirm this, though at a lower level ("little inattentive, distracted or tired") (Figure 1).

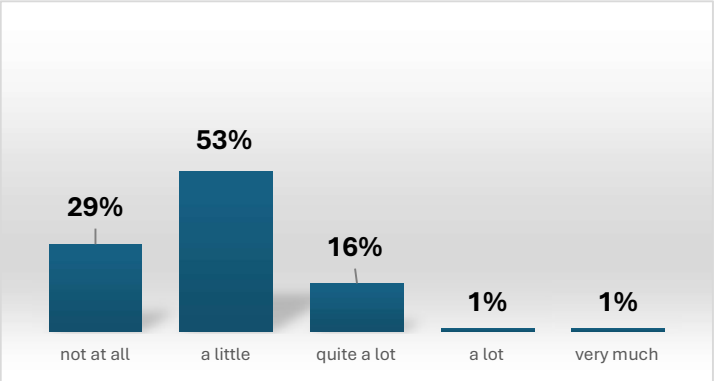

Fig. 1 - “Do you find yourself feeling inattentive/distracted/tired at the workplace?" (Sample of 370 workers, Inail 2024)

The graphs showing the causal factors for this psychological state indicate that environmental factors (e.g. noise, temperature) have the greatest impact, followed by prolonged physical exertion (e.g. lifting weights, prolonged use of

personal protective equipment) and organizational aspects (e.g. relations with colleagues, shift management) (Figure 2).

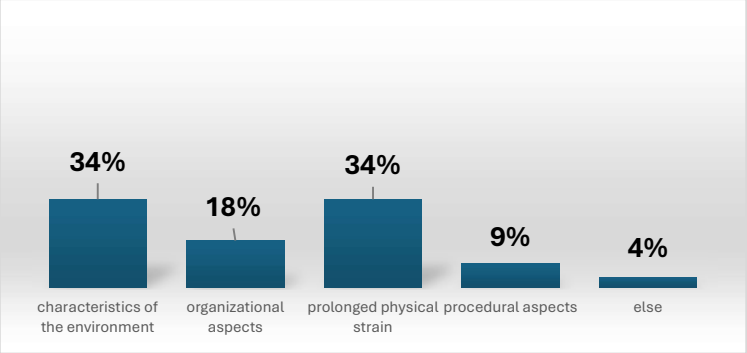

Fig. 2 - “What makes you inattentive/distracted/tired in the workplace?" (Sample of 370 workers, Inail 2024)

Thus, it becomes clear that education and training activities are necessary to increase workers' awareness to make them properly educated and trained as well as aware of what working in confined environments entails, in terms of responsibilities, risks to their own health and safety, and operating practices.
Finally, these results confirm the importance and non-negligible impact of psychological factors on the performance of activities, whether they are environmental, organizational, relational, or originating from physical exertion.

5 The Inail simulator

For this reason, Inail researchers from the "Safety of processing and production plants Laboratory”, in a logic of prevention through innovation, designed and built a physical simulator to replicate in a protected and effective way all types of risks for workers operating in these environments. The simulator (Figure 3) has been designed to alter the cognitive conditions of those who use it, making them experience situations of danger and consequently extremely realistic risks, typical of confined environments (poor visibility, cramped spaces, communication difficulties, poor ventilation and emergency rescue difficulties, etc.). It is transportable; it can be connected to the electricity grid of the host company or organization and is equipped with structures and systems that allow it to be safely used. Access to the upper part of the simulator is via a ladder that can be anchored to the external wall, protected from falls by a retractable perimeter metal parapet. The same is useful for practicing the descent through a vertical manhole. It is also equipped with:

- a control room with control system in order to record the events of the training activity;
- a horizontal manhole;
- coloured pipes and valves and four different locks (each with its own key) to simulate LOTO (Lock-Out Tag-Out) conditions;

- internal movable walls;
- systems that influence sensory capabilities, such as various types of noises reproduced via a speaker, harmless fumes of different colours, etc;
- camera systems to record videos of the implemented operations, to analyse and eliminate any critical issues that may arise.

An aspect to underline is the possibility, through the simulator, of increasing awareness of the difficulty of emergency recovery of non-cooperating personnel, which leads to greater attention in the application of work procedures to facilitate the possible intervention of rescuers. The Inail simulator has so far been patented in Italy, USA, China, Canada, Brazil, India and is currently being examined by the European Patent Organization (EPO) for a future patent.

Fig. 3 - The Inail simulator (Inail, 2024)

6 The reconstruction of confined spaces for the implementation of training activities in virtual reality

To further minimize the risks that workers may encounter in confined spaces, training them on the actions to be performed, using virtual reality, can be very helpful. To this end, as part of a research project financed by Inail in which the Department of Industrial Engineering of the Federico II University of Naples and the Department of Computer Engineering of the Sapienza University of Rome participate, we are working on the virtual reconstruction of real confined spaces. In the past, Inail researchers have already been dealing with projects involving the use of 4.0 technologies in the training of workers [3] and in the implementation of 'virtual training pills' (VTP), i.e. delivering learning content in the form of short educational games by using a common technological platform based on virtual, interactive and immersive reality[4]. The ambitious goal is to integrate physical training in the field and virtual reality training activities as much as possible, so that the two can coexist and support the worker both in normal work activities and in training ones[5]. For this purpose, we reconstructed an underground sump located near the runways at Fiumicino Airport in Rome. The sump is used to contain a preconditioning pipe to be connected to a nearby aircraft to provide hot or cold air to the interior spaces, thus allowing the jet

to remain with the internal air conditioning and heating system turned off to avoid wasting fuel. The sump corresponds to the description of a typical confined space: in fact, it is characterized by a narrow space, with limited access and exit routes, not intended to be continuously occupied by workers, but where workers occasionally access to perform maintenance or control operations.
In Figure 4 an actual photo of the area outside the sump and a glimpse of the inside of the sump.

Fig. 4 - Actual photo of the area outside the sump with open hatch and a glimpse of the inside of the sump (Inail, 2024)

The reconstruction of the environment was carried out using a laser scanner with which 4 scans of the indoor space and 2 scans of the outdoor environment were acquired, allowing us to obtain the complete point cloud of the site. A mesh model of the reconstructed manhole was then created from the processed point cloud. The latter served as the basis for subsequent three-dimensional modelling of the environment and the actual facility. The work procedure was then studied, and the work instrumentation required for the purposes of simulation was integrated. This reconstruction is preliminary to the virtual reality reproduction of the work environment: one of the objectives of this project, in fact, is to allow operators to perform in virtual reality, through viewers or other tools, exactly the same operations that they will have to perform when they will physically operate in these environments, so that, before physical access, they can familiarize themselves with the type of environment they will find themselves dealing with through its virtual reconstruction.
The images that follow are the result of the virtual reconstruction work, inside and outside the sump, and reproduce step-by-step the procedure to be followed before entering and once inside the confined environment, in which we have assumed that the worker had to perform one of the typical operations that are normally performed.
The working procedure involves a series of successive steps. First, the work area is demarcated through cones or safety tape (Figure 5).

Fig. 5 - Virtually reconstructed image of the work area delimited by cones (Inail, University of Rome “Niccolò Cusano”, University of Naples “Federico II”, 2024)

Subsequently, the external switchboard that controls the energies inside the sump is de-energized to avoid risks to the worker designed to enter the confined environment.
The atmosphere outside and inside the sump is then sampled by a multi-gas detector. The latter (Figure 6) is a device equipped with sensors capable of verifying both the sufficient presence of oxygen (normally, the oxygen level in the atmosphere is 20.9 percent) and the possible presence of hazardous gases.

Fig. 6 - Virtually reconstructed image of a multi-gas detector (Inail, University of Rome “Niccolò Cusano”, University of Naples “Federico II”, 2024)

The most common detectors are normally capable of detecting the presence of carbon monoxide, explosive atmospheres and hydrogen sulphide, but they can also be designed to detect other gases, depending on the type of environment and the potential atmospheres that may possibly be produced in them. The procedure requires that the external sampling be carried out on the edges of the access hatch to the sump, when the hatch is closed, while when the hatch is open, sampling be then carried out inside the sump by means of 3 successive detections: the first at the top level, the second at the middle level, and the third at the bottom level. Figure 7 shows the sampling sequence: from left to right, first outside with the tailgate closed and then inside on 3 levels, top, bottom and middle level respectively. The dashed

yellow circle indicates the location of the multi-gas detector.

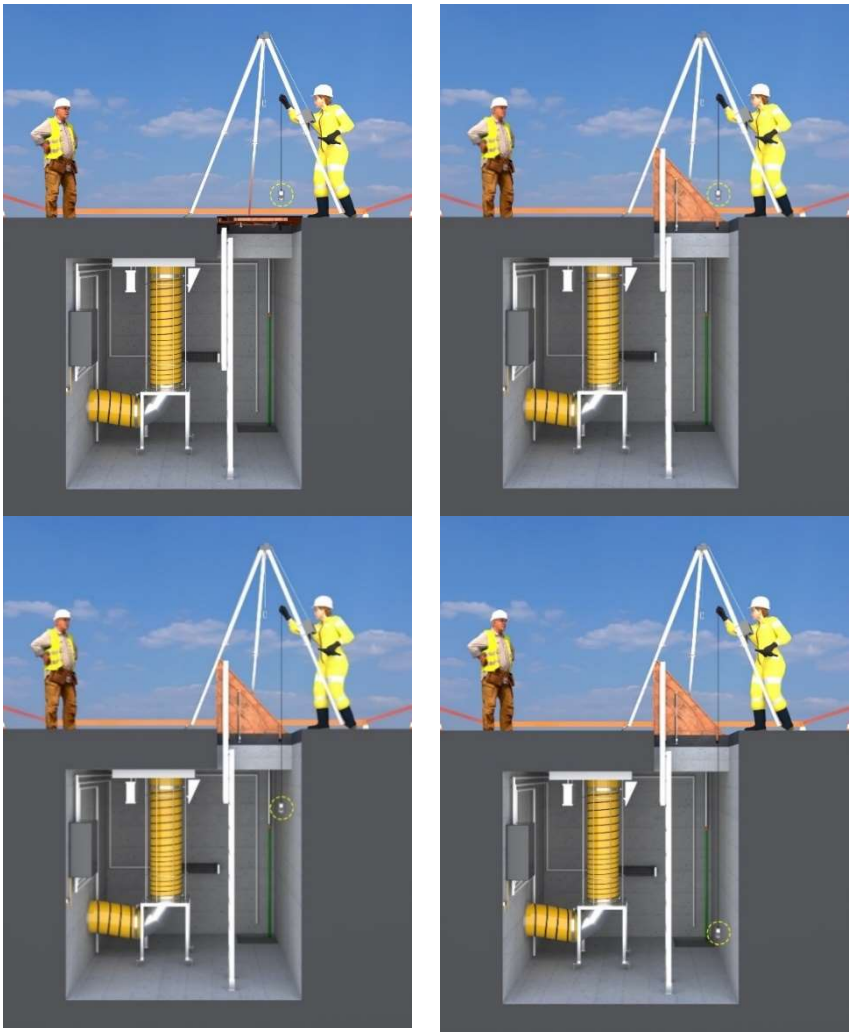

Fig. 7 - Virtually reconstructed image of the sampling sequence, outside and inside the sump. The dashed yellow circle indicates the location of the multi-gas detector (Inail, University of Rome “Niccolò Cusano”, University of Naples “Federico II”, 2024)

The reason why the air sampling procedure inside the sump is done on 3 levels - top, middle, and bottom - is related to the characteristic of gases to stratify on different levels due to their different weights, so some gases may be, for example, at the bottom of the confined space and only surface sampling may not be able to detect them.
Having ascertained that there are no oxygen deficiencies or the presence of hazardous atmospheres, the worker designated to enter the sump to carry out any maintenance or inspection operations, in case of absence of an internal staircase, is harnessed and lowered inside using the tripod, without the need for respiratory protective equipment. The multi-gas detector is also clipped onto the worker's suit so that it can signal any formation of hazardous atmospheres or oxygen deficiency during work activity within the confined environment (Figure 8).

Fig. 8 - Virtually reconstructed image of the harnessed worker being lowered into the sump. The multi-gas detector is attached in the upper chest area (Inail, University of Rome “Niccolò Cusano”, University of Naples “Federico II”, 2024)

The interior of the sump, also obviously virtually reconstructed, looks like in Figure 9.

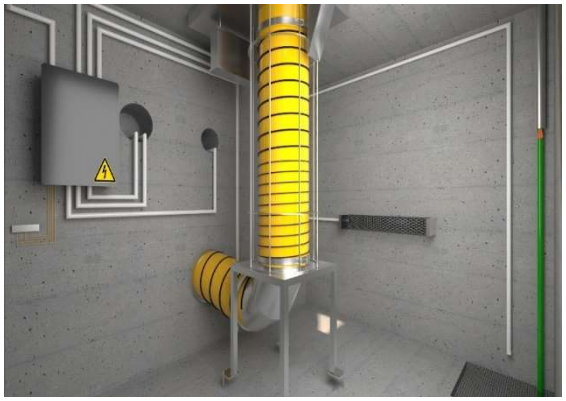

Fig. 9 - Virtually reconstructed image of the sump interior (Inail, University of Rome “Niccolò Cusano”, University of Naples “Federico II”, 2024)

Access to the interior may be required both for routine maintenance activities and for corrective maintenance activities because of any malfunction of some equipment support elements present in the manhole.
Once inside, in the task reproduced in this work, we assumed that the operator performed a routine operation, which consisted of the visual observation of the silver clamp that secures the tubing in its housing, preventing it from slipping out of position (Figure 10).

Fig. 10 - Virtually reconstructed image of the operator visually checking the clamp securing the pipe in its usual position (Inail, University of Rome “Niccolò Cusano”, University of Naples “Federico II”, 2024).

Finally, once the operation is finished, the worker is pulled out again by the tripod and the sump door is closed.
The presence of other workers outside the sump is due to the need to maintain continuous contact with the worker inside the confined environment: in fact, the correct procedure requires that there should always be at least one person operating as a supervisor who is outside the confined environment, possibly also ready to activate help in case of emergencies.
Based on previous experiences of using serious games[6] (games that focus on education) to simulate real work scenarios and train workers on specific safety procedures, the next part of the work, in which we are engaged, will show the virtual reality simulation of the worker performing these same procedural steps, using a visor that will allow him or her to fully immerse him or herself into the rebuilt work environment. In this case, the worker will have a first-person view of the virtually reconstructed environment in which he/she will carry out the steps required by the work.

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Innovative University Education System for OSH Professionals in the Czech Republic

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Abstract
The demand for university-educated professionals capable of solving complex occupational safety and health (OSH) challenges is increasing, particularly in the Czech Republic, where professional competence in OSH risk prevention is required by law. While vocational training provides various preparatory courses, university-level education is becoming essential for addressing today's evolving safety needs. This paper presents an innovative education system developed by the Faculty of Safety Engineering, VSB – Technical University of Ostrava. The programme equips future OSH professionals with practical skills by integrating project-based learning, Collaborative Online International Learning (COIL), immersive XVR simulation tools, and access to hi-tech laboratories such as the Industry 4.0 lab. These innovations offer a comprehensive, hands-on approach to safety education that prepares students for the complex challenges of modern work environments.

1 Introduction

Occupational Safety and Health (OSH) education plays a critical role in preparing professionals to protect the safety, health, and well-being of employees in diverse work environments. OSH professionals (managers) and practitioners (technicians) are essential to promote safe workplaces by assessing risks, implementing safety measures, and ensuring compliance with national and local safety laws. The importance of their role is underscored by occupational incident and disease statistics provided by ILOSTAT [1], EUROSTAT [2, 3], and national statistical offices, which consistently highlight the pressing need for competent OSH professionals.
Frameworks such as the **INSHPO** Global Competency Framework (2017) [4], which describes the roles and responsibilities of OSH professionals, have been developed to set global benchmarks for OSH competency. At the European level, the European Network of Safety and Health Professional Organisations (**ENSHPO**) [5] has introduced qualification standards that recognise OSH expertise and harmonise competence requirements across the EU. These include the EurOSHM (Occupational Safety and Health Manager) and EurOSHT (Occupational Safety and Health Technician) certifications. These standards are voluntary, but respond to the growing demand for professionals who contribute to both operational safety and strategic business development. In the Czech Republic, the National Qualifications Framework ensures consistency with the ENETOSH standards. The OSH technician [6] and the

OSH manager [7] are included in the **National Register of Qualifications** [8], which is a publicly accessible register of all professional qualifications and complete professional qualifications, which are distinguished, verified and recognised in Czechia.

The demand for university-educated OSH professionals continues to grow both within the Czech Republic and worldwide [9]. This trend reflects the increasing complexity of workplace environments [10] and the need for highly qualified personnel to effectively manage safety risks. Furthermore, education in skills of the 21st century, such as collaboration, communication, creativity, and critical thinking, is crucial to success and adaptability in the rapidly changing global environment of today. In response to this demand, the Faculty of Safety Engineering at VSB – Technical University of Ostrava was established in 2002. Its foundation was driven by the needs of industrial companies seeking skilled safety professionals capable of meeting modern challenges.

In the Czech Republic, the professional competency in OSH is governed by the § 9 of **Act No. 309/2006 Coll.** [11]. Employers are responsible for evaluating and preventing risks to employees' health and safety. For organisations with 26 or more employees, these tasks must be performed by the **professionally competent person**. Professional competency requires at least secondary education with a graduation certificate, relevant practical experience (duration based on education level), and a certificate proving the successful completion of a professional competency test. If the individual has a university-level education in the OSH field, a minimum of one year of practical experience is required. Although not mandatory, higher education in OSH is increasingly valued by employers seeking qualified OSH professionals.

This article aims to showcase an innovative OSH education system developed at the Faculty of Safety Engineering, VSB – Technical University of Ostrava. The presented system addresses the growing need for qualified OSH professionals by integrating modern teaching approaches, aligning with legislative requirements, and responding to the evolving demands of industrial enterprises.

2 Overview of the Education Programme

The Faculty of Safety Engineering (FSE) is the only institution in the Czech Republic offering complex higher education in industrial safety, including occupational safety, process safety, fire safety, public protection and crisis management, and physical security. FSE provides a bachelor's programme in Occupational and Process Safety (3 years) and a master's programme in Safety Engineering (2 years). The Bachelor's programme focusses on risk assessment and management in OSH and process safety, while the Master's programme expands to complex SHE (Safety, Health, Environment) systems and managerial skills, preparing graduates for leadership roles in safety management. This structure ensures a smooth transition from foundational to advanced competencies.

a. Curriculum Design

Bachelor's degree programme in Occupational and Process Safety:

Graduates of the Occupational and Process Safety bachelor's programme are equipped for careers in small, medium, and large industrial enterprises, including multinational corporations, as well as in public administration and private practice. The programme's primary goal is to prepare specialists capable of performing the role of OSH technicians and professionally competent persons in risk prevention. The curriculum is tightly bound with legislative requirements for professionally competent persons in risk prevention according to Act No. 309/2006 Coll. [11]. Allowing the graduates to gain the certification in the OSH field.

Through a combination of mandatory courses, students gain the skills to address key safety challenges such as preventing major accidents, protecting against explosions, and environmental safety. Elective courses allow students to deepen their expertise, for example, in fire protection, which is highly valued in practice.

Graduates develop comprehensive knowledge of occupational and process safety risk prevention. Practical skills are enhanced through internships, site visits, and hands-on training in modern simulation facilities, such as CESIT, which incorporates virtual reality and crisis management scenarios. This well-rounded curriculum ensures that graduates are capable of addressing safety issues in diverse industrial settings, developing preventive measures, and effectively communicating solutions in both professional and interdisciplinary contexts.

Master's degree programme in Safety Engineering:

The follow-up master's programme in Safety Engineering builds upon the bachelor's foundation by focussing on greater complexity, a broader generalist approach, and the development of advanced managerial skills. Unlike the bachelor's programme, which emphasises technical and operational aspects of safety, the master's programme prepares students to address complex interdisciplinary challenges in safety, health and environment (SHE) management at a strategic level.

Students learn to manage integrated safety systems, align safety practices with organisational goals, and lead multidisciplinary teams. The curriculum includes advanced topics such as risk governance, process optimisation, and crisis management, equipping graduates to take on leadership roles in large enterprises or multinational organisations. The emphasis is on decision making, strategic planning, and the ability to navigate complex systems, ensuring that graduates are well prepared for managerial positions in safety engineering.

b. Integration of Modern Approaches

Traditional approaches, such as compulsory internships and excursions, often fall short of providing students with in-depth practical experience. Internships, while valuable, are typically short (several weeks) and highly dependent on the quality of the placement, which students often arrange themselves. Similarly, excursions offer only brief insight into industry practices without opportunities for active participation.

To address these limitations, **project-based learning (PBL)** was incorporated into the curriculum, creating a bridge between theory and practice.
PBL is a learning method in which students actively participate in solving real-world problems over an extended period [12]. It emphasises collaboration, analytical and critical thinking, and hands-on application of theoretical knowledge. Furthermore, the impact of PBL on the development of interpersonal competences in higher education was shown [13]. In the FSE study programme, PBL is implemented in partnership with industrial companies to provide students with opportunities to tackle real challenges and develop practical solutions. For example, key partners like ABB and STANT collaborate on projects that include:

- Update internal traffic regulations based on past incidents.
- Analysis of ergonomic risk factors at selected workstations and design of a new workplace layout.
- Pilot implementation of a questionnaire to identify psychosocial risks.
- Development of a workplace OSH training programme to support managers.
- Design of a toolkit to support the "Safety Ambassadors" programme.

Collaborative Online International Learning (COIL) [14] enhances PBL by integrating internationalisation into the educational experience. Connect students and educators from various countries and cultural backgrounds, fostering online collaboration on research or practical projects. This approach enables global teamwork without requiring travel, promoting intercultural competence and broadening students' perspectives. By making international learning opportunities accessible to all, COIL helps prepare students for the global nature of modern industries. Currently, COIL projects are being developed and piloted as part of the **COLOSH project**, further enriching OSH education with innovative and international dimensions.
Through the integration of PBL and COIL, the programme prepares students not only for the technical challenges of their careers, but also for the global and collaborative nature of modern industry. These methods provide a well-rounded, practical and internationally focused education that equips students with the skills needed for success in the field of occupational safety and health.

3 Innovative Tools and Resources

Innovative facilities, tools, and resources have been developed through the REFRESH project [15] and Erasmus+ KA2 projects such as RiskMan, OshDigit, and COLOSH. The REFRESH project focusses on transforming the post-coal mining landscape of the Moravian-Silesian region by addressing technological and social challenges in areas such as renewable energy, digitalisation, Industry 4.0, and environmental applications. A key feature is the creation of three interconnected "living laboratories" located in a new VSB-TUO campus building and other modernised facilities. The Erasmus+ projects aim to enhance the capacity of the FSE and its partners to transition to international digital learning. They also support educators by developing

high-quality and engaging teaching resources for OSH education, ensuring readiness for modern, global, and digital training environments.

a. XVR Simulations

The integration of digital tools into education aims to equip future graduates with the ability to apply modern technologies meaningfully in their professional and daily lives. As part of this effort, the **XVR simulation** software [16] has been experimentally implemented in the teaching of safety engineering. XVR, widely used for training emergency and safety personnel (especially The Integrated Rescue Services), enables immersive virtual reality (VR) simulations of various crisis scenarios. Simulations include traffic accidents, fires, hazardous substance or mixture response, natural disasters, etc. The three levels of management are supported: tactical (onsite response), operational, and strategic decision-making during emergencies.

FSE integrates the XVR Simulation environment into its OSH-related curricula to provide students with hands-on experience in managing real-world safety challenges [17]. Using 3D modelling in Unity, the team has expanded the XVR library by creating customised objects and scenarios tailored to specific educational needs. These simulations enable students to develop critical skills in risk assessment, decision making, and legal compliance. Key examples include:

- Fire in a Warehouse of Flammable Liquids and Mixtures: Two scenarios demonstrate the consequences of workplace conditions. In the first, poor housekeeping leads to a worker's death, while in the second, an organised workplace prevents the accident. Students learn to assess the impact of workplace organisation on fire safety and emergency response.
- Forklift Crash in the Warehouse: This simulation depicts a forklift accident, a common but potentially severe incident. Students analyse root causes, evaluate risks, and propose preventive measures to avoid similar situations.
- Warehouse - Hazard Hunt: Students identify workplace hazards, develop risk scenarios, and apply relevant legal regulations to propose control measures, strengthening their ability to link theory with practical problem solving.
- Shopping Centre - Hazard Hunt: This scenario focusses on public areas, including truck movement, loading/unloading zones, and parking areas. Students learn to identify and address the risks that arise from interactions between work-related activities and public spaces.
- Bhopal Disaster: Based on the catastrophic chemical plant incident, this simulation helps students understand the complex and concurrent causes of industrial disasters, highlighting the importance of risk management and systemic safety planning.

These immersive simulations allow students to deeply engage with OSH-related challenges, fostering their ability to analyse, interpret, and manage risks in diverse industrial and public settings.

b. Hi-Tech Laboratories

The **Industry 4.0 Lab** and other advanced facilities play a crucial role in enhancing practical learning for FSE students by integrating cutting-edge technologies into the curriculum. Currently, students visit the **Smart Factory** testbed at the Faculty of Electrical Engineering and Computer Science, featuring a production line with Industry 4.0 elements, such as mobile robots, 3D printing, IoT, image recognition, 3D object identification, machine learning, and virtual reality environments. The testbed is evolving into a digital twin, combining physical and virtual systems, allowing students to explore advanced manufacturing processes, simulate workflows, and understand the interplay between physical operations and their digital counterparts. FSE is also developing its own collaborative robotics lab, reflecting the growing importance of collaborative robotics (CR) in Industry 4.0. Students will learn how to assess and manage risks associated with the integration of collaborative robots into workplaces, focussing on functional safety and workplace safety. They will gain insight into how these robots, equipped with advanced sensors, enable safe cooperation with humans, share the same workspace, and reduce risks associated with hazardous substances, repetitive tasks, or poor ergonomics.

The laboratory will teach students how to approach risk assessments, integrate cybersecurity measures, and apply predictive maintenance techniques to ensure safe and efficient operation of autonomous systems. By engaging in hands-on projects and interdisciplinary research, students will be prepared to address the challenges of modern, technology-driven workplaces, aligning with the principles of Industry 4.0 and occupational safety.

c. Other innovative teaching tools

Innovative teaching tools developed through the **RiskMan** and **OshDigit** projects enhance practical learning in OSH education.

The RiskMan Toolkit offers tools in five categories, including case studies, risk assessment examples, online risk assessment tools, safety games, and virtual reality training. Examples include case studies on musculoskeletal disorders, root cause analysis exercises, and VR-based hazard identification training. These tools promote interaction, gamification, collaboration, and teacher-guided learning, making them adaptable for both face-to-face and blended learning environments. [18]

The OshDigit Toolkit focusses on digital learning in OSH and includes videos from workplace XVR simulations, virtual site visits, and occupational hygiene measurements, as well as interactive presentations on topics such as nanomaterial risk assessment, psychosocial risks, and digitalisation of work. These tools help bridge the gap between theory and practice, offering students virtual workplace experiences when physical site visits are not feasible. [19]

Both toolkits are designed to enhance student engagement, link learning to real-world scenarios, and support teachers in delivering modern and effective OSH education. They are available online: RiskMan Toolkit: riskman.vsb.cz, OshDigit

Toolkit: oshdigit.vsb.cz.

4 Discussion and Conclusion

The implementation of innovative methods and tools such as PBL, COIL, XVR simulations, and high-tech laboratories has introduced new dimensions to OSH education at FSE, creating stronger connections between theory and practice. Although the evaluation of their impact on student competencies is still ongoing, initial feedback from students and employers suggests positive outcomes. Students appreciate the opportunity to participate in solving real problems. Even if it means stepping out of their comfort zone. Employers recognise that FSE graduates are well prepared for practical safety roles, as evidenced by the faculty's fourth place ranking in the "School Recommended by Employers" poll.

These innovations equip graduates with essential skills, especially in risk assessment, problem solving, and collaboration, while fostering adaptability to emerging technologies and global demands. Early successes, such as hazard identification training with XVR and projects in industrial companies, show the potential of these methods to address modern OSH challenges.

Furthermore, participation in global networks like CONRIS, U!REKA and ENETOSH improves the quality and scope of OSH education at FSE. CONRIS promotes collaboration in risk, safety, and security management through joint projects, research, and curriculum development, promoting innovative educational approaches. U!REKA aims to create a joint campus by 2025, equipping students and lifelong learners with green, digital and transversal skills for the future. ENETOSH provides a platform for exchanging knowledge and best practices in the education of safety, health, and well-being. These networks enable FSE to adopt cutting-edge practices, uphold high international standards, and prepare graduates for local and global workplace challenges, reinforcing their position as a leader in modern OSH education.

However, challenges remain. Students come from different types of secondary schools with varying levels of preparedness for safety education. There is a need to shift from legislation-based programmes to those rooted in scientific knowledge. Balancing broad general OSH competencies with deep specialisation is another challenge. Rapid advances in technology and industry add further complexity. Addressing these issues requires constant updates to curriculum and teaching methods.

In conclusion, the integration of innovative approaches has made FBI a leader in modern OSH education in the Czech Republic. Although further evaluation is needed, these methods have the potential to significantly improve graduate preparedness for complex workplace challenges. The broad adoption of such practices, combined with international collaboration, will be crucial to advancing OSH education worldwide and preparing future professionals for evolving industry demands.

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Neurophysiological embodiment characterization in Virtual Reality environments with different grades of immersivity: preliminary findings

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Abstract

Objective: The study aimed to objectively measure the neurophysiological embodiment in Virtual Reality (VR) environments with varying levels of sensory stimuli. The research sought to address limitations of subjective measures and identify robust neurophysiological markers. *Methods*: Eighteen healthy participants experienced VR environments characterized by different levels of multisensory stimulation: visual-only and a combination of visual, auditory, and vibrotactile inputs. EEG, ECG, and EDA signals were recorded during these sessions. EEG features were derived, while Skin Conductance Level (SCL) and Heart Rate Variability (HRV) were extracted from EDA and ECG signals, respectively. Subjective workload and embodiment questionnaires were also collected for validation. *Results*: Statistical analysis demonstrated that richer sensory stimulation increased the embodiment and reduced perceived workload. EEG-derived features (e.g., Global Field Power in theta and alpha bands) and SCL were significantly sensitive to both task difficulty and sensorial stimuli ($EMBO_1$: $F = 9.712$, $p < 0.001$, $\eta^2 = 0.372$; $EMBO_2$: $F = 12.091$, $p < 0.001$, $\eta^2 = 0.207$; SCL: $F = 6.221$; $p = 0.009$; $\eta^2 = 0.251$). *Conclusions*: The $EMBO_1$, $EMBO_2$ and SCL indices were successfully identified embodiment-specific neurophysiological patterns, even if it was demonstrated also their association with other confounding factors like mental workload, confirming their limitation and the need of further advance in developing a more transversal measurement for the embodiment in VR. *Significance*: This study highlights the potential of combining multimodal physiological data to develop robust, context-independent measures of embodiment. Developing and validating an embodiment-specific neurophysiological measurement would pave the way for advancing VR applications in training, rehabilitation, and immersive system design, particularly in scenarios where user engagement and realism are critical. Therefore, future research will investigate the reliability of a multimodal approach for combining the presented measurements in a unique embodiment index.

1 Introduction

The consistent increase of data in neuroscience has fuelled the development of sophisticated tools for understanding how our brains and bodies work, both in health and disease. This has opened exciting possibilities for applying this knowledge in real-world settings, with Virtual Reality (VR) emerging as a particularly promising area. VR allows us to create immersive experiences that go beyond the limitations of traditional laboratories, providing a powerful platform for research and intervention.

A key factor in the effectiveness of VR is the feeling of truly "being there" – a phenomenon defined as embodiment. Embodiment encompasses not just visual immersion, but also a sense of presence, agency, and ownership of a virtual body. Understanding the biological underpinnings of embodiment is crucial for developing more effective VR applications in diverse fields like healthcare and rehabilitation.

While previous scientific research [1], [2], [3], [4], [5] has explored the neural and physiological correlates of embodiment using measures like EEG (brain activity), ECG (heart function), and EDA (skin conductance), these studies often relied on subjective questionnaires and lacked a comprehensive, objective measure. In fact, the limitation of the abovementioned subjective measurements corresponds to the subjective bias related to each user's perception of the embodiment in VR. Moreover, the identified physiological markers were not exclusively linked to embodiment, as they could also reflect other mental processes. This aspect is crucial in the context of the embodiment evaluation in VR, since digital environments can impact also on other mental states totally unlinked with the sense of presence perception. Therefore, the actual state-of-the-art lacks a transversal approach for the objective evaluation of the embodiment in VR [6], especially within the contexts in which the users are performing activities modulating other mental states [7], [8].

To address these limitations, this study aimed to preliminary investigate specific neurophysiological parameters, which were previously demonstrated to be associated with the embodiment variations in VR. In this regard, a VR experience was designed in order to elicit varying levels of embodiment and collected physiological data from participants using a multimodal approach.

The proposed preliminary investigation was based on the assessment of the embodiment neurophysiological evaluation within the conditions characterized by the minimum and the maximum level of sensorial stimuli. Therefore, the objective of this first preliminary investigation consisted of establishing the reliability of the proposed neurophysiological indices in objectively evaluate the embodiment modulations in VR, and its robustness to other mental states variations.

2 Material and Methods

Participants

This study involved 18 healthy young men (average age of 26.5, with a standard deviation of 3.2 years) with no history of neurological or psychiatric conditions and normal vision. Ethical approval was obtained from the Sapienza University of Rome, adhering to the Declaration of Helsinki standards. All participants provided written informed consent.

In order to create an immersive VR experience, a virtual racetrack scenario was created through the Unity3d software. Participants accessed to this virtual environment through an head mounted headset (Oculus Rift), experiencing it from the driver's seat. They controlled the car using a Logitech racing wheel (without a gear shifter), and to ensure consistency, the car's speed was kept constant. Participants were simply asked to keep the gas pedal pressed down. To enhance the sense of immersion, we incorporated vibrotactile feedback through a belt equipped with vibrating motors, and audio feedback was delivered through headphones.

Throughout the experience, the participants' skin sweat activity (EDA) was monitored as an indicator of their autonomic nervous system response. This was done using the NeXus-10 MKII system with sensors attached to the index and middle fingers of their non-dominant hand. Additionally, the Electroencephalographic (EEG) and the Electrocardiographic (ECG) signals were collected through a 38-EEG channels system and 3-ECG electrodes system respectively.

After each experimental session, participants completed two questionnaires. The first, the NASA Task Load Index (NASA-TLX) [9], measured their perceived difficulty of the driving task. The second questionnaire assessed their sense of presence and embodiment in the virtual environment [10].

Experimental design

A realistic virtual reality driving experience was created to investigate how different sensory cues affect a driver's ability to spot targets in their environment. In this regard, two conditions were tested: one with high visual distractions and one with low distractions. Before starting, participants got comfortable with the VR setup, which included a steering wheel and pedals. They then completed two initial driving sessions to calibrate the brain activity (EEG) measurements that were performed. In the "Easy" condition, they drove on a clear, sunny day. While, in the "Hard" condition, they drove in foggy, rainy weather with thunder, making it harder to see. In parallel, participants performed a multisensory task where they had to collect transparent spheres that randomly appeared on either side of the track while driving. The goal was to collect as many targets as possible, as quickly as possible. To make the "Hard" condition even more challenging, the number of targets was increased. These targets appeared randomly from the ground or the sky, and their position (left or right) was unpredictable to keep the driver’s alert. Each participant completed four 3-minute driving sessions in both the "Easy" and "Hard" conditions, with different combinations of sensory cues:

- Visual only (V): Participants relied solely on their vision to spot the targets.

- Visual and Auditory (VA): A "beep" sounded when a target appeared, indicating its location. Participants also heard car engine sounds and, in the "hard" condition, rain and thunder.
- Visual and Vibrotactile (VV): A vibrating belt worn by the participant provided tactile cues about the target's location, vibrating on the left or right side accordingly.
- Visual, Auditory, and Vibrotactile (VAV): This combined all three sensory cues.

It is important to highlight that, given the exploratory nature of the presented study, the neurophysiological embodiment assessment was performed by only considering the experimental conditions characterized by the minimum and the maximum level of sensorial stimuli (i.e., the V and the VAV condition respectively). To further enhance realism, the steering wheel vibrated in sync with the car engine and thunder sounds. By presenting auditory and vibrotactile feedback simultaneously with the visual targets, we aimed to simulate how the senses work together in real life. After each session, participants took a break from the VR headset to prevent any discomfort and then answered questionnaires about their perceived workload and how immersed they felt in the virtual environment. The order of the "Easy" and "Hard" conditions, as well as the different sensory cue combinations, was varied across participants to ensure balanced results

Neurophysiological signal recording and processing

EEG recordings were conducted using 38 channels (Fp1, Fpz, Fp2, F3, F4, F7, Fz, F8, AF3, AF4, AF7, AF8, FC3, FC4, FCz, C3, Cz, C4, T3, T4, CPz, C5, C6, CP3, CP4, P3, Pz, P4, P7, P8, PO7, PO8, PO3, PO4, O1, Oz, O2, POz) at a sampling rate of 256 Hz, with the Galileo BEPlus amplifier (EBNeuro Spa, Italy). Vertical and horizontal electrooculogram (EOG) signals were recorded simultaneously using two bipolar channels around the right eye, also at 256 Hz, to capture eye blinks and saccades during task execution. To eliminate power line noise, a 50-Hz notch filter was applied to all recordings, followed by band-pass filtering between 2 and 40 Hz. The Independent Component Analysis (ICA) was used to remove eye blink and muscle artifacts from the EEG. For two participants whose blinks were not fully removed by ICA, the o-CLEAN method was also applied for ocular artifact correction [11]. Further artifact sources were addressed using specific EEGLAB toolbox algorithms [12]. The ICA-processed signal was segmented into 1-second epochs, and any epochs with signal amplitudes exceeding ±80 μV were labeled as artifacts. Global Field Power (GFP) was computed from artifact-free epochs as an indicator of EEG activity, representing synchronization in specific cortical regions within certain frequency bands [13]. Frequency bands for EEG analysis were defined according to each participant's Individual Alpha Frequency (IAF) [14], [15], calculated by recording 1 minute of eyes-closed data before the experiment. The frequency bands were set as follows:

- Theta = [IAF − 8 ÷ IAF − 4] Hz;
- Alpha = [IAF − 2 ÷ IAF + 2] Hz;
- Beta = [IAF + 2 ÷ IAF + 20] Hz;

For each epoch, GFP was calculated over EEG channels using a 1-second Hanning window to minimize ripples. Once preprocessing was complete, EEG features relevant to embodiment evaluation were derived based on previous research findings [1], [2], [16], [17]:

$$EMBO_1 = \frac{Theta_{frontal}}{Alpha_{parietal}} = \frac{\frac{1}{n}\sum_{i=1}^{n} x_{i,theta}^2(t)}{\frac{1}{m}\sum_{i=1}^{m} x_{i,alpha}^2(t)},$$

$$EMBO_2 = \frac{Theta_{frontal}}{Alpha_{parietal} + Beta_{frontal}} = \frac{\frac{1}{n}\sum_{i=1}^{n} x_{i,theta}^2(t)}{\frac{1}{m}\sum_{i=1}^{m} x_{i,alpha}^2(t) + \frac{1}{n}\sum_{i=1}^{n} x_{i,beta}^2(t)},$$

Where *n* and *m* corresponded to the number of frontal and parietal EEG channels respectively; while $x_{i,band}^2$ corresponded to the the *i-th* EEG channel filtered within the selected EEG frequency band.

Besides the EEG-based features, the Electrodermal Activity (EDA) and the Electrocardiographic (ECG) signal were collected. The first one was measured using sensors on the fingers. This data was analyzed to extract a measure called Skin Conductance Level (SCL) [18], which reflects changes in the body's overall arousal or excitement level. The ECG signal was processed to identify individual heartbeats and calculate the time between each beat. This information was used to determine heart rate and heart rate variability (HRV), which provides insights into the balance between the sympathetic and parasympathetic nervous systems.

Subjective measurements

To gather subjective feedback on the perceived difficulty and sense of embodiment during the VR driving task, participants completed two questionnaires after each session. The first was the NASA Task Load Index (NASA-TLX), which measures perceived workload across six dimensions, such as mental demand, physical demand, and frustration level. Participants rated each dimension on a scale of 0 to 100, and these scores were combined to create an overall workload index. The second questionnaire focused on embodiment and consisted of three questions with answers rated on a scale of 1 to 7. These responses were averaged to produce a final embodiment score.

3 Results

The analysis of the NASA-TLX questionnaire revealed that participants perceived as easier the tasks in which the sensorial stimuli increased ($F = 14.071$; $p < 0.001$; $\eta^2 = 0.455$). Similarly, the statistical analysis performed on the embodiment questionnaire showed a main effect of the embodiment variation across the experimental conditions ($F = 11.895$; $p < 0.001$; $\eta^2 = 0.398$). In summary, these findings suggest that a richer sensory experience in VR leads to a stronger sense of embodiment and can even make challenging tasks feel less difficult.

Concerning the neurophysiological measurements, the statistical analysis revealed that the two EEG-based parameters were significantly higher when both the sensorial

stimulation and the task difficulty increased ($EMBO_1$: $F = 9.712$, $p < 0.001$, $\eta^2 = 0.372$; $EMBO_2$: $F = 12.091$, $p < 0.001$, $\eta^2 = 0.207$) (Figure 1).

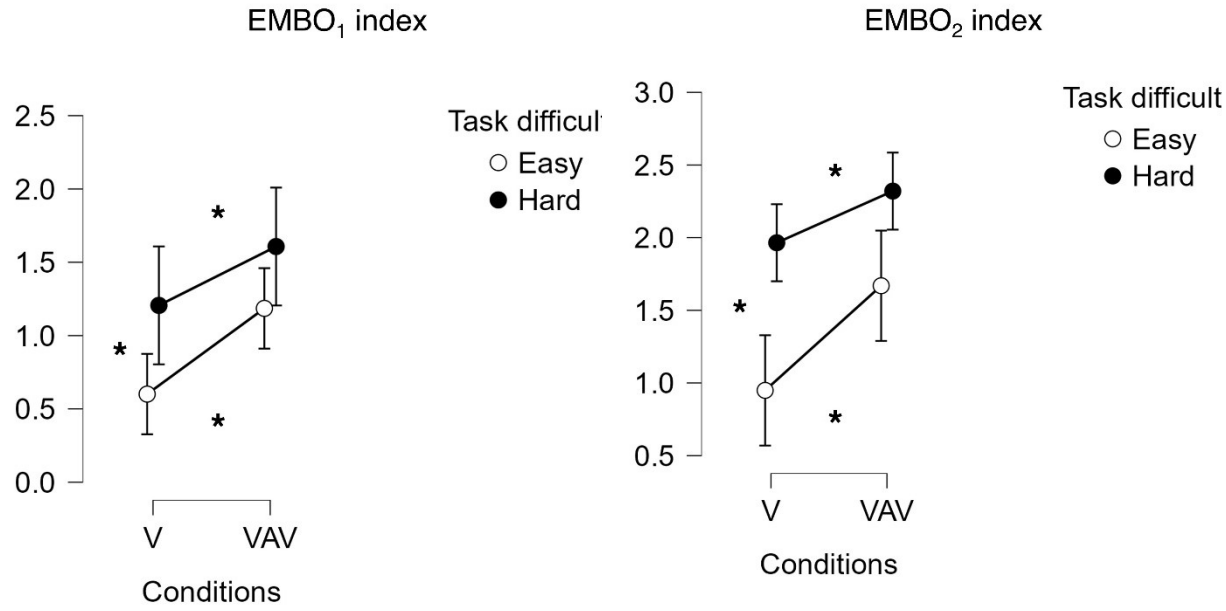

Fig. 1. The statistical analysis performed on the EEG-based parameters demonstrated their sensitivity to both the sensorial stimuli and task difficulty.

Similarly, the SCL parameter resulted to be significantly higher during both the richer conditions in terms of sensorial stimuli and the hardest ones ($F = 6.221$; $p = 0.009$; $\eta^2 = 0.251$).
(Figure 2).

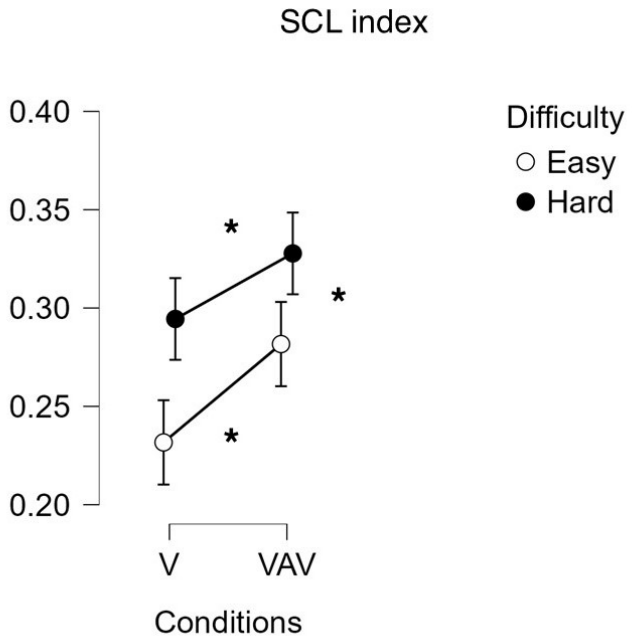

Fig. 2. The statistical analysis confirmed that also the SCL parameter was statistically sensitive to both the embodiment modulations and the task difficulty variations.

4 Discussion and Conclusion

This study explored how brain and body signals, like those measured by EEG, ECG, and EDA, can be used to objectively measure embodiment in virtual reality (VR). The goal was to find reliable physiological indicators of how immersed and engaged users feel in VR experiences. The presented analysis was firstly focused on existing physiological markers of embodiment. In this regard, it was demonstrated that such markers were sensitive to changes in embodiment but, more importantly, they were also influenced by other factors, such as the mental effort required for the VR task. This highlighted a key limitation of current methods: they can be affected by mental processes unrelated to embodiment.

In fact, the statistical analysis performed on all the neurophysiological signal identified from the scientific review (i.e., $EMBO_1$, $EMBO_2$ and SCL) revealed how such parameters were associated with the embodiment modulations. At the same time, the results demonstrated also their dependence from the task difficulty. More specifically, the $EMBO_1$, $EMBO_2$ and SCL indices resulted to be statistically higher during the conditions characterized by the higher sensorial stimuli. In parallel, the repeated measure analysis showed also a significant statistical effect of the task difficulty (Easy vs. Hard), confirming their relationship with other mental processes than the sense of presence. Such results were also supported by the outcomes emerged by the analysis performed on the subjective measurements.

Essentially, this study demonstrates the potential of using physiological data to objectively measure embodiment in VR and, at the same time, underline the principal limitations of the previously validated methods for doing so. This has important

implications for designing and optimizing VR experiences, particularly in applications where a strong sense of embodiment is crucial, such as rehabilitation and training. As a future step, a multimodal approach was identified for combining all the presented neurophysiological measurements in a unique parameter, in order to highlight their "common mode" (i.e., the relationship with the embodiment modulations, which was demonstrated along this work) and minimize their singular associations with other mental processes beside the sense of presence.

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Innovative systems for OSH training: VR Tour case study for LOTO procedure

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Abstract
Occupational safety and health (OSH) training is fundamental to reduce risks and ensure workers' well-being. In digital transformation context, virtual reality (VR) represents a tool able of simulating hazardous scenarios in which learning-by-doing, through an experiential learning model, is possible without being exposed to risk situations. The literature shows that a systematic approach to the design of OSH training interventions using VR is still lacking. This work presents the first investigation conducted as part of the Fereo project - Organizational Training and Resilience Engineering with New Enabling Technologies (Bric Inail 2022- ID63), namely the study and the evaluation protocols. In fact, one of the project objectives is to develop, implement and evaluate the effectiveness of a VR Tour on the LOTO (Lockout Tagout) procedure for the maintenance of machines and plants. The training modules have been implemented following the Skill-Rule-Knowledge framework to determine the appropriate display of information for workers to understand and operate systems while considering factors such as attention, response time, memory, and hand-eye coordination. The VR Tour was developed in three scenarios: "Trial & Error", "LOTO & Variability", "Supervisor Training". An evaluation protocol, including control groups and questionnaires, assesses the experience, effectiveness, and usability of the solution, focusing on Cybersickness, Presence and Task-Load. Future steps will involve extending the scenarios to include the role of supervisors with the opportunity to verify that operators are performing activities correctly and customizing the scenario. This experimentation in VR technology is expected to provide a broader perspective and enable organizations to improve the training and the management of workers' health and safety. The purpose of this study is to outline clear suggestions for the VR solutions design and implementation according to the quality, effectiveness and both technical and methodological specificity required by OSH training.

1 Introduction and background

The introduction of digital technologies has generated new opportunities and challenges for occupational safety and health (OSH). Particularly, emerging risks and unforeseen contingencies are increasingly evident, stemming from the complex interplay between human agents, machines, technological systems, and environmental factors [1], [2]. To mitigate the potential for injuries and accidents, organizations must strategically invest in education and training initiatives [1]. However, traditional training methodologies have proven inadequate for the demands of a digitally transforming work environment [3], [4]. The current literature emphasizes the necessity for innovation in both training content and delivery tools to align with the rapid technological advancements and safeguard employees across all organizational levels, from senior management to frontline staff [5], [6], [7].

Theoretical and empirical research underscores that experiential learning, particularly through direct engagement with realistic scenarios, fosters a deeper comprehension of critical events, enhances the mastery of practical skills, and promotes the development of complex problem-solving and other essential soft skills [2], [6]. Consequently, in the context of increasingly complex tasks and emergent risks, immersive training programs, notably those employing Virtual Reality (VR), show significant promise. VR has been validated as a robust training modality across diverse fields [8], [9] offering the unique benefits of environmental flexibility, scenario reproducibility, and safe exposure to risk-laden situations, which collectively render it highly effective for OSH training [10]. VR-based training enables workers to engage in learning-by-doing experiences within an immersive and risk-free virtual environment. This approach facilitates simultaneous training for multiple individuals and allows for customization based on the specific characteristics, prior experiences, needs, and roles of the workers within the organization.

Despite its potential, the literature indicates a gap in systematic approaches for designing VR-enhanced OSH training interventions [11]. Addressing this gap, within the Fereo project (Organizational Training and Resilience Engineering with New Enabling Technologies, Bric Inail 2022- ID63) an innovative solution has been designed. The latter refers to the development of a VR training solution on the Lockout Tagout (LOTO) procedure for the maintenance of machines and plants, that simulates various scenarios, mirroring real-world situations operators may encounter, thus not only innovating the training tools but also the content and overall approach to OSH management. The training framework leverages the Skill-Rule-Knowledge model [12], [13] and incorporates Safety II principles to advance the handling of OSH issues. Furthermore, protocols have been established to assess the efficacy and usability of the VR training solution. This research presents the study's preliminary findings, including the study protocol and the evaluation protocol designed to assess different aspects of their VR experience, i.e., cybersickness, mental workload, presence and usability. These preliminary results are the starting point for testing the developed solution in an initial operational setting and, later, at large industrial scale.

2 The study protocol

2.1 The reference procedure (LOTO)

The application context and scenarios focus on maintenance procedures, specifically the LOTO procedure. The selection of LOTO procedures as the foundation for developing a VR training solution is based on substantial evidence from the European Agency for Safety and Health at Work (EU-OSHA) [14], which identifies maintenance activities as a critical area prone to occupational accidents. Maintenance tasks inherently involve complex risk factors and potential exposure to dangerous energy sources. Consequently, LOTO procedures are of significant relevance, serving as a well-documented method to ensure worker safety by effectively managing and mitigating hazards during equipment servicing and maintenance. Beside manufacturing, some other production contexts are strongly impacted by improper LOTO application, e.g. construction [15], and oil and gas industry [16]. Research indicates that many accidents are linked to inadequate, unauthorized, or improper use of LOTO practices, highlighting a persistent gap between established safety standards and their practical implementation in the workplace [17], [18] .

The LOTO procedure is a multi-step safety protocol designed to isolate and secure hazardous energy sources before equipment maintenance begins [19]. It typically consists of six phases: (1) preparation for machine shutdown, (2) machine shutdown, (3) isolation of energy sources, (4) application of locking devices and warning tags, (5) dissipation of residual energy, and (6) verification of isolation. This structured approach ensures that machinery cannot be reactivated inadvertently, providing a critical layer of protection for workers. Despite the procedural rigor, training remains a pivotal component. The effectiveness of LOTO protocols depends not just on the operator's understanding and execution of these steps but also on their situational awareness and ability to recognize and mitigate potential hazards. Many incidents have been linked to unsafe operating conditions and a lack of risk awareness [17]. Serious accidents continue to occur due to lapses in LOTO applications, highlighting perceptual, comprehension, and projection challenges faced by operators during different phases of LOTO processes. During maintenance activities operators, driven by the pressure of time-sensitive tasks and productivity demands, may undervalue or bypass safety measures. This negligence is exacerbated by communication barriers, resource constraints, and conflicting priorities among stakeholders. As maintenance workers grapple with these operational complexities, the need for robust and immersive training becomes even more essential.

The VR-training solution selected the maintenance of an industrial compressor. The selected procedure involves managing three distinct energy sources (i.e., electrical, pneumatic, and thermal) and navigating hazards such as electric shocks, rotating machinery, and high-pressure air. The process requires various locking devices and tags to ensure comprehensive energy isolation. Figure 1 illustrates an image of the virtual environment, which aims to replicate this maintenance context realistically.

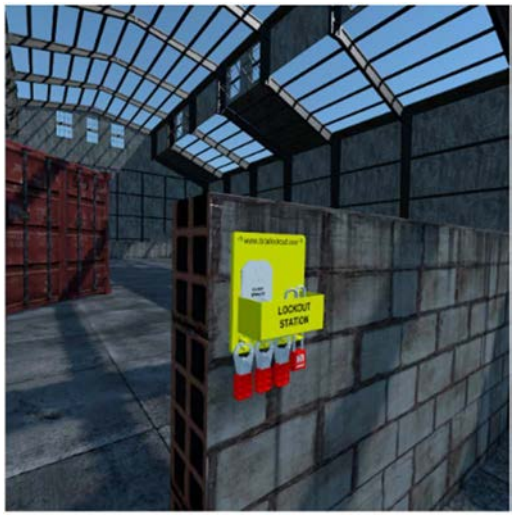

Fig. 1- Padlocks for the LOTO procedure completion in the virtual environment.

The procedure requires the worker to secure themselves and the compressor before conducting the maintenance activity. After simulating it, the same worker has to return the system to its initial state, i.e. the operational state. These steps require the worker to equip themselves with the personal protective equipment (PPE) needed to carry out the maintenance and to inform the operators present in the plant of the maintenance activity they intend to carry out. At this point, following the LOTO procedure, they shut down the compressor and switch off the power sources via the electrical panel, applying padlocks to provide evidence. Only after these steps have been completed the worker can perform maintenance on the compressor. As outlined in Section 2.1, what has been illustrated is the basic procedure. This procedure is then tailored to three scenarios that have different training objectives and potential users.

2.2 The reference framework (SRK) and VR scenarios

The Skill-Rule-Knowledge (SRK) framework is chosen to enhance the VR-based training from a Safety-II perspective. Namely, safety management based on Safety-II shifts focus from merely preventing failures, as seen in Safety-I, to enhancing an organization's ability to succeed across a range of conditions, thus promoting high levels of safety performance [20]. At the heart of Safety-II is systems thinking [21], which encourages understanding the complexities and interdependencies within systems. Rather than attributing safety to individual components, this approach considers safety as emerging from interactions within the system, promoting an awareness of how changes in one part of the system can impact the system as a whole. Resilience engineering is another foundational element in Safety-II [22]. It emphasizes a system's ability to function effectively during both anticipated and unexpected conditions. Resilience engineering aims to bolster the system's ability to adapt, learn, and recover from disruptions, maintaining safety through its capacity to absorb and respond to various challenges. Proactivity further distinguishes Safety-II from Safety-I [23]. Rather than reacting to incidents after they occur, Safety-II calls for a forward-looking stance. This proactive approach involves anticipating potential issues and preparing for them in advance,

thereby reducing the likelihood of accidents or failures. Continuous learning and adaptability are also central to Safety-II, which advocates for ongoing learning from both successful and unsuccessful outcomes. This principle encourages organizations to refine their safety practices based on insights gained from everyday operations as well as from broader industry developments [24]. Finally, Safety-II recognizes human performance variability as an asset [25], in contrast to Safety-I's tendency to view human variability as a source of error. Safety-II appreciates human adaptability and variability in performance as critical resources that enhance system resilience and promote safety under changing conditions. In sum, Safety-II fosters an approach to safety management that values adaptability, proactive planning, continuous learning, and human resilience, thereby creating systems that are better prepared to maintain safety across a wide range of operating conditions.

These principles are incorporated into the design of the VR solution by defining different scenarios. Specifically, scenario 1 and scenario 2 reflect different situations that the trainee might encounter in practice. The first (scenario 1) is a situation where everything goes as it should. This means that the application of the knowledge gained in training is sufficient to pass the test and complete the maintenance task without incident or the possibility of an incident. Scenario 2, on the other hand, places the worker in unexpected situations, and the mere application of known procedures is not sufficient to successfully complete the test. In this sense, scenarios 1 and 2 reflect different levels of learning and behavior that can be linked back to the SRK framework. Such a framework, developed by Jens Rasmussen, is a cognitive model used to categorize human behavior and decision-making into three distinct levels [13]. As depicted in Figure 2, and detailed after on, each level reflects different types of situations the worker is faced with, and therefore the cognitive level involved in coping with the scenario.

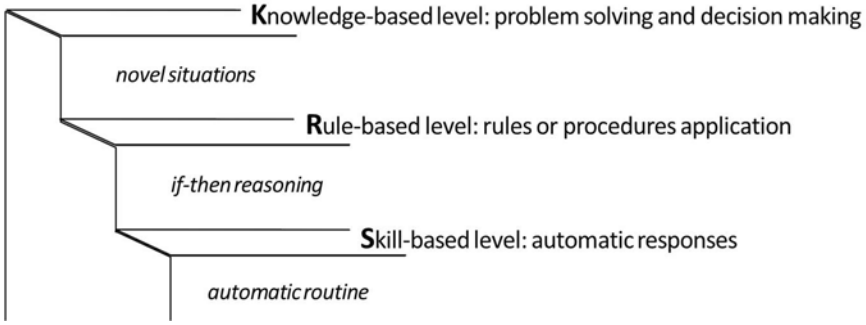

Fig 2 – Categorization of human behavior into three cognitive levels according to the SRK framework.

Specifically, a third scenario, in which a new user of the VR solution serves as the differentiating factor, is now being developed after two others have been established.

- Scenario 1 - Trail & Error (skill-and rule-based training): the goal is to ensure that workers internalize the LOTO steps and can execute them automatically. If

participants make errors, such as missing a step in the procedure, they receive immediate feedback and must restart the process. As such, this scenario reflects a behavior governed by learned rules and procedures. Individuals apply specific "if-then" rules to manage routine but non-automatic situations. This is often used when safety protocols need to be followed, such as adhering to steps in a LOTO procedure.

- Scenario 2 - LOTO & Variability (knowledge-based training): this scenario builds on the previous training but introduces elements of unpredictability. Participants must use procedural knowledge and adapt to unexpected variables, such as communication challenges or emergent hazards. The VR environment requires operators to combine procedural adherence with situational assessment and decision-making. They must interact with avatars and use observation and initiative to ensure safety. At this level, the highest level of cognitive processing is used when individuals encounter novel or unpredictable situations that cannot be addressed through existing skills or rules. As such, it involves problem-solving, analysis, and the application of theoretical knowledge. Workers must assess the situation, draw on their broader understanding, and develop a new solution.
- Scenario 3 - the "Supervisor Training" will incorporate the role of supervisors, who will serve as experts overseeing the maintenance activities. Supervisors will verify procedural compliance and offer guidance within the VR simulation, ensuring that operators perform tasks correctly. This scenario will also allow for the review and potential updating of existing safety procedures, providing a comprehensive approach to continuous safety improvement.

3 The evaluation protocol

The evaluation protocol sets out the guidelines for carrying out the experiment and for the initial phases of results evaluation. For the VR training experiment, the Meta Quest Pro headset, equipped with an integrated eye tracker, has been selected, because of its advanced features that are critical for an immersive and high-quality VR experience. These features include a 4K high-resolution display (2048 x 2048 pixels per eye), a 120 Hz refresh rate, 3D spatial audio, and six degrees of freedom (6DoF) tracking. Together with its ergonomic design for lasting comfort and a robust processing system, the device ensures minimal impact on the learning process, allowing the focus to remain on training rather than on potential technological limitations. Specifically, the evaluation protocol consists of the following four steps.

- Phase 1 - recruitment and training: participants are first recruited and introduced to VR technology, gaining familiarity with how to interact within the virtual environment.

- Phase 2 - testing phase: participants test specific features of the VR system, ensuring they are comfortable and prepared for the full experiment.

- Phase 3 - experiment execution: participants engage in the core VR training experience, during which various data points, such as eye gaze, movements, and actions, are collected to analyze user interactions and learning outcomes.

- Phase 4 - questionnaire administration: participants complete a subjective questionnaire designed to assess different aspects of their VR experience.

The subjective questionnaire aims to assess on a 7-level Likert scale cybersickness, mental workload, presence, and usability of the VR training solution. Before assessing such aspects, participants complete a personal data section which includes information on gender, age, educational background, nationality, industry sector, computer literacy, prior experience with VR technology - both in general and as a training tool, level of confidence in using VR, and the specific contexts in which they have used VR previously. This information is crucial for contextualizing the results and understanding the diverse participant profiles.
Cybersickness is tested through the Cybersickness in Virtual Reality Questionnaire (CSQ-VR) [26], which measures symptoms related to cybersickness, a form of discomfort resulting from sensory conflicts in VR. Participants should rate the whole range of cybersickness symptoms, including nausea, disorientation, and oculomotor symptoms.
Mental workload is analyzed through the NASA-Task Load Index (NASA-TLX) [27], used to evaluate the mental effort required during the VR task, which is crucial as excessive mental workload can impair learning. This section consists of six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. Participants rate each dimension, providing a comprehensive measure of mental workload.
Presence, a critical factor in immersive training effectiveness, is assessed though the Presence Questionnaire (PQ) [28] to evaluate the extent to which participants perceived the movement and interaction as natural, and felt involved in the experience; furthermore, how long it took them to get used to the experience by focusing on the task at hand rather than the mechanisms used to accomplish it, and whether they noticed any latency between their own actions and the virtual movements.
Finally, usability is detected by the System Usability Scale (SUS) [29] to assess the ease of use of the VR system, whether the training experience is complex, self-paced, or requires technical support, and to evaluate the integration of various features.
This questionnaire should be administered immediately after the VR experience to maximize the accuracy and relevance of participants' response.

4 Conclusion and future work

The VR training solution proposed aims to provide a realistic, engaging, and adaptive training environment that enhances workers' abilities across all three cognitive levels, i.e., skill-, rule-,–knowledge-based, preparing the user to handle both routine and unforeseen safety challenges effectively. As such, the solution aims to improve workers’

ability to act appropriately under varying conditions by aligning training objectives with the different cognitive demands of skill, rule, and knowledge levels. The designed experiment will first be tested in a laboratory environment to verify its usability, and all aspects defined in step 4 of the evaluation protocol. Once the technological solution and its content have been approved and optimized, it will be tested in the operational environment to evaluate its effectiveness also from a training perspective. In this regard, an additional plan will be defined to compare the results of traditional and innovative training from the perspective of the tool used. Specifically, the following question will be answered: what aspect of training is improved (or worsened) by using an innovative, interactive technology solution?

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Innovative methods of specialist training to improve and monitor the correct application of Biotech legislation

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Abstract
There has been an exponential growth in the application of biotechnological techniques. **The Inail Project:** "*Prevention and protection of health and the environment in laboratories using advanced and innovative biotechnological methods*", aimed at promoting staff training and awareness to ensure compliance with the directive 2009/41/EC by users of biotechnological techniques, with innovative methodologies characterized by close synergy between students, safety managers and researchers as well as the use of neuromanagement analysis. This project has been awarded a certificate of merit as a Good Practice 2024 downloadabled from the ISSA database. **Goals of the Project**: connecting multiple skills; verify and develop innovative tools and devices in order to reduce worker exposure; train and raise awareness of the worker keeping in mind that the worker's behavior is the crucial point of the safety process. **Results:** There has been a proportional increase in notification requests for contained use of Genetically Modified Microorganisms (GMM) presented to the Ministry of Health in the last two years, underlining how the widespread training/information activity through motivational methods has been successful. Furthermore, to enforce the requirements laid down with art. 16 of Dir. 2009/41/EC – Vigilance: a group of experts was trained for inspections of the plants and activities carried out by the notifiers who use GMMs, by a **Inail project financed by the Ministry of Health**. Through the inspections it was possible to verify how the containment measures required by the law were actually implemented and at the same time monitor the actual training effectiveness directly in the field. **Conclusions.** Success of innovative training; increase in the number of notifications; increase in demand for training; the inspection activities represented a positive moment of direct dialogue with experts in order to improve safety. New perspectives: it is important to continue with innovative training activities and, at the same, time promote new inspection activities at a national level.
Keywords: biotechnology regulation, safety culture, biosafety, risk perception, innovative and motivational methodology

1 Introduction

The biotechnology sector in Italy is constantly growing, with 13,000 employees and 571 companies [1]. The applications of molecular biology techniques in the biomedical field currently represent the sector where biotechnologies have

made the most significant contribution both in terms of therapeutic products and research and development. Biotechnology is one of the advanced research sectors that has seen significant efforts to develop guidelines and regulations aimed at protecting human, animal and environmental health. This effort is also driven by the need to harmonize legislative structures and administrative aspects across the various EU Member States. The promulgation of Community rules that regulate the use of genetically modified organisms and microorganisms, verification and control plans, supervision of waste management and organization of emergency measures, have helped to reduce the probability of negative effects occurring. Legislative Decree No. 206 of 2001 (Directive 2009/41/EC) establishes that anyone intending to use a GMM must receive prior authorization from the Italian Competent Authority, the Ministry of Health. With the implementation of this provision, the Competent Authority, through a Technical Health Committee which include Inail as a member, evaluates and authorizes the plants where the activities (research, development and production) are carried out and the type of genetic manipulation, as well as the foreseeable, immediate or future risks that the GMM or the combination of GMMs used may present for human and animal health and for the ecosystem in general. To date, there are about 730 public and private plants, authorized by the Ministry of Health according to Legislative Decree No. 206 of 2001 for the application of the most advanced biotechnology methods [2,3]. Many of these authorized plants are located at universities and hospitals, which proved to be the real critical point in the application of the Directive. Risk assessment arising from the use of GMMs is sometimes neglected, as Universities have to manage prevention within a very complex and flexible organizational reality. This is due to the autonomy and freedom of research, teaching and the high staff turnover and availability of ad hoc funding. There is a real difficulty in implementing an integrated safety management system which should be desired by top management and shared - in spirit and objectives - by all university components. Therefore, a project was created in order to increase the culture and skills aimed at prevention and protection of health and the environment, with particular attention to activities and structures intended for teaching, research and development that use GMM or GMOs in a contained environment.

2 Materials and Methods

The main objective of the Inail Project “Prevention and protection of health and the environment in laboratories using advanced and innovative biotechnological methods” (started in 2020 and concluded in 2023), was to enhance the culture and skills for the prevention and protection of health and the environment in laboratories using innovative and advanced biotechnologies. The participants in the project were identified among the plants employers and the researchers who use

biotechnological methods in the university/hospital departments, with the task of starting a constructive dialogue between the users, Inail researchers and the Ministry of Health to verify experiences, discuss legislative aspects and explore the specific needs of users. All the activities have been aimed at promoting safety, as the implementation of a complex systemic process which presupposes the crossing of scientific and technical skills, very diversified from a disciplinary point of view, but with the common and undeniable objective of uniting all efforts aimed at rationalizing and improving working environments. The goals of the project were:

- Increase the **culture and skills for prevention** and the protection of health and the environment in case of application of biotechnological techniques.
- **Create a network** between safety managers of universities, hospitals and institutions for an effective and systematic comparison on basic knowledge and new work evidence which can emerge in compliance with Legislative Decree 206/2001 A digital platform, www.biotechsafety.org [5], created by researchers from the Santa Lucia Foundation, was made available to the network.
- Develop useful **interactive products** for the network, where it is possible to find up-to-date information on training workshops as well as on regulations and biosafety for biotechnology users. 1) A software system called "SafeLab" was designed which, once specific checklists selected for gene therapy constructs and related containment levels were archived in specialized laboratories, proved to be very useful for training activities. https://18.102.127.48/home. 2) An interactive product SWAY has been developed, which provides basic training and regulatory tools useful to those approaching the world of biotechnology for the first time. The topic of biotechnology and the various problems connected to it, which are highly topical, is addressed in this context in its basic knowledge, and can then be the subject of further updates and additions by Inail researchers who are experts in the subject. Link: https://sway.office.com/M5OT2HD8dv4wlwNO?ref=Link [6]
- **Transmit educational messages to worker in innovative ways.** In previous projects we used emotions, giving importance to the *emotional dimension*, its resonance and its value may represent a *motivational engine* to trigger change processes and unaware dimension, to achieve the main goal. The "gentle push" was an useful model to be applied to the *conscious choices of workers*, whose path may be oriented on an educational model, stimulate the adoption of *good practices* and *virtuous behavior* even in everyday life: the methodology provides in summary the use of simple, small adjustments, which can however bring enormous impacts, influencing people's choices [4]. In this project we **applied also neuroscientific techniques to measure emotions**, giving importance of the unconscious dimension. So, a

neurocognitive analysis was carried out to test the potential effect of a specific biosafety training. We know that safety depends on a set of factors such as: emotions, the propensity to obey the rules, the ability to cope with cognitive overload and other factors which today, thanks to neuroscience, can be investigated in a much more precise and objective way than has ever happened in the past.

- **Train and motivate** researchers to carry out a correct risk assessment in the case of use of GMMs and to notify the competent authority of plants and uses with biotechnological experimental activities. Various training events were held, aimed at informing and raising awareness among numerous experts and university and high school students on the topic of biotechnology safety. The training events took place in Northern, Central and Southern Italy, recording the participation of numerous experts from all over Italy. Furthermore, information initiatives were carried out, aimed at students and operators in the sector: for example, webinars and trade fairs which had the aim of illustrating the application of the main biotechnological methodologies and aspects related to safety.
- **Apply long term strategies skills** to allow workers to be proactive rather than reactive to future changes to build an agile workforce and a culture of "lifelong learning". we know that safety depends on a set of factors such as: emotions, the propensity to obey the rules, the ability to cope with cognitive overload and other factors which today, thanks to neuroscience, can be investigated in a much more precise and objective way than has ever happened in the past. The experience of the Inail research project on Neuroscience and Safety in collaboration with Fondazione Santa Lucia, has highlighted how the emotional influence linked to safety decisions is fundamental in leading a person to adopt the right attention to safe behaviours. Decisions, in fact, are not just the result of logical calculations, but the outcome of a complex process in which cognition and emotion play an important role. Emotions are dominant in all organizational processes, including those underlying workplace safety. Through this convergence between neuroscience and security we have attempted to offer tools to act on the dynamic, often unconscious, forces that shape decision-making processes. Emotions play a fundamental role in the risk perception. In fact, decision making is a complex mental function influenced by multiple aspects of cognitive, behavioral and emotional processes. Several tasks have been developed that assess different types of decision making. A "healthy" decision-making process is fundamental for managing our daily lives: we often find ourselves having to make countless decisions, even quickly and unexpectedly, most of the time in contexts in which there are no elements that can predict the outcome of the decision and therefore without the possibility of evaluating the possible risks and benefits. It is precisely personal experiences that, subjected to analysis and studies, can provide us with information relating

to the possible results associated with a certain decision, and it is precisely through these studies that it emerges that decisions made on the basis of experience involve emotional and motivational factors [9-10].

- Furthermore, to enforce the requirements laid down with art. 16 of Dir. 2009/41/EC – Vigilance: **a group of experts was trained for inspections** of the plants and activities carried out by the notifiers who use GMMs, by a Inail Project financed by the Ministry of Health. The aim of the Project was to update the inspection staff already trained with a previous project and train new inspectors as well for the evaluation and control of the plants and activities carried out by the notifiers who use GMMs, according to the Italian legislative decree 206/2001.

This project has obtained a certificate of merit as a Good Practice 2024 downloadable from the ISSA database.

3 Results and Discussion

The key word of the Project is the Promotion of Safety understood as the implementation of a complex systematic process which presupposes a crossroads of skills, techniques and sciences, very diversified from a disciplinary point of view, but with the common and undeniable objective of uniting all efforts aimed at rationalizing and improving work environments. We have focused our activities on:

- Hence the importance of the project to connect multiple skills.
- Verify and develop innovative tools and devices in order to reduce worker exposure, in the case of plant deficiencies of obsolete structures.
- Finally, train and sensitize the worker bearing in mind that the worker behavior the is the crucial point of the safety process.
- Then, to enforce the requirements laid down with art. 16 of Dir. 2009/41/EC – Vigilance (Art. 17 of the Lgs. D. 206/2001): we have trained a group of experts for inspections.

In many cases, in fact, it is known that the human factor is the real weak point of security systems. Therefore it was essential to provide an adequate development plan to improve skills through targeted training, educational and learning activities and at the same time implementing adequate actions that increase awareness of the real and potential consequences of one's work activities and behaviors as well as benefits deriving from improved personal performance.

We achieved the following results:

- Several training workshops were held in Northern, Central and Southern Italy (Fig1).
- A network between researchers of universities and research institutes, and regulatory institutions, that provide an exchange of experiences and solutions, gathered through an effective and systematic comparison of theoretical knowledge and practical daily working experience (https://www.biotechsafety.org/)
- Development of interactive products_SWAY that contains and updates all project activities (https://sway.office.com/M5OT2HD8dv4wlwNO?ref=Link)
- Innovative use of neuromanagement techniques to operate more effectively on the attentional, perceptive and decision-making processes of GMM users. The convergence between neuroscience and safety is to try to offer tools to act on the dynamic forces, often unconscious, that shape decision-making processes.
- We have also transmitted educational messages to young workers using methods of proven effectiveness (non-traditional education, peer education) which are based on both rational (training, information) and irrational (emotional, motivational, social drive) components. Risk perception is only partially dependent on rational factors such as logic; instead, it is strongly influenced by emotional and cognitive factors of which we are scarcely aware.
- Through the inspections it was possible to verify how the containment measures required by the law were actually implemented and at the same time monitor the actual training effectiveness directly in the field.

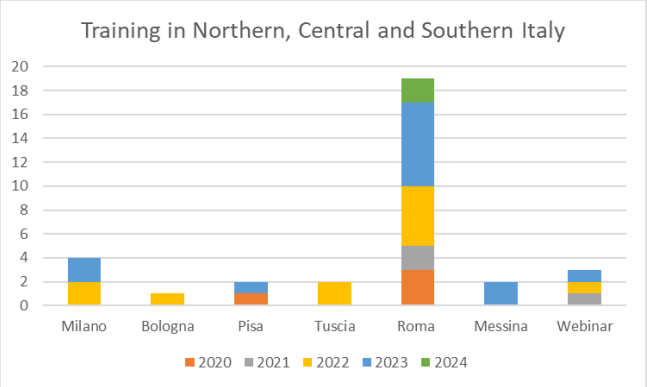

Fig. 1. Training activity was held in northern, central and southern Italy. In this histogram the various training activities carried out over the years have been divided by region. It should be noted that these took place mainly in 2022 and 2023 (during the project activities) and in Rome because it was in Central Italy, easily reachable. In addition to the specific training held in northern and southern Italy, the webinars have reached all Italy.

3.1 Evaluating the results

The innovative methodology used in the project was of great interest and appreciation, as great participation and interest in the training activities highlighted by the satisfaction questionnaires (data not shown). The positive outcomes of the training provided were highlighted both by the satisfaction questionnaires and by the neuromanagement analysis. The neuromanagement analysis, carried out to test the potential effect of specific biosafety training for GMM laboratory users, reached overall positive results:

- the use of neuro-metric instruments and attentional behaviour allowed to investigate emotional and cognitive correlates with the perception of risk behaviour in a biosafety and biotechnological containment laboratory.
- Overall, the neurocognitive analysis carried out to test the potential effect of a specific biosafety training achieved a greater neuro-cognitive activation for the trainees. This is not observed in the conscious knowledge survey (questionnaire) while it is evident in the levels of neuro-physiological activation.

But above all, it is worth underlining the proportional increase in notification requests for contained use of GMMs presented to the Ministry of Health in the last two years (fig.2-5).

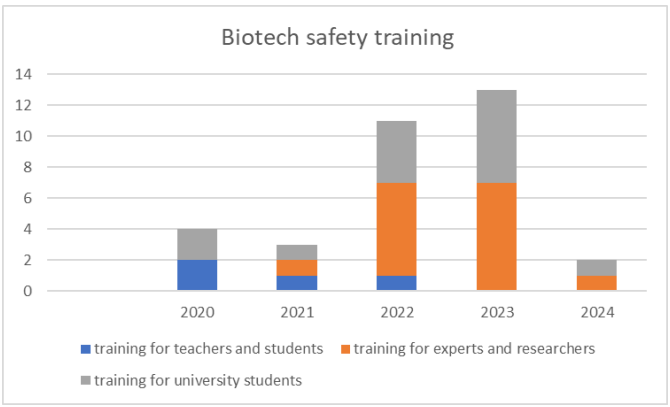

Fig. 2. Biotech security training from 2020 to today, divided by type of courses held.

In fact, the project aimed to reach not only researchers and experts on biotech safety but also young researchers and high school students, to induce awareness already in the early educational phases.

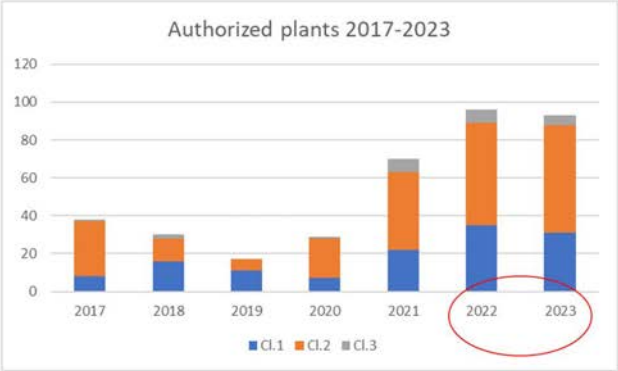

Fig. 3. Authorized plants from 2017 to 2023, divided by type of containment class (Class 1, Class 2, Class 3). The histogram shows the authorizations granted by the Ministry of Health, the competent authority, from 2017 to 2023, for those notified plants in which biotech operations will take place (Source Ministry of Health).

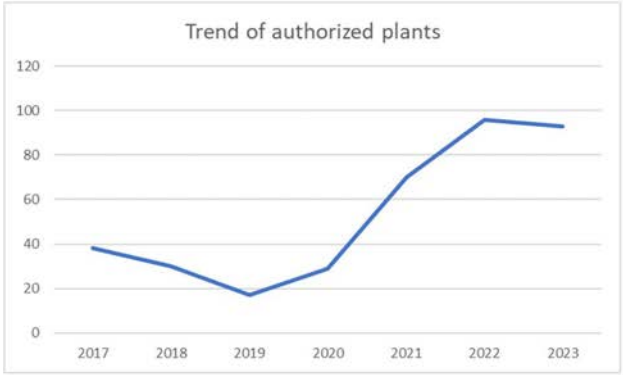

Fig. 4. Trend of authorized plants from 2017 to 2023. (Source Ministry of Health). It is clear that the number of GMM plant authorizations has increased from 2021 to 2023, probably due to the considerable training effort.

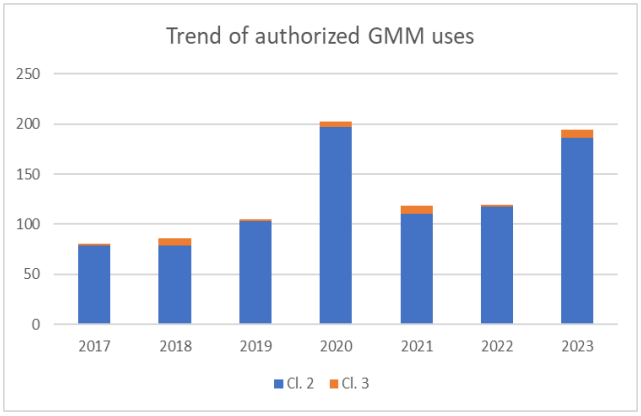

Fig. 5. Trend of authorized GMM uses from 2017 to 2023, divided by type of containment class (Class 1, Class 2, Class 3) (Source Ministry of Health). The evident peak for the year 2020 represents the request for authorization to use GMM during the Sars-CoV2 pandemic. Particularly interesting is the number of authorizations granted in 2023 for the use of class 2 and 3 GMMs, in relation to the training provided in the years 2022 and 2023.

Finally, after having established a group of qualified inspectors, the first inspections have been carried out, to date, for the purpose of continuous improvement of safety.
Following the first inspections carried out, it was interesting to note various aspects of perception of the inspection visit. In some cases the inspectors were welcomed and discussed the introductory aspects only with the Safety Managers,

and the users who were subsequently met directly in the laboratories were not present; while in other cases the inspectors were welcomed by all those responsible for the research activities, who considered that moment very interesting to discuss the specific safety aspects linked to the use of GMMs in contained use.

4 Conclusions

The success of the training activity was achieved by giving great importance to inspiring and motivating in order to achieve the objectives of the project. The model application allows to act on the attitudes of individuals, pushing them to adopt actions oriented towards the best achievable preventive results. We used **Innovative approach**, we studied emotions in risk perception. Decision-making is a complex mental function influenced by multiple aspects of cognition, behavioral and emotional processes. Several tasks have been developed that evaluate different types of decision making. The personal experiences subjected to analyses and studies, can provide us with information relating to the possible results associated with a given decision, and it is precisely through these studies that emerges that decisions made based on experience involve emotional and motivational factors.

Following the awareness-raising activity carried out at the Universities, new courses ad hoc were created on biotechnology safety for Phd students, and the degree and master's courses were updated (at the University of Rome La Sapienza and the University of Messina). But above all, it is worth underlining the proportional increase in notification requests for contained use of GMMs presented to the Ministry of Health in the last two years, underlining how the widespread training/information activity through motivational methods has been successful.

As summarized in Table 1, there has been an increase in the number of notifications and a greater demand for training. The inspection activities have provided a positive moment of direct dialogue with experts in order to improve safety. Moving forward, it is important to continue with innovative training activities and, at the same time expand inspection activities at a national level.

Strengths of the project	Critical issue	Perspectives
Success of innovative training	Sometimes the spirit of the contained use rule is disregarded	Increase the training of new inspectors, we are too few
Increase in the number of notifications	General training on the risk of biological agents and not specific to GMMs is often carried out, in some plants examined.	Encourage inspection activities as they allow continuous improvement of safety at a national level
Increase in training demand	Often companies use consultants and probably the researcher is aware of the risks.	Continue with innovative training activities
Appreciation of inspections for direct discussion with experts for the purpose of improving safety		

Table 1. Brief summary of the project's strengths, critical issues highlighted after the inspections carried out and the new perspectives for new project developments

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The impact and effectiveness of Virtual Reality applied to the safety training of workers in open-cast mining

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Abstract
This paper presents the results of an interactive virtual reality (VR) training course designed to enhance health and safety management procedures in quarrying processes. The course was developed with consideration of best practices, as well as voluntary and mandatory standards applicable to marble mining activities. It integrates experiential learning with a performance monitoring system that traces completion rates, time taken, and scores based on user choices. The primary objective was to evaluate the impact of VR training on various user groups categorized by age, prior safety experience, familiarity with equipment and processes, and VR proficiency. The study involved 40 participants and analysed 15 variables, i.e. occupation, age, health and safety skills, process, equipment and VR skills, physical impact of VR, number of attempts before completion, percentage and time of completion, achieved scores, retention of experience, and user feedback before and after the training. Performance measurement was conducted using two methods: a Microsoft Forms questionnaire consisting of 16 questions completed by participants one week after the training, and Simula Solution, which automatically tracked and measured performance metrics (time, percentage, and score) during each training session. The survey identified which demographic groups are most influenced by VR training.

1 Introduction

Occupational health and safety training is a legal requirement in many countries in various sectors, underlining its status as a regulatory imperative [1]. In Italy, workers are required to attend a health and safety course in accordance with the frequencies and methods prescript by the mandatory legislation applicable throughout the country. Traditionally, safety training methods consist of videos, slides and safety manuals, which tend to induce a passive learning environment [2,3]. Increasingly, information technology facilitates the management of measures for improve Safety at the work. Studies on Artificial Intelligence are infrequent in quarrying. Quarrying can be dangerous, and safety is a major preoccupation in this field. It thus shares a common interest with the mining industry. The objective of teaching is to empower all operatives to achieve their job in a method that is acceptable to the company and the staff. Operators are very important to improve safety and productivity which reduces the cost

of mining. Thus, latest technique available is Virtual Reality Training (VR) [6]. The modern-day concept of VR originated from the development of the stereoscope in the 19th century. Modern VR technology had its initial introduction with the development of the Sensorama device in the 1960s, which was designed to incorporate five short films, engaging multiple senses, including vision, hearing, olfaction, and haptics, creating an immersive experience for the users [7]. Increasingly, strategies to prevent risks focus on technological innovation and often prevention strategies include training and education activities through virtual reality. This technology has an unparalleled emotional impact on users, potentially changing established risk behaviour. Virtual reality simulations have been used for some years for industrial and military training, vehicle driving and advanced 3D design; a more recent development of training simulators are virtual reality applications for occupational safety training. The user, after having learned the fundamentals of their professional activity, is able to experience within interactive simulations the risks of the work activities to be carried out and to undertake, through immersive soft-ware applications, an effective learning by doing process [8]. These training practices allow for the development and enhancement of skills necessary for the industry 4.0 paradigm and lend themselves to be usefully applied to the dynamics of accidents in open-pit quarries. As highlighted by the most recent theories in cognitive economics and cognitive sciences, the perception of risk and stress associated with a work activity involves various individual cognitive dimensions that depend on both emotional responses and rational calculations.
This research project aims to promote safety education and training for workers in the open pit industry through virtual reality (VR) simulations. The other objective of the study is to understand the role played by user characteristics on the outcome of the virtual reality experience also in terms of discomfort and symptoms. As it is also known that there is a specific literature around the use of virtual reality in the work environment but not in quarry sector. The study aims to analyse the retention capacity of the training experience and the learned procedures by the tracking and validation of the learning process. An additional important feature of the project is its capability to reproduce emergency situations through virtual reality, thereby allowing the assessment of response times and procedures enacted by workers for resolution and for the potential activation of external assistance. This project is conducted under the research programs of the National Institute for Occupational Accident Insurance (Inail) and Siena University and is focuses on identifying the evolution of smart safety technologies and AI in Quarry sector. In section 2 the materials and methodologies applied in the course are presented, in section 3 results, discussion and conclusions are reported.

2 Material and methods

Once identified a qualitative and quantitative relationship between the keywords resulting from the network analysis applied to 30 individual injury cases recorded in Tuscany Accident Observatory of the Prevention Department (AOPD) archives we obtained five clusters useful to define the four specific objectives of the project (Table

1).

General VR-Training objectives		Time
1.	Primary upstream cutting course (OS1)	6th month
2.	Tipping benches course (OS2)	12th month
3.	Squaring and Sectioning course (OS3)	18th month
4.	handling and road transport course (OS4)	24th month

Table 1. Scheduled general project objectives on VR training courses. Source: Authors.

The project uses a pioneering VR course delivery system which potentially offers effectiveness and efficiency for the entire training process, from onboarding to tracking. The system relies on a dedicated platform that automates the steps of downloading and installing the helmet application, allowing users to access courses. Each user's session is tracked in real time and the platform generates aggregated session reports per user at the end, detailing all relevant data. Inail and the LabVR UNISI laboratory have applied an experimental method of evaluation of VR experiences whose validation methodology (questionnaires-platform-experiment) is built with a view to standardization.

The content of the VR training course is based on the principles of the Functional Resonance Analysis Method (FRAM), which postulates that the hazard of certain activities or production steps increases with the variability of the system to which they belong. Through FRAM, critical functions that amplify the variability of the system associated with the process were detected and, consequently, the corresponding skills that dampen it and increase resilience in the system were determined [10]. Further key contents were detected from Multiple Factor Analysis (MFA) by mean is explored and visualized MFA dataset where individuals are described by variables structured by groups [11].

For each scene, there is a different virtual environment (e.g., a yard or a quarry face), which may include machinery, tools, and virtual operators (characters that can be subject to simple interactions). Starting from the lowest point, the user must explore the areas and apply the correct procedure in the varied context (e.g. choice of Personal Protective Equipment (PPE), different quarry methods, risks, unforeseen events). The user will need to prepare, initiate, and supervise the various operations (functions) of the procedure. Within the virtual environment (e.g., at blocks, tools, characters) it will be able to activate interactive hotspots and to make decisions (Figure 2).

To complete the course and achieve a good final assessment score, the user must demonstrate an understanding of their implications. The equipment used in the experiment are Meta Quest 2 that are all-in-one virtual and augmented reality lab helmets manageable in networking for teaching in minimal multi-user (dyad) sessions equipped with a pair of Oculus Touch controllers. This equipment is provided by the Laboratory of virtual reality of the University of Siena (LabVR UNISI). The laboratory is also equipped with advanced technologies such as the Cave Automatic Virtual Environment (CAVE), which is used to test the simulations created for the Oculus Quest

2. Furthermore, the use of specialized software for the creation of digital content and personalized experiences on Unity platform provides users with the opportunity to explore complex and interactive scenarios (Figure 2).

Fig. 2. Course OS1. Detail of the simulation of the drilling phase that precedes the detachment at the mountain. The user interacts with the pointer, verifies the compliance of the operational phase by correcting non-conformities (a). A stranger worker intervenes in the drilling area resulting in a hazardous situation that the user must resolve. Source: Author's processing by Software Simulation Results.

Title 1	Modality	Frequency	Percentage
Activity	quarryman & others	8	0,20
	researcher	10	0,25
	student	22	0,55
Age	20-35	25	0,63
	35-50	6	0,15
	over 50	9	0,23
H&S skills	advanced	8	0,20
	elementary	14	0,35
	intermediate	18	0,45
Quarrying skills	advanced	4	0,10
	elementary	30	0,75
	intermediate	6	0,15
VR skills	advanced	5	0,13
	elementary	22	0,55
	intermediate	13	0,33
Completion (%)	70÷100	39	0,98

	upto70	1	0,03
Score (pt)	upto70	3	0,08
	70÷100	37	0,93
Time (min)	10÷15	12	0,30
	over15	12	0,30
	upto10	16	0,40
Retention1	1error	12	0,30
	all-errors	11	0,28
	no-errors	11	0,28
	forgotten	6	0,16
Retention2	process	16	0,40
	PPE*-other	7	0,19
	machinery	4	0,10
	forgotten	13	0,33

Table 4. MFA dataset. Outcome on quantitative variables on user performances and opinion on VR-Training and specific objective OS1. (*PPE: Personal protective equipment). Modalities, frequencies and percentages on 40 users. Source: Authors processing on MFA dataset by R.

Opinion1			Retry n.			Discomfort			Opinion2		
Mod.	Freq.	Perc.	Mod.	Freq.	Perc.	Mod.	Freq.	Perc.	Mod.	Freq.	Perc.
0	1	0,03	0	21	0,53	0	1	0,03	0	0	0,00
1	1	0,03	1	9	0,23	1	26	0,65	1	0	0,00
2	0	0,00	2	5	0,13	2	7	0,18	2	0	0,00
3	0	0,00	3	2	0,05	3	4	0,10	3	0	0,00
4	2	0,05	4	1	0,03	4	0	0	4	0	0,00
5	2	0,05	5	1	0,03	5	0	0	5	1	0,03
6	5	0,13	6	1	0,03	6	0	0	6	1	0,00
7	5	0,13	7	0	0,00	7	0	0	7	14	0,35
8	10	0,25	8	0	0,00	8	0	0	8	3	0,08
9	5	0,13	9	0	0,00	9	0	0	9	7	0,18
10	9	0,23	10	0	0,00	10	0	0	10	15	0,38

Table 5. MFA dataset. Outcome on quantitative variables on user performances and VR-Training experience opinion on specific objective OS1. Modalities, frequencies and percentages. 40 users. Source: Authors processing on dataset by R.

The aggregation criterion provided 4 groups of variables described as follows: a) characteristics of the volunteers in terms of age, type of occupation, skills in health and safety in the workplace, skills in quarrying activities and skills in virtual reality; b) parameters related to individual VR experiences such as completion time, score and score achieved; c) ability to memorize the number and type of errors while also remembering the right procedures (Table 2); d) number of attempts before completion, discomfort and physical discomfort experienced during the experience, opinion before and after the experience (Table 3). The factors and modalities reported in tables 2 and

3 have been reorganized into groups as shown in Table 4. At this point, by applying the MFA it was possible to find an immediate interpretation of the correlation between variables listed in Tables 2 and 3 and compare the information contained in each group represented in Table 4. The results of MFA are summarized in figures 3, 4 and 5 and in the Discussion section.

MFA Group	Variables included in the MFA groups	Data type
Gr1	retry, discomfort	quantitative
Gr2	completion (%), score (pt), time (min)	qualitative
Gr3	activity, HSS skills, quarry skills, VR skills	qualitative
Gr4	age	qualitative
Gr5	retention1, retention2	qualitative

Table 5. MFA dataset. Outcome on quantitative and qualitative variables. Creation and validation of groups on user performances and VR-Training experience. Specific objective OS1. 40 users. Source: Authors processing on dataset by R.

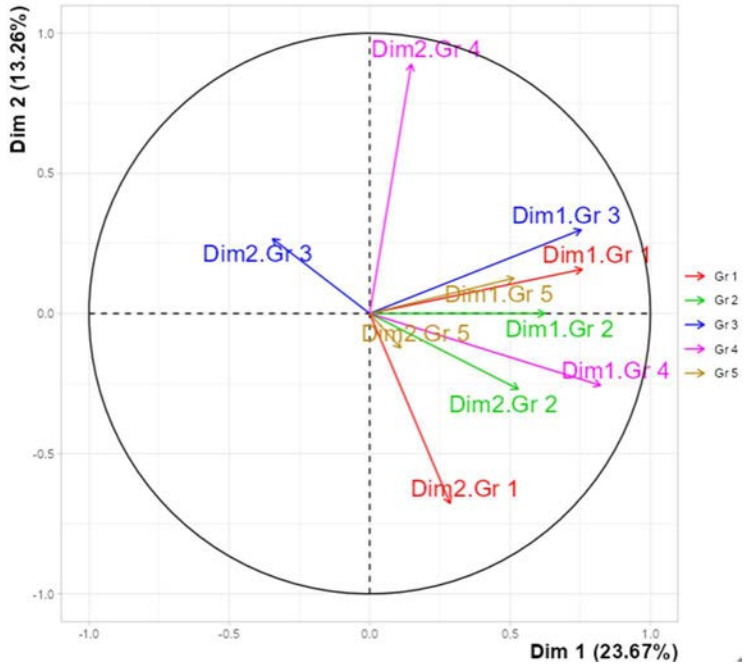

Fig. 3. MFA. Correlation circle. Plain Dim1-Dim2 (Table 5). Source: Author's processing by R.

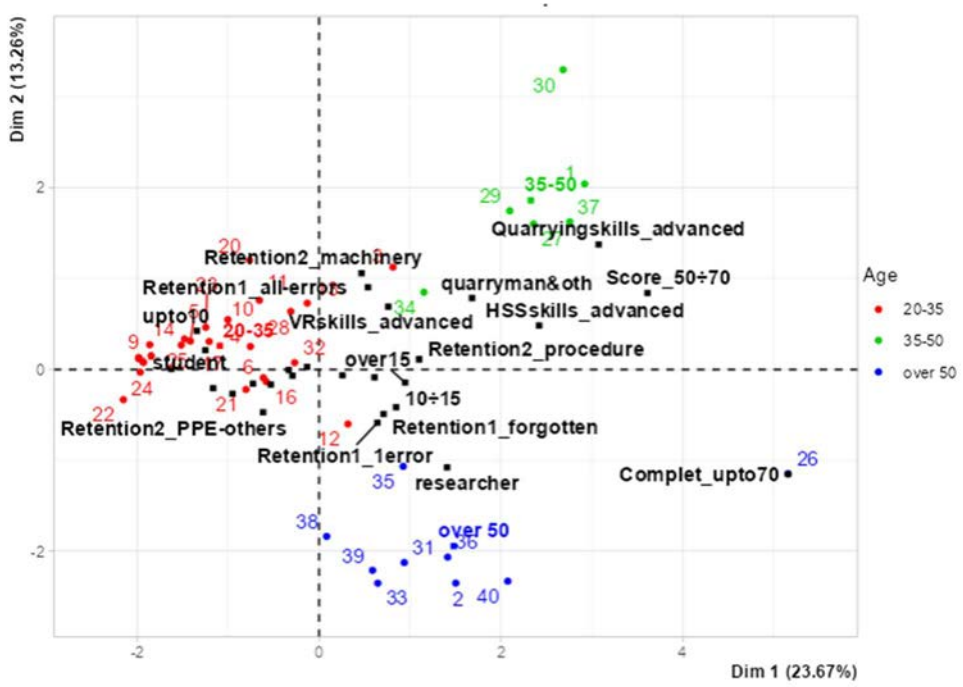

Fig. 4. MFA. Representation of variables, users by age. Each user is coloured according to the legend. Plain Dim1-Dim2. Source: Author's pro-cessing on MFA dataset by R.

Fig. 5. MFA dataset. Representation of variables, users and error retention capability after the experience. Each user is coloured according to retention indicated in the legend. Plain Dim1-Dim2. Source: Author's pro-cessing on MFA dataset by R.

3 Discussion and future directions

Our study, focused on applying VR-training to the quarrying sector integrated production and health and safety processes. The resistance of this industry to adopting technological innovations, is aligned with results of Scorgie et al., that noted that VR training has only a marginal impact in this sector. According to Sacks et al., safety training is a primary mechanism for improving human behaviour in dangerous work environments [9]. The concept of VR in safety training is not new but, in this sector, the immersive VR technology is uncommon [10]. Italy's marble sector has left an indelible mark on sculptural works like Michelangelo's Pietà. This tradition and extraction methods passed down through generations. Perhaps, the sector's resistance to adopting innovative technologies stems from a desire to protect the historical essence inherent in traditional extraction procedures. Administering VR training in this sector, could effectively address these resistances. By blending innovation with respect for historical practices, VR training has the potential to significantly impact safety while preserving the cultural identity of quarrying operations.

One of the objectives of our study was to identify the factors with the greatest impact on the performance of users who joined the trial. In this regard, the most characterizing factors of the experience were the age and activity of the users. The second objective was to assess the ability of users to remember mistakes, both in terms of quantity and type, immediately after the completion of the experience and a week later. Simula Solutions software captured the quantitative variables to each participant's experience. Retention 1 and Retention 2 variables measured participants' ability to recall information. The most significant factors were the participant's activity, age, and skill levels. The student group, primarily aged between 20 and 35, had low skills in health and safety procedures and mining operations, but moderate VR proficiency, showed a strong correlation with "no errors," (no "game out" events), and times under 10 seconds. The quarry workers and others aged 35 to 50, with high levels of expertise in health and safety and mining procedures, with moderate VR skills. Their performance was closely associated with "game out" events and "Retention 2 = procedures" (reflecting correct sequential order of operational phases), with completion rates averaging up to 70%. Finally, the group of researchers, all aged over 50, demonstrated medium to high expertise in health and safety, elementary skills in mining procedures, and moderate VR proficiency and performance with completion rates ranging from 70% to 100%, with "Retention 1 = 1 error" being a strong indicator (Figures 3 and 4).

Regarding Retention1 and Retention2, the Simula Solutions software made it possible to record the number and type of errors made by the user and therefore it was possible to verify the capacity of Retention 1 and 2 through comparison with what the user declared. In case of discrepancy, the "forgotten" modality was assigned. With respect to Retention2 and its modalities, interesting results have emerged related to the combination with age (Figures 4 and 5). About age, it was observed that the "younger" group of users, mostly "students" aged between 20 and 35, achieved better performance in terms of time, percentage of completion and score achieved. Conversely, the same group achieved the worst performance in the ability to remember

both the number and the type of mistakes made. This result, to be explored in further studies, could be traced back to a greater aptitude of digital natives (20-35 years old and students) to juggle serious games. The other significant aspect concerned the difficulty of this group in remembering the number and type of errors committed (Figure 4). Probably, this difficulty could be related to a general lack of experience in the field of Health and Safety and in the field of production processes that characterizes those who have not yet entered the world of work and who therefore have not yet undergone the mandatory training courses, provided for by national legislation for workers, in any sector. In a completely opposite way, the group of users aged between 35 and 50 mostly "quarry workers", obtained worse performances in terms of time, percentage of completion and score achieved. On the contrary, the same group achieved the best performances in the ability to remember both the number and the type of errors made. The group over the age of 50, mostly researchers, on the other hand, was placed in an intermediate position between the previous two. The result relating to Retention2, and the type of mistakes made and remembered by users is also interesting (figure. The most frequent error concerned the “operating procedures” and therefore the order in which the activities were carried out, which was almost identical in the three age groups and activities (6, 5, 5 proceeding from the youngest to the oldest group). Errors in the use of machineries concerned only the group of students and quarry workers (2, 2) while errors in the use of PPE concerned only students and researchers (5, 7) (Figure 5).

Retention measurements are particularly crucial when comparing the effectiveness of VR-based training to traditional methods. The disparity is most evident in long-term outcomes, as shown in studies reviewed by Chittaro & Buttussi and Lovreglio et al. [12,13], which measured retention over periods of 2 to 3 weeks and not in the long-term impact of safety training solutions. Burigat and Chittaro suggest that immediate feedback is an effective approach for delivering knowledge and enhancing self-efficacy in safety training contexts [14,15]. Scorgie et al. observed that only a small proportion (9.6%) of studies on VR explicitly incorporated theoretical frameworks during the development and testing of VR applications. They detected a significant gap in long-term retention measurements, with only 36% of studies addressing this aspect [10]. Study strengths concern the user-centred approach that contrasts with the passive approach normally used in workplaces [16]. Furthermore, to our knowledge, this is one of the few studies to investigate the impact of VR-based safety training in quarry sector. The VR-Training "learning by doing" has proven to be effective especially in those who had no previous skills in health and safety and quarrying. Critical issues are related to the limits, to date, of measuring the effectiveness of VR training compared to other methods, that will be explored in further developments.

Several aspects that are still unclear will be tested and explored in future studies, particularly with regard to the effectiveness and efficiency of the experience, one or two months after the training. In addition, further studies are underway to analyse the physical discomfort experienced during the session and the number of errors and repetitions recorded before completion.

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Gamification and innovative tools for OSH information and training on work-related road accidents and transport safety

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Abstract

Road traffic accidents are a public health and occupational health and safety problem: more than 1 million people die in the world every year and it is estimated that work-related road accidents account for more than 40% of all fatal accidents at work. Inail data from recent years confirm this trend: over 15% of all reported injuries are related to road accident, and about 40% of all reported are fatal. The driving system requires a dynamic balance between different components (Human-Vehicle-Infrastructure), with the human factor bearing the most weight: 90% of all road accidents, including work-related ones, are linked to human error and/or alterations in psycho-physical condition. More than 20% of accidents are specifically linked to sleep disorders and disturbances. By integrating the concept of road safety with preventive and educational attitudes (individual-health, vehicle-environment-safety), this work aims to present two case studies of innovative info-training in the Occupational Safety and Health (OSH) sector as risk reduction initiatives to implement the culture of road safety in the workplace as well. Innovative solutions for OSH info-training have been implemented using digital technologies such as virtual reality, digital serious game, and simulations. The widespread use of ICT and connected devices significantly affect learning systems: “make”, “do it by yourself”, “share”, are the keywords of a new shared and open culture. According to the latest research, our observations support the idea that digital gamification can be a strategy that directly aims to increase involvement, relationship, and motivation in OSH training. It strikes the ideal equilibrium between education and entertainment, encouraging more deliberate decision-making and teaching risk and insecurity awareness in a safe environment. A new "mental habit," social and emotional competencies, and a positive, secure attitude are all developed when workers learn how to behave actively.

1 Introduction

Since 2015 road safety (RS) has been considered as a prerequisite for ensuring healthy lives, promoting well-being and making cities inclusive, safe, resilient and sustainable by the United Nations (UN). Global data published by the World Health Organization (WHO) show that more than 1 million people die in the world every year due to road accidents. Road crashes represent the leading cause of death for children and young adults (5–29 years) and the eighth leading cause of death for all age groups superior to HIV/AIDS, tuberculosis and diarrhoeal diseases. Two thirds of road traffic fatalities occur among people of working age (18–59 years) and more than 50% of all RA deaths are among vulnerable road users: pedestrians, cyclists and motorcyclists. Road traffic crashes cost most countries 3% of their gross domestic product [1]. The European Transport Safety Council (ETSC) identifies road use as necessary and important for working life although it still causes too many injuries, disabilities and fatalities. It is estimated that work-related road accidents (RA) account for more than 40% of all fatal accidents at work: in Europe, 4 out of 10 accidents have fatal consequences. Inail data from recent years confirm this trend: RA account for about 15% of all reported occupational injuries and fatal accidents for over 40% of all reported deaths [2]. The issue of RA is still getting worse, partly due to the notable rise in road traffic that has been observed in the last few years following the pandemic's peak severity. The European Commission (EC) published data on deaths caused by RA in 2022: with traffic levels returning to pre-pandemic levels, the number of road fatalities is predicted at 20,600, a 3% rise from 2021. The average number of deaths in the European Union (EU) was 46 per million people; 52% of victims died on extra-urban roads, 39% in urban areas, and 9% on motorways. For every 4 road fatalities, 3 were men (78%) and of the total road victims, 45% were drivers or passengers of cars, 18% pedestrians, 19% users of two-wheeled motor vehicles (motorcycles and mopeds) and 9% cyclists [3]. A significant feature of RA is its association with employment: a lot of people commute to and from work on the road. In addition to driving a car, that is either privately or publicly owned or rented, road trips for work may require walking or riding a bicycle. In addition, many people work next to or on the street. Consequently, business travel, commuter travel, and travel for work-related reasons are all considered work-related road trips in Italy. Work-related car accidents are a leading source of fatalities and chronic injuries in the workplace and when driving for work, even in the absence of systematic monitoring of work-related road deaths and serious injuries. In EU it is estimated that between 40% and 60% of all fatal workplace accidents are road accidents while using the road for work and commuting. In Italy the year 2022 has been marked by a return to mobility and a greater use of personal transportation, even though smart working is still widely used. This has undoubtedly decreased the number of people making regular trips from home to

work and vice versa, but the percentage of daily trips made in one's own vehicle is still rising [4].
The driving system requires a dynamic balance between different components (triad Man-Vehicle-Infrastructure), with the greatest weight represented by the human factor: 90% of all road accidents, including work-related ones, are linked to human error and/or alterations in psycho-physical condition and accidents related to sleep disorders account for over 20%. RA represent a problem of absolute priority for public health, due to the still high number of deaths and permanent and temporary disabilities caused significant economic, social, and human costs are estimated correlated with road safety (RS), which makes it a critical issue for all European countries' preventative departments and health systems. The same factors, or similar ones always cause or contribute to RA issues in both personal and working circumstances are driving behaviour and psychophysical state; road traffic; conditions and transportation system safety; and risks related to transporting hazardous materials. Aggression, social status, inappropriate drug and alcohol use, diseases, poor vision, use of psychotropic substances, excessive daytime sleepiness, fatigue, drowsiness, using mobile devices while driving, and disregarding traffic laws are just a few of the many risks associated with human factor, which has a predominant influence [5].

1.1 Road safety and motivational technologies: gamification and digital tools

Applying digital technologies and innovative tools to OSH training can increase participation, relationships, and motivation. It can also incorporate instructional and informative components into this dynamic, encouraging more thoughtful decision-making and the adoption of safer, healthier, and more appropriate attitudes. When compared to other predisposing factors, such as the availability and safety of transportation options, traffic on the roads, and the risks involved in transporting hazardous materials, the human factor—that is, the conduct and psychological state of the driver—is the primary one. The use and gradual development of new learning strategies that incorporate the application of virtual reality principles, specifically gamification, is crucial when it comes to the field of effective training and information that seeks to financially guide the adoption of functional behaviours to make driving safer [6]. Such technologies offer the possibility to influence the behaviour and/or the attitude of workers, as illustrated by the emergence of the concept of gamification. It is long recognised that playing can bring about enthusiasm and a feeling of exaltation [7] but gamification, as defined nowadays, emerged in 2008 in the digital media industry and attracted more attention from 2010 onwards [8]. It is mostly defined as the use of game-design elements in non-game contexts, but it indeed differs from actual games, real-world simulations and the use of game theories in organisational matters because it is used typically to change behaviours or to improve user experience and user engagement. Indeed, gamification is used in a wide range of human activities, including education,

healthcare, and transportation safety. As a result, gamification research is now being seen as a developing multidisciplinary discipline (e.g., computer science, social sciences, engineering) [8,9,10,11].

The current state of research on motivational technologies related to Road Safety in Europe identifies two areas of developing investigation: person-centred technologies and system-focused technologies, for which there is still promising data of sufficient interest to infer the possibility of future broadening and deepening. The emphasis of both strategies is on human fault and on the potential for managing it, either in advance of an incident or after the aftermath. According to a recently published review motivational technologies aim to reduce the likelihood of accidents and mitigate their consequences overall through preventive action. These devices, which are all based on gamification and entertainment, are even though they are described differently, tools that engage positive psychological changes in people and improve learning, though there is currently little research on long-term benefits and potential drawbacks. Regardless of the mode of transportation, the individual approach to error management is prevalent, except for a small number of studies that are applied to air and sea travel. Most of these studies are still centred around RS, with the main objective being to increase the safety of bikers, walkers, and vehicles [12]. To concentrate on the pre-event phase and try to prevent accidents, RS research have primarily employed the person-based approach. This means promoting safe behaviours, such as crossing the street carefully, and lowering risky individual behaviours, such as speeding. While most accident investigations aim to improve safety regulations, procedures, and situations by identifying the reasons behind accidents or involving people in data collection to make cities safer, some studies focus on the post-event phase and offer a systemic approach to mistake management. By altering users' mental states to encourage safe driving, gamified road research has mostly aimed to reduce dangerous behaviours. Safe behaviours and safety-related abilities (such as safe road crossing and bicycle situational awareness) are the goals of serious road games. Thus, challenges or goals, simulations or virtual worlds, textual, graphic, or audio feedback, points or scores were the most often used motivational affordances. Psychological outcomes like pleasure or enjoyment, perceived usefulness or usability, engagement, flow, or motivation are the focus of most of the research. A few psychological outcomes, including locus of control, sense of fear, risk awareness, and self-efficacy, were only examined in serious games. By transportation domain, the literature analysis's findings also differ. The factors that are evaluated the most in the roadway domain are perceived usability or usefulness, enjoyment, and motivation, flow, or engagement. Because road users' psychological and behavioural states are crucial in the RA causation, more than 90% of road accidents are caused by human error, preventing them—that is, intervening before an incident occurs—is a sensible strategy for motivational technology interventions in the transportation sector. Using affordances like feedback,

challenges, and points to gamify driving and intervene in drivers' psychological states (like boredom or fatigue) and mitigate risky behaviours (like speeding and lane departure), gamify driving has been the subject of numerous studies with the aim of improving safe driving. For example, by increasing the cognitive load, gamification might reduce monotony and injury risk. Affordances that are outcome- and progression-based, like challenges and feedback, are the most widely used when considering all modalities. This is due to the fact that chances for success and progress may be easily incorporated into routine activities and jobs, such as driving, as well as simulations and virtual environments that aim to completely immerse the player in the game world. Additionally, as gamified driving incorporates everyday situations, feedback and challenges are appropriate affordances since they may be given in real time through ambient colours or music, preventing distractions and excessive cognitive effort that could compromise safe driving. [13,14,15,16].

2 Objectives

Learning systems are significantly impacted by the pervasive use of ICT and connected devices: "make," "do it yourself," and "share" are the hallmarks of a modern, open, and shared culture. This work aims to present two case studies of innovative info-training in the OSH sector using an experimental, multidisciplinary, and multi-sectoral approach. By combining the idea of road safety with preventative and educational attitudes (individual-health, vehicle-environment-safety), the case studies are considered as risk reduction initiatives that also aim to promote the culture of road safety in the workplace. The paper describes the experimental paths based on the use of innovative learning technologies to develop an immersive virtual experience and a digital serious game for the OSH info-training. The virtual laboratory was developed as an immersive journey to learn, experience and feel the signs, symptoms and consequences of obstructive sleep apnoea syndrome (OSA) on health and driving. OSA is a substantial cause of driver drowsiness, and the most frequent medical cause of excessive daytime sleepiness, in accordance with recent studies that confirmed a 2 to 7-fold increased risk of accidents in individuals with OSA. OSA occurs in all age groups and in both sexes (male/female ratio of 3:1). In Italy, recent data estimate the prevalence of people with moderate-severe OSA to be approximately 20% of the adult population but only 4% of patients with moderate-severe syndrome are diagnosed and only 2% of them treated: acceptance and adherence to treatment is generally low (30% to 60%) [5,17,18].

The Sleep-Ro@D digital seriuos game, dedicated to raising awareness and promoting sleep hygiene, aims to reduce the risk of road accidents, including in work settings, and was designed as an educational-participatory intervention and an innovative tool aimed at modifying incorrect behaviour and habits, integrating scientific principles and the results of literature analysis (sleep, work, health and driving) into the game dynamic. Sleep deprivation, sleep-wake circadian rhythm misalignment and untreated sleep disorders are becoming increasingly important

for the well-being and psychophysical health, cognitive functioning and emotional state regulation of both the general and working-age population. Sleep disorders are still underestimated and underreported both in clinical practice and, even more so, in the health surveillance of workers and represent a significant risk factor for OSH. In fact, according to recent studies reduced quantity and quality of sleep can frequently induce excessive daytime sleepiness (EDS), fatigue and cognitive impairment and, consequently, negatively influence psychophysical performance by increasing the risk of work-related accidents by more than 13% and road accidents by more than 21% [19,20,21].
These information and training activities, included in Inail scientific research projects, are intended to put into practice a vision for a participatory, integrated, and holistic approach to risk management in the workplace as a component of the individual, where the development of the worker's abilities and hard and soft skills converge. The activities and tools, which can be freely consulted on the project site (www.oshroad.it) were implemented as part of the BRIC Inail 2018 ID04 SLeeP@SA (in collaboration between Inail and Sapienza University of Rome) and BRIC Inail 2022 ID06 OSH-Ro@D (in collaboration between Inail, Sapienza University of Rome and University of Genoa) national research projects.

3 Materials and methods

Data analysis: a first analysis on the causes of injuries and RA was conducted through global, European, and Italian datasets combined with some person-related determinants, according to the Italian National Prevention Plan 2022–2025, including age, gender, health status, drug and psychoactive substance intake, and distraction.
Literature review: a search was carried out for scientific articles on the topic of 'sleep and driving' by consulting the online databases PubMed, Web of Science, Scopus using the following mesh terms: a) terms related to sleep: e.g. 'sleep', 'nap', 'awake', etc. "b) descriptions of sleep quality/quantity: e.g., "extended", "restricted", "duration", "deprivation", “Osa” etc.; c) terms related to driving: e.g., "driving", "automobile", "motor vehicle", "road traffic", etc. d) terms related to driving performance/compromise: e.g., "accident", "crash", "injury", "speeding", "lane position", etc. To further enhance road safety culture and education using digital technologies, an examination of best practices in the areas of road safety awareness and communication was conducted to explore innovative training and communication tools.
Multidisciplinary working group: a multidisciplinary team made up of professionals with different backgrounds was created (neurology doctor with expertise in sleep disorders and OSA, occupational physician with expertise in accidents and road injuries, a digital designer with expertise in communication, gamification and VR, and expert in digital technologies training tools) to focus the data and literature

analysis on sleep disorders/(OSA) and distraction, which is brought on by exhaustion and excessive daytime sleepiness and lowers driver performance.
Evaluation Questionnaire: using Microsoft Forms, two ad hoc questionnaires were created to assess and validate the digital tools realised collecting data in anonymous and aggregated forms (subject to consent for research purposes) in compliance with EU DPGR data protection regulation 2016/679.
Pre-testing: Osa Virtual Lab was tested during the Advanced Training Course of Sapienza University and Inail on 'Road accidents, work and health' (year 2021/2022-2022/2023) and at the international exhibition event Maker Faire 2022 (Rome October 2022) while SLEEP-RO@D was tested during the international exhibition event Maker Faire 2023 (Rome October 2023).

Digital tool type	**Evaluation tool**	**Training activity description**
Virtual reality Laboratory on Obstructive Sleep Apnoea Syndrome (OSA). It is an immersive journey to learn about the risk of driving implemented for use through the oculus Meta Quest 2 - All-In-One VR Visor achieving a total immersion experience even auditory through 3D positional audio, hand tracking and tactile feedback.	16 items: socio-demographic; ATECO classification (Classification of Economic Activity); ICT knowledge; previous immersive experience, effectiveness of the information; clarity of content, involvement and immersion. The questionnaire was prepared using the Microsoft Forms application and participants completed the online questionnaire after completed the immersive experience. All questions were assigned a value Likert scale between 1 and 5, where 1 corresponds to "not at all "and 5 to "completely".	The innovative training activity was developed through an immersive journey to learn, experience and feel the signs, symptoms and consequences of OSA on health and the impact on driving. The course, which takes about 20 minutes, includes moments of both immersive 'static' and interactive learning. After wearing visors (oculus) and virtually entering into a classroom various experiences and activities, with different communication and interactive formats, are placed: Augmented reality poster on RA and risk behaviour; 3D video of anatomical reconstructions of OSA; Storytelling of a worker suffering of OSA; Videos on the experiential workshop with special glasses simulating visual alterations resulting from alcohol, drugs and medication; Immersive illustrative cards where learner can have interactive insights into the data, signs, symptoms and consequences of OSA.
Digital serious game SLEEP-	28 items: socio-demographic; working	The video game uses data analysis, literature study, and information into

RO@D is a single player game developed as a digital info-training intervention with the goal of changing people's and employees' behaviour and habits regarding the quantity and quality of sleep.	status; ATECO sector; night shift; serious games knowledge; perception of boredom; motivation; ease of use; loss of time passing; immersion; identification; tutorial; graphics; perception of sleep in OSH; evaluation of sleep (4 validated items belonging to the anamnestic instrument of the Pittsburgh Sleep Quality Index - PSQI); time needed to fall asleep, overall duration of night sleep, possible snoring symptoms, overall sleep assessment, daytime tiredness/sleepiness, use of sleeping medication. The questionnaire was prepared using the Microsoft Forms application and participants completed the online questionnaire after completed the game round.	the game dynamics to enhance understanding and encourage the change of unsafe habits and behaviours that could worsen sleep deprivation. It is based on scientific theories: according to research studies, sleep-influencing elements and factors were selected so that the player may personalise their avatar right from the start of the game. The player makes experience of the effects of the previous choices during the play turn and due to the previous choices could improve or worsen the indicators of sleep recovery and well-being. There are two difficulty settings in the game, and gaming lasts for about 5 to 10 minutes. In addition, there are also three bonuses that can be used during the game: 1) coffee consumption; 2) quick break; and 3) driver's snooze to assist the player in reducing the effects of excessive sleepiness while driving. At the end of the game cycle, the levels reached, and the decisions taken, feedback and recommendations are provided using different communication tools (text, storytelling, short graphic videos).

Table 1 – Scheme of the innovative training tools

4 Main results

4.1 Virtual reality on Obstructive Sleep Apnoea Syndrome

The immersive training experience was tested on a convenience sample of 57 participants: 54.4% women (n=31) and 45.6% men (n=26), with an average age of 45.1 years (SD=11.4 years) and medium-high education (Diploma 21.1%; Degree 45.6% and Postgraduate 33.3%). All participants belonged to the working age group between 18 and 65 years and held a driving licence. General knowledge about the use of VR as a training tool concerns 45.6% of the respondents. The sample's prior

exposure to virtual or immersive technologies was 61.4%. Just 25.7% of those who said they had prior experience with virtual reality did so in a research or educational setting, compared to 40% who did so in a job setting and 34.3% in a gaming one. The subjective evaluation of ICT knowledge is intermediate for 68.4% of respondents (using spreadsheets, slide shows, cloud, and collaboration platforms); advanced for 28.1% (website management, data, programming, and platform creation); and basic for 3.5% (word processing, email, and Internet). Only 1.8% of participants thought the training experience in this lab was not very immersive, whereas 86% reported it was totally and very immersive and 12.3% thought it was quite immersive. Only 1.8% of participants thought the creative training course was not very engaging, while 98,2% thought it was quiet, very and totally engaging and 15.8% (see Fig. 1).

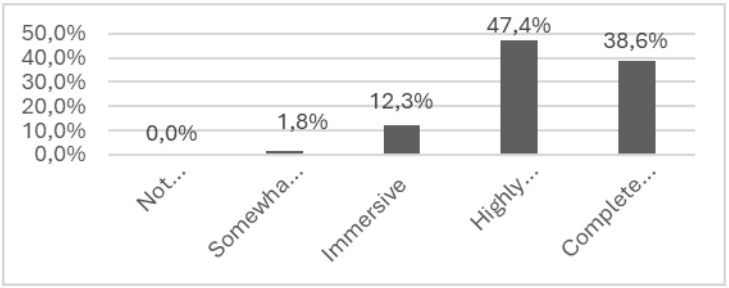

Fig. 1 How do you consider immersive the virtual lab experience?

Concerning the many virtual lab activities, with various interactive and communication formats: according to 61.4% of participants, the AR poster about risky behaviour and traffic accidents was totally and extremely effective; 84.2% of respondents said Mario's storytelling, about a worker with sleep apnoea, was very effective and comprehensive; according to 80.7% of respondents, the 3D animation video depicting anatomical reconstructions of the obstructive sleep apnoea condition was entirely and highly effective; videos of the experience session with the visors mimicking the visual changes brought on by drugs, alcohol, and medication were deemed exceptionally and totally beneficial by 77.2% of participants; and according to 68.4% of respondents, the immersive illustration cards that allow learners to gain interactive insights into the facts, symptoms, indicators, and outcomes of OSA are excellent and totally effective. Only three people—two men and one woman—with an average age of 50.0 years old report some problems related to the VR experience, one participant reported some minor optical discomfort, and another participant had some trouble juggling the oculus, glasses, and protective mask. 94.7% of participants said they have had no issues at all.

4.2 The digital serious game SLEEP-RO@D

The digital serious game was tested on a convenience sample of 154 subjects: 44.4% women, 55.6% men (98.7% Italian and 1.3% Spanish and English). The average age is of 33.6 years (SD±15.0). 68.2% participants report being workers (main occupational

ATECO classification: professional, scientific, and technical activities 25.5%; public administration and defence 16.7%; information and communication services 13.7%; health and social work 9.8%; manufacturing and transport and storage 4.9%; trade, accommodation and catering 4.9%; education 3.9%). The 29.9% of the total sample of respondent's report being familiar with serious games and the 63.0% report being unfamiliar. SLEEP-RO@D was rated as having a very good and pleasurable user experience by the 87% of the participants. Figure 1 shows the answers relating to the distribution of agreement/disagreement related to gaming:

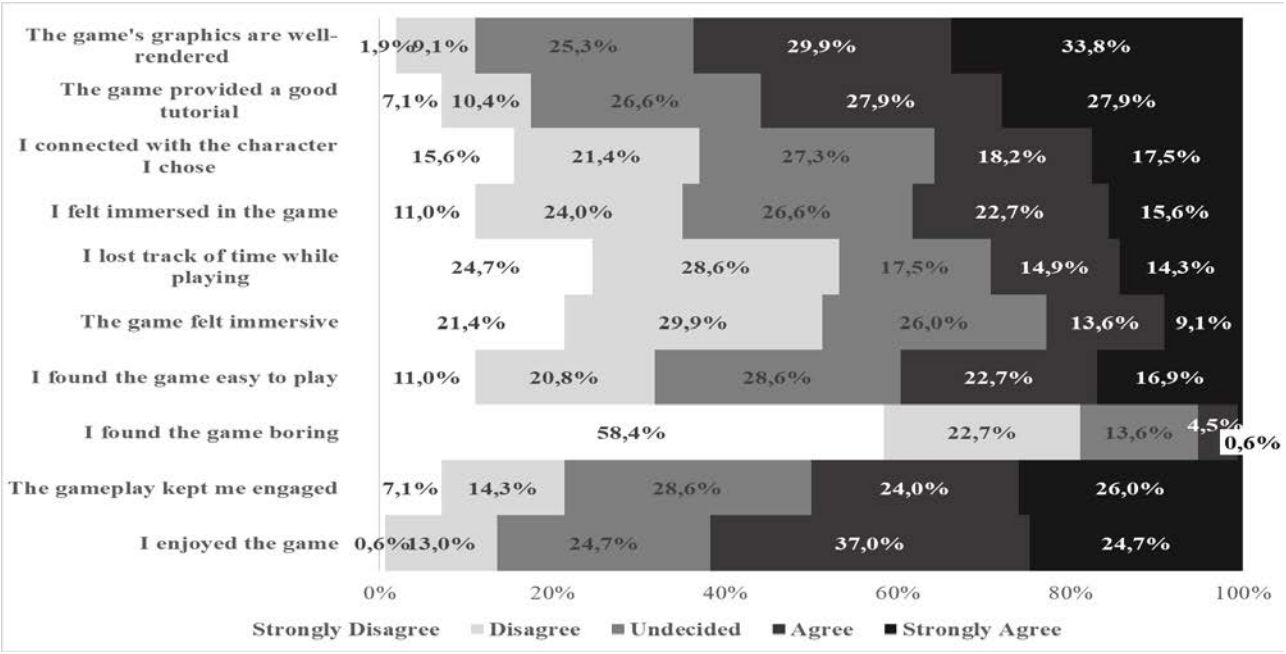

Fig. 2 Percentage distribution of agreement/disagreement questions related to gaming

Considering the challenges associated with obtaining a good night sleep, our study highlights the importance of paying close attention to sleep hygiene practices: the 62% of the participants report not sleeping satisfactorily and the average number of hours of sleep per night reported is around 6 hours. The 20% of the sample even assert sleeping less than 6 hours per night (below that what recommended for all ages by the National Sleep Foundation minimum 7-8 hours per night). The respondents, thinking about the last period (the last 4 weeks), report snoring during sleep with a frequency of 26.0% and 46,8% of the sample reported to be sleepy during the day. Of the 27 subjects reporting taking sleeping medication 'rarely', 'sometimes' and 'often', 14 were male (51.9%) and 13 were female (48.1%), with a mean age of 36.2 years (SD±11.9; range 16-56 years).

5 Discussion and conclusion

Information, education, and training play a crucial role in enhancing OSH conditions, as established by Italian legislative Decree 81/08 and ss.mm.ii and EU legislation. It

is not enough to simply incorporate technological tools as an aid to traditional methodologies to respond to the transformations of the screen generation learning processes, which are characterized by the simultaneity and coexistence of cognitive activities. Instead, it is necessary to develop new systems, models, and methodologies of formal, informal, and non-formal knowledge transfer. In the specific OSH field, worker education is a complex process that is declined through the relational institutes of information, education and training, all equally functional to the maturation of a safety culture. The empowerment of the worker, seen as the active competence of the individual and the group's capacity to think and act, to take initiatives in an autonomous and conscious manner to manage and prevent risk, is a key to achieving this important objective [22]. In recent years, digital workshops and training courses are emerging as innovative tools to promote opportunities for psychological growth and well-being and greater active involvement in educational processes to encourage conscious choices and develop correct and safe attitudes. Through attention, perception, memory, learning, thinking and reasoning, problem-solving, language and emotions, cognitive processes allow us to acquire information about the environment and to process it at the level of knowledge as a function of behaviour. Specifically, their functioning concerns the modalities and procedures adopted by the human mind to choose where to direct attention, to acquire and process information from the senses, to remember some of the most important information and neglect or eliminate others, and to make the most appropriate decisions in relation to needs. Innovation brings about the need to adapt innovative formal, informal and non-formal knowledge transfer systems, models and methodologies to technological change. Indeed, in an increasingly complex and constantly evolving world, technologies play an increasingly pervasive role in living and working environments, the impact of which alters the cognitive, relational and empathic structures of human beings, breaks down traditional conceptions of space and time, and changes the approach to knowledge and the organisation of reality. In this perspective, laboratory teaching is combined with the constructivist and shared learning aspects that the Net and immersive technologies favour, offering the possibility of simultaneously implementing in the teaching action dimensions that, in other contexts, would be difficult to reconcile, such as the personalisation of contents; learning in the context of experience; the role of emotions in stabilising memories. In the field of occupational health and safety, the use of technologies as learning mediators is a stimulating and creative opportunity for the maturation of technical-scientific content, exploiting the combination of interactivity and the possibility of customising training material. In the experimentation of the workshops, it was possible to observe that the use of innovative technologies for training (AR/VR, simulations and videogame) was particularly appreciated as the subjects considered them dynamic and fun, allowing them to increase motivation, attention and interaction.

This study highlights how the usage of virtual reality (VR) and digital gamification as learning experiences may be necessary to speed up the transfer of new and distinct information in OSH training. Technology-enhanced knowledge structures now have an experiential role that affects and changes relational, cognitive, and emotional structures. In fact, almost all participants in the two innovative training experiences in our study considered them particularly engaging, amusing and effectives. Through immersive experiences, a different form of worker involvement is activated, more direct and interactive, which stimulates the worker to feel part of their own information/training path, and this determines a greater awareness of risk that orients choices and attitudes that become safer and more appropriate to the contexts of reference. In accordance with recent literature studies on the use of immersive virtual reality and digital serious game in training and education these tools increase attention, motivation and improves interactions between workers/learners. VR has the great advantage of supporting learning through action and play and it is able to induce greater involvement and motivation in its users due to its ability to share and collaborate in the learning experience with individuals who are not only spatially distant but also culturally and experientially assorted. Through the immersive and interactive pathway, led by the multidisciplinary team worker can learn about one of the emerging causes of road accidents, also related to work, and the importance of early OSA diagnosis to bring this epidemic to light. The ability to interact with the virtual things (experiential didactics) encourages "active" learner participation by stimulating their interest and curiosity about settings, people, facts, and historical events that can be represented in innovative and creative ways using modern technologies. Studies on cognitive processes have been concentrated on how they operate on an individual level, but current research is also concentrated on how the pervasive use of technology affects these processes. For instance, the use of digital technology can lead to changes in the many ways that learning occurs while also opening up new prospects for adult education. One considers the significant benefits to learning and training provided by VR, which can fully engage the perceptual apparatuses to determine a complete sensorial immersion, and which can encourage people to solve problems through creative and decision-making processes also determined by interactions in the group and/or in the network [16,22]. Road accidents are a public health and occupational safety and health critical issue and more than 90% of RA are associated to human error (psycho-physical condition, vigilance, and incorrect behaviour). Driver/worker performance is often affected by fatigue and excessive daytime sleepiness. Sleep is in fact a necessary element for health and safety at work as well. “Teaching health” is a fundamental point for a total worker health and to be effective it must be integrated, innovative and participative. Recent studies have shown that gamification can be a methodology directly aimed at increasing involvement, creating a perfect balance between learning and entertainment. Games have a special quality of social bonding providing context and motivational aspects that can

be used to improve dynamics and solutions, and educational elements can be integrated into the gameplay, which will be subconsciously acquired by the players during gaming. By focusing primarily on the simulation expedient, various outcomes can be attained: games are developed that accurately mimic real-world scenarios and practices, requiring players to hone their skills in a virtual competition; or, as is increasingly common in educational institutions, games are designed to enhance users' academic and didactic knowledge, to enhance human performance in a particular behaviour, or, in other words, to teach road users how to act appropriately by training them in an environment that is not real but is quite similar to the one to which the experience will be applied. According to our study and testing, playing digital serious games offers possibilities to experiment while working and explore, practice, and interact with digital content, allowing players to learn about risk and insecurity in a secure setting. Learning subjects' active behaviour develops a new "mental habit," social and emotional skills, and a positive, safe attitude [6,23].

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Guru: a multisensory training system for high-risk work environments

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Abstract

High-risk work environments, such as those with confined spaces or hazardous material exposures, present unique challenges that demand advanced training solutions. Current training regimens often lack the capability to simulate realistic environments and scenarios, resulting in a training gap that leaves workers inadequately prepared for the complexities of their jobs. Moreover, traditional methods rarely address the psychological and emotional responses workers may experience in a crisis. Traditional training methods often fail to simulate realistic environments or address the psychological responses workers may experience. The GURU project, presented in this short paper, addressed such gaps, by enhancing training through advanced technologies. The project utilizes augmented reality (AR) and virtual reality (VR) to create detailed simulations, providing workers with realistic experiences without associated risks. Additionally, biosignal monitoring technologies like electroencephalography (EEG) and electro dermal activity (EDA) are incorporated to assess and adapt to workers' emotional and cognitive states, ensuring they are mentally and emotionally prepared for high-stress situations. Key innovations include using machine learning algorithms to dynamically adjust training scenarios based on real-time data, enhancing the relevance and effectiveness of the training. The project also integrates sensory stimuli across visual, auditory, and vibrotactile inputs to maximize worker immersion, improving their retention of safety protocols and crisis response. The project aims to develop a model that personalizes training by leveraging neurophysiological and behavioral data, resulting in more efficient learning and safer workplace behaviors. Artificial intelligence is employed to analyze data and adjust scenarios dynamically, maintaining an optimized training environment. The GURU project is expected to significantly reduce workplace accidents, enhance training effectiveness, and lower costs by reducing the frequency and severity of incidents. Overall, the GURU project represents a comprehensive effort to improve workplace safety training by integrating advanced technology and

human psychology, offering a scalable and versatile solution adaptable across various industries.

1 Introduction

High-risk work environments, such as confined spaces or hazardous material exposures, present unique challenges that demand advanced training solutions. The concept of safety in the workplace as a non-negotiable value underscores its critical role in fostering healthy and inclusive economic development. This principle hinges on the belief that every employee, regardless of their role or the industry in which they operate, has the right to work in an environment that prioritizes their physical and psychological well-being. Ensuring a safe work environment minimizes the risk of accidents and injuries, which in turn protects an organization from costly downtime, legal issues, and potential damage to its reputation. Beyond compliance, promoting a culture of safety increases employee morale and engagement, as workers are more likely to be productive when they feel their health and safety are prioritized. Additionally, workplace safety can significantly reduce costs associated with workers' compensation claims, medical expenses, and lost labor. Ultimately, investing in comprehensive safety practices and training not only protects employees but also enhances operational efficiency and fosters a positive public image, making it an essential practice for any responsible employer. Current training regimens often lack the capability to simulate realistic environments and scenarios, resulting in a training gap that leaves workers inadequately prepared for the complexities of their jobs. Moreover, traditional methods rarely address the psycho- logical and emotional responses workers may experience in a crisis. The GURU project (acronym of the project), presented in this short paper, addresses these gaps by:

- Enhancing Realism: Using Augmented Reality (AR) and Virtual Reality (VR) to create detailed simulations of high-risk environments, providing workers with experiences as close to reality as possible without the associated risks.
- Emotional and Cognitive Engagement: Incorporating biosignal monitoring technologies like electroencephalography (EEG) and electro dermal activity (EDA) to assess and adapt to the emotional and cognitive states of workers during training, ensuring that they are not only physically but also mentally and emotionally prepared for high- stress situations.
- Dynamic Adaptation: Utilizing machine learning algorithms to dynamically adjust training scenarios based on the workers' neurophysiological real- time data, enhancing the training's relevance and effectiveness.

Through these innovations, the GURU project aims to significantly improve the safety and efficacy of training programs, ensuring that workers are better equipped to manage and mitigate risks in their respective high-risk work environments. This proactive approach not only enhances individual worker safety but also contributes to broader occupational health and safety advancements.

2 Background

This section is dedicated to an overview of how VR/AR technology is used for training purposes and highlights the benefits of virtual training. High-Risk Environments are characterized by exposure to dangerous elements and complex operations, which usually make them prone to accidents and occupational hazards. For this reason, the health and safety of employees should be the priority. To minimize casualties, the employees should be trained to acquire lifesaving skills and injury/illness prevention, develop necessary mental preparedness and gain firsthand experience of the dangers they might encounter at the time of an actual emergency [1].

Traditional training methods include classroom lectures, videos and printed safety manuals. These methods have proven to be insufficient because they often lack realistic simulations that reflect the unpredictability and intensity of actual work conditions. One of the major limitations is the inability to simulate the psychological and emotional responses that employees experience during high-stress situations. As a result, employees may feel unprepared when faced with real-life emergencies, which can lead to unsafe behaviors, accidents, or even fatalities.

In recent years, thanks to the technological advancements of VR and AR, the use of such technologies in the field of training is spreading, significantly changing how organizations approach learning and development [2]. These technologies provide lifelike simulations of dangerous scenarios and employees are free to experiment without the limits of real environments. Employees can practice the skills necessary for acting in hazardous situations in a risk- free environment [3].

In scientific literature, it's possible to find a lot of studies that have benefited from VR/AR technology for training purposes. As examples, [4] showed that VR can enhance learning outcomes, potentially resulting in lower accident and fatality rates on construction sites. Research by [5] showed that VR training increases the capabilities of hazard identification, leading to better knowledge retention than conventional instructional media methods. Similarly, a study by [6] showed that, before VR training, trainees could identify only 31 percent of potential hazards. However, after undergoing VR training, their ability to identify hazards increased significantly, to 70 percent. Similarly, research by [7] found a 15 percent improvement in safety performance following VR training. Moreover, it has been shown that experiencing hazards in simulations can trigger reflection processes, which can bring memories of previously encountered hazards [8]. Encountering these experiences improves trainees' safety awareness and helps them develop strategies to mitigate risks in the future [9].

These findings suggest that VR training is effective in improving both hazard management and overall safety performance. However, VR can complement conventional training programs but cannot re- place hands-on experience and real-world drills [4] [10] [11].

In addition, while VR and AR can create visually and spatially accurate immersive environments, they do not inherently account for the emotional and psychological

states of employees, which are critical to effective crisis management. For this reason, biosensors must be integrated to monitor the emotional and psychological states of employees. Portable devices such as wristbands, wireless straps, or headbands are easy to use. Additionally, eye tracking, EDA, and photoplethysmography (PPG) are particularly useful biomarkers of stress and/or cognitive load in XR training contexts. However, a limited number of studies employed real-time analysis of biosignals which indicates current challenges in implementing such systems and the need for more work in this area [12].

Another important thing for the VR/AR training system to be effective is that it must be dynamically user adaptive. Based on Yerkes–Dodson law, adaptive training can provide optimal level of physiological or mental arousal to maximize employee's performance and learning [13]. Based on the Cognitive Load Theory (CLT), intrinsic load (e.g., inherent complexity of the information) should be managed, extraneous load should be reduced (e.g., by using appropriate training medium), and germane load (i.e. the load that directly contributes to learning and the construction of mental schemas) should be increased (e.g., by increasing the training variability). A little number of studies [14] [15] [16] used: i) physiological responses to identify the trainee's cognitive load, stress level, and emotions as a basis for providing personalized training; ii) machine learning (ML) or optimization algorithms including artificial neural network (ANN) [17] [18] [19]. The algorithms were used for extracting features from various sources of performance measures, classifying employee's state, and providing an optimized adaptation to match the employee's performance, cognitive and physical capabilities.

The GURU project wants to overcome these research gaps. By combining immersive simulations with real-time emotional and cognitive assessments, the project aims to create an adaptive training environment that can respond to the unique needs of each worker. biosignal technologies, such as EEG and EDA sensors, monitor the trainee's physiological responses to stress, allowing the system to tailor training scenarios dynamically based on the individual's emotional and cognitive state. This personalized approach aims to improve decision-making, emotional regulation, and overall crisis response by ensuring that workers are not only physically trained but also mentally and emotionally prepared for high- pressure situations. Through these innovations, the GURU project seeks to not only reduce workplace accidents and injuries but also optimize the efficiency of training programs, making them more effective and cost-efficient across a wide range of industries.

3 Guru Project Overview

The overarching goal of the GURU project is to revolutionize the training of workers in high-risk environments through the development of an integrated multisensory system that seamlessly blends physical and virtual realities, known as mixed reality. This innovative approach aims to enhance the realism of training scenarios and dynamically adjust to the unique learning needs and conditions of individual workers.

The core contribution of this paper is the creation of an integrated multisensory system that merges physical and digital realities to train workers in environments characterized by serious and specific risks, offering the capabilities to provide real-time measurement of a worker's cognitive and emotional state. The ability to assess in real-time various behavioral, cognitive, and emotional parameters of the worker, through analysis of movement, haptic feedback, and the neurophysiological dimension of the worker (namely biosignals such as EEG and EDA), allows for the dynamic modulation of the training (e.g., operational scenario, level of difficulty, risk situation) tailored to the individual worker. Consequentially, it optimizes the effectiveness of the training itself, both in terms of time and quality thereby reinforcing the learning of safe behaviors in work environments characterized by serious and specific risks.

4 Usage scenario

In this section, we describe the immersive training environment and interactions facilities developed during the GURU project. The user engages with the system by wearing a range of advanced devices, including a Virtual Reality (VR) headset, haptic gloves, an exoskeleton, and neurophysiological sensors. These devices are designed to simulate high-risk work environments while capturing the user's physical and cognitive responses in real time.

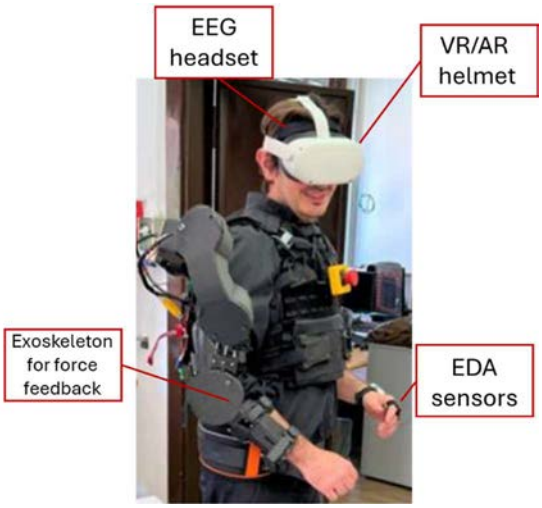
Before beginning the training, the user is briefed on the objectives and the specific tasks they will perform. The system guides the user through a series of activities that assess their readiness and ability to interact with the virtual environment. The first task, referred to as Task "0," ensures the user can comfortably navigate the virtual space and perform basic movements such as head rotation, arm positioning, and finger manipulation. This foundational task prepares the user for more complex, scenario-based training mod- ules that follow.

By integrating real-time feedback from multiple sensors, the GURU system dynamically adapts to the user's performance, ensuring a fully immersive and responsive training experience tailored to the individual's current cognitive and physical state.

The training begins as the user approaches an electrical panel for the first task: safely shutting off the electrical current by pulling down a lever. Throughout the interaction, the lever provides visual, auditory, and haptic feedback, ensuring that the user perceives the completion of the action. The system confirms the power interruption with additional sensory cues such as light, sound, and vibration, creating a multi-sensory confirmation.

Next, the user interacts with a toolbox, retrieving the necessary tools for the subsequent tasks. When selecting the locking mechanism, essential for securing the electrical panel, the system provides multisensory feedback to confirm the selection. In the third task, the user applies the locking system to the designated slot on the panel, following the LockOut procedure. Sensory feedback continues to play a vital role, guiding the user in ensuring proper installation of the locking system.

The fourth and fifth tasks involve manipulating valves to control gas flow. In Task 4, the user closes the upstream valve by rotating it, an action accompanied by visual and auditory cues, as well as hap- tic feedback that simulates the resistance encountered during the process. In Task 5, the user opens the vent valve, experiencing similar resistance and sensory confirmation. The sound of steam releasing further enhances the immersive experience, signaling the successful completion of the task.
In Task 6, the user consults a pressure gauge to check the pipeline pressure. After confirming that the pressure has stabilized, the user proceeds along a pre- defined path toward the next operational area. Here, in Task 7, the user operates a Multigas device to assess the air quality before physically entering the area. Through a combination of visual, auditory, and haptic feedback, the system guides the user in operating the device and confirms when the air quality is safe.
Upon entering the operational area, the user performs Task 8: opening the gate valve. Again, multi- sensory feedback ensures the user completes the task accurately. The Multigas device is used once more in Task 9 to verify air safety before proceeding to Task 10, where the user closes the downstream valve. Like the earlier valve operations, this task involves force feedback that mimics real-world resistance.
The next sequence of tasks involves using an open-end wrench to manipulate nuts on the threaded compression fittings. In Task 11, the user retrieves the tool from the toolbox, receiving feedback at every stage—from grabbing the wrench to tightening the nuts. The system ensures that appropriate pressure is applied evenly, preventing damage to the pipe or seals.
In Task 12, the user carefully removes a damaged pipe section from its connections. This is followed by Task 13, where the user installs a new pipe section. Throughout these tasks, the system continues to provide sensory cues that guide the user, ensuring that the new pipe is correctly positioned and the nuts are evenly tightened. In the final step, the user checks for leaks by visually inspecting the connections and, if possible, applying slight pressure to verify system integrity.



Throughout the entire scenario, the GURU system leverages real-time feedback to ensure that the user performs each task safely and effectively. This integration of visual, auditory, and haptic feedback enhances the user's sense of presence and embodiment, providing a highly realistic, adaptable training experience within simulated high-risk environments.

5 System architecture and components

The GURU system architecture consists of several interconnected layers and components that enable real- time interaction, feedback, and adaptation within a simulated training environment. These components are categorized into Hardware, Software, and Control/Feedback systems.

The need to provide a full sense of embodiment to the user *led* to the implementation of an effective natural “grip” system for all interactable objects inside the VR scenario.

In order to achieve this goal, two distinct grabbing modes have been implemented and proposed to the stakeholders through usability tests. The main difference between the two modes lies in how a particular hand configuration (Pose) is handled by the system when the user interacts with objects inside VR environment. Specifically, one mode relies on a set of predetermined hand poses, obtained through manual orientation of the hand rig bones, (Static Poses) while the second mode uses runtime functions to calculate the pose that “best fits” to the object the user is inter- acting with (Dynamic Poses). The following is a brief description of the two grabbing modes:

1. Static Poses: Each interactable object comes with a set of hand poses modeled on the object itself. Each pose is located in a point in space near the object, where the user is expected to call the grab event. The system chooses the pose nearest to the current hand position and rotation, so that the tracked hand snaps to the object giving the illusion of grabbing it. The system can be further im- proved by updating the rotation of the hand pose relative to the user.
2. Dynamic Poses: Similar to Static Poses, in this mode each object comes with a set of hand poses. This time each pose is not modeled on the object but is calculated by the system itself taking into account the real hand position and the mesh of the object. In particular, each dynamic pose starts as an open palm where each fingertip “detects” the closest point on the object mesh and attaches to it, adapting the pose to the object itself through an interpolation phase.

Given those two modes, interactable objects have been grouped into three distinct groups:

- Liftable objects: Objects that can be lifted and carried freely by the user. In some cases, liftable objects can interact with other objects to trigger simulation events.
- Translatable objects: Objects than can be translated by the user along a given direction.
- Rotating objects: Objects than can be rotated by the user along a given axis.

6 Neurophysiological model of embodiment

Neuroscience has made remarkable progress in recent years, driven by the increasing availability of data and the development of advanced analytical techniques. This has allowed researchers to translate findings from basic research

into practical applications, even in the context of virtual reality (VR). A crucial aspect of VR effectiveness is the sense of "being there" known as embodiment. Embodiment goes beyond visual immersion to include a feeling of presence, agency, and ownership of a virtual body. Understanding the biological basis of embodiment is essential for developing more effective VR applications in fields like healthcare and rehabilitation. While previous research has investigated the neural and physiological correlates of embodiment using measures like EEG (brain activity), ECG (heart activity), and EDA (skin conductance), these studies often relied on subjective questionnaires and lacked a comprehensive, objective measure. Furthermore, the physiological markers identified were not unique to embodiment and could be influenced by other mental processes. This research work aimed to address these limitations by investigating the transversality of the previously validated indices for objectively evaluating the embodiment in VR. In this regard, a preliminary analysis was performed on a dataset collected in VR experience designed for eliciting varying levels of embodiment. The final objective of this research activity consisted of selecting the most sensible neurophysiological parameters for evaluating the embodiment in VR during the GURU scenario.

6.1 Neurophysiological Model of Embodiment: Preliminary insights

The considered dataset was collected within a realistic virtual reality driving simulator to investigate how different combinations of sensory cues (visual, auditory, and touch) impact a driver's ability to detect targets under varying levels of visual distraction. Participants completed driving tasks where they had to collect targets appearing on either side of the road, with the difficulty increased by adding fog, rain, and thunder sounds to create a high perceptual load condition. To summarize, the experimental conditions were divided into two dimensions: i) different level of sensorial stimuli (only Visual (V), Visual and Auditory (VA), Visual and Vibrotactile (VV), and all three (VAV)); ii) different level of task difficulty (Easy and Hard). Throughout the experiment, data was collected on brain activity, skin conductance, and heart rate variability, alongside subjective reports on workload and sense of presence. The selected neurophysiological indices for characterizing the embodiment variations across the experimental conditions were: EMBO1, defined as the frontal Theta over the parietal Alpha EEG Global Field Power (GFP) ratio; EMBO2, defined as the frontal Theta over the parietal Alpha and frontal Beta EEG GFP ratio; the Skin Conductance Level (SCL), one of the two components of the Electro Dermal Activity (EDA); the Heart Rate (HR) and its variability (HRV), two cardiac features derived from the Electrocardiographic (ECG).

6.2 Neurophysiological Model of Embodiment: Preliminary Results and Outcomes

The statistical analysis revealed that the EMBO1, EMBO2, and SCL parameters were

significantly sensitive to the embodiment variations across the different experimental conditions. More specifically, the repeated measure statistical analysis performed on EMBO1 and EMBO2, the two pure EEG-based indices, showed a significant main effect of the embodiment variation ($EMBO_1$: $F = 9.712$, $p = 0.001$, $\eta^2 = 0.372$; $EMBO_2$: $F = 12.091$, $p = 0.001$, $\eta^2 = 0.207$;).
Similarly, also the SCL parameter resulted to be sensitive to the embodiment variations ($F = 6.221$; $p = 0.009$; $\eta^2 = 0.251$). Such results were consistent with the ones emerged by the statistical analysis performed on the subjective reports. In fact, the sense of presence questionnaire revealed that the participants significantly discriminated among the different experimental conditions in terms of perceived embodiment variations (F = 11.895; p ¡ 0.001; 2 = 0.398). More importantly, the statistical analysis showed also a significant main effect of the task difficulty associated to the three selected measurements (i.e., EMBO1, EMBO2, and SCL). This was confirmed also by the statistical outcome observed from the analysis performed on the subjective ratings of the task difficulty provided by the participants ($F = 14.071$; $p = 0.001$; $\eta^2 = 0.455$). Taken all together, these preliminary results demonstrated the sensitivity of the selected neurophysiological parameters to the embodiment variations in VR. Additionally, it was demonstrated that further work is needed to increase their transversality, since such parameters resulted to be sensitive also the other mental processes than the embodiment perception. In this regard, a future research step was already approached for developing a unique neurophysiological embodiment index. Such an index will be computed by combining among them the three parameters presented along this work through the Information Theory methodology.

7 Expected outcomes and impact

The GURU project outcomes are centered on transforming the training landscape for high-risk work environments through innovative, technology-driven approaches. By integrating advanced virtual and augmented reality technologies with real-time monitoring of cognitive and emotional states, the project promises a paradigm shift in workplace safety training. The key expected outcomes include:

- Enhanced Training Effectiveness: The multisensory and adaptive nature of the training system is anticipated to significantly improve knowledge retention and practical skill acquisition, ensuring workers are better equipped to handle high-stress and high-risk situations.
- Reduction in Workplace Accidents: The realis- tic and personalized simulations aim to bridge the gap between theoretical knowledge and on- ground application, directly contributing to a de- crease in the frequency and severity of workplace incidents.
- Operational and Cost Efficiency: By reducing accidents and improving training retention, the system is expected to lower associated costs such as downtime,

medical expenses, and compensation claims, leading to broader economic benefits for industries.

- Scalability and Industry Versatility: The adaptive framework ensures the system's applicability across various industries and scenarios, extending its impact beyond the initial deployment and paving the way for broader adoption in sectors where safety is paramount.

In conclusion, the project not only addresses critical gaps in current training methodologies but also sets a new standard by leveraging cutting-edge technology and insights from human psychology. These outcomes underscore the project's potential to make workplaces safer and training programs more impactful, aligning with broader objectives of sustainable industrial growth and workforce well-being.

8 Conclusions

The successful achievement of these objectives aims to lead to several critical advancements, including a significant reduction in workplace accidents by better preparing workers to handle unexpected situations. Enhanced training effectiveness will result from the high levels of engagement and better retention of critical safety protocols, which are facilitated by realistic simulations. Additionally, the project promises cost efficiency by potentially reducing the frequency and severity of workplace incidents, which, in turn, decreases the financial burdens associated with workplace injuries and insurance claims. The technologies developed through the GURU project are expected to be adaptable across various industries and risks, highlighting the system's versatility and scalability. This adaptability makes it a valuable tool for numerous applications involving high-risk operations. Furthermore, by setting new standards for safety training that combine cutting-edge technology with advanced learning methodologies, the project is poised to offer a pioneering solution to workplace safety training. In conclusion, the GURU project represents a comprehensive effort to not only meet the current demands of workplace safety but also to adapt to and preemptively address future challenges through a holistic approach that integrates technology and human psychology.

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Safer Energy Plant Inspections with Robots: A Pilot Project between Baker Hughes and Sarlux

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Abstract

This paper presents a pilot project between Baker Hughes and Sarlux, leveraging legged robots to enhance energy plant safety through the integration of advanced analytical capabilities. The pilot took place in the Sarlux refinery, with the objective of inspecting machines that already had remote monitoring systems to further enhance their surveillance.

Refineries are complex industrial facilities that process crude oil into various petroleum products. While essential for meeting global energy needs, the refining process could potentially present safety concerns that must be addressed during inspections.

The project aims to enrich plant inspection processes by utilizing the robot's agility and versatility to streamline inspections and reduce risks associated with manual procedures. The autonomous legged robot, equipped with sensors and data analytics capabilities, conducts comprehensive inspections throughout the refinery. Using real-time data analysis and machine learning algorithms, the robot provides accurate and timely insights on machine health, operational efficiency, and potential safety hazards.

Our study explores the robot's ability to navigate complex industrial environments, collect and process data from various sources (including gas leak detectors, vibration analysis sensors, and thermal imaging cameras), and generate comprehensive reports for decision-makers. We also investigate the integration of the robotic system with different inspection sensors and the development of custom algorithms for specific inspection tasks.

The results demonstrate that robots successfully navigated challenging terrains and hard-to-reach areas. Real-time data analysis allows for immediate identification of potential issues, enabling proactive maintenance. Furthermore, the reduction in human exposure to hazardous environments can lead to enhanced overall safety for plant personnel. The results of this project have the potential to transform plant inspection and maintenance practices across the energy industry and beyond, highlighting the vital role of innovative technologies in advancing workplace safety and operational excellence in industrial settings.

1 Introduction

1.1 Scope of work

The primary objective of this project was to evaluate the feasibility and the effectiveness of adopting autonomous inspection robots on the refinery site. The advantages of robotic inspections aim to enhance plant safety and efficiency, as a matter of fact with periodic and automatic inspections, it's possible to detect and react promptly to eventual malfunctions, while reducing human time exposure to hazardous environments. Robotic Inspections are a powerful tool that is not meant to be a direct replacement of the human operators on-site, they are instead meant to support the daily workers' activities, promoting a safe and healthy environment.Each movement or analysis carried out by the robot in the plant was studied and calibrated in the field by the Salux and Baker Hughes team. The aim was to understand how the robot can moves in a real and dynamic industrial environment, made of people and objects in motion and non-linear path (or e.g. example with adverse weather conditions)

The scope of our pilot project was focused on testing autonomous missions of a legged robot around a predefined area of the refinery, specifically the T1 zone at Sarlux. In this area two compressors produced by Baker Hughes have been installed and are currently functional. The compressors' main parameters are continuously monitored by Baker Hughes remote platform for delivering advanced data-driven monitoring and diagnostic services and analytic (iCenter).

In this context the adoption of a robotic inspecting system can be used to validate the data acquired by the monitoring center, robotic inspections can be used also to expand the control room capabilities by inspecting elements that are not currently covered by the smart sensors that are installed on the machines.

In fact, the other objective of the project was to demonstrate that the added value of the using of an automated robot is to collect a lot of data in less time but with greater quality, to obtain asset integrity management. at 360°, with a high frequency of inspection in the field.

The scope of this project also included developing a comprehensive data management system, which would enable the robot to collect, process, and store data from the inspection points, and provide real-time feedback to the operators.

There are many studies as state of the art that present the concept of autonomous robotic industrial inspections. Some of them propose highly innovative robotic systems such as [1], [2] showing a mobile robot with a hybrid locomotion system and [3] describing a serpentine robot, while others focus on more specific task, such as pipeline inspecting robots [4], [5] and remote offshore underwater applications [6]. Finally, there are also few of them who performs a nice review of the current state of the art like [7], [8], [9].

These works are however mostly incomplete, they are performed in simulations or on controlled well-known environments with strong constraints. The novelty of our work is the engineering phase of integrating a laboratory solution into a use-case

environment tackling all the correlated challenges. Among those, HSE (Health, Safety, and Environment) played a significant role, a proper training of all the operators has been conducted allowing a safe work directly on the refinery site, secondly all the administration procedures have been performed beforehand to have all the requirements according to law and company policies met.

2 Methodology

2.1 Description of the Environment

The study took place in the Sarlux refinery, a complex industrial facility that processes crude oil into various petroleum products. The refinery's environment presented challenging terrain for the legged robot, with obstacles such as pipes, machinery, and uneven surfaces that required the robot to navigate through hard-to-reach areas. The refinery's layout, comprising various production units, storage tanks, and processing facilities, also posed a complex environment for the robot to operate in. The presence of hazardous materials, such as flammable gases and chemicals, justifies the adoption of an efficient inspection process and the Sarlux's desire to continuous improvement and research of innovative technologies.
The refinery's remote monitoring systems, which were already in place, provided a foundation for the integration of the legged robot's advanced analytical capabilities, enabling the robot to conduct comprehensive inspections and provide real-time insights on machine health, operational efficiency, and potential safety hazards.

2.2 *Sarlux refinery*

Sarlux facilities are located at about 22 km south-west of Cagliari in Sarroch, Sardinia, Italy. Sarlux Refinery is a refinery in Europe with a crude oil processing capacity of 300,000 barrels per day. It is integrated with IGCC power plant (capacity 575MW) and Sarlux North Plant Petrochemicals facilities. This high complex Refining and Power site has a combined Nelson Complexity Index of 10.1. The Refinery and the North Plant are further integrated with Sasol Sarroch Italy plant. All the heavy fuel oil for the IGCC power plant for its gasification units to produce power is supplied from the Refinery. Sarlux Refining, Power and North Plant are 100% owned by Sarlux (subsidiary company of Saras).
The Refinery has 3 Topping Units, 2 Vacuum Units, 2 Mild Hydrocracking Units, a Fluidised Catalytic Cracking Unit, an HF Alkylation Unit, hydrotreating & desulphurization Units, etc. Hydrogen is supplied from three sources; CCR unit, IGCC Plant and the North Plant.
The mission was conducted in the Topping 1 area, where the process of Atmospheric Distillation, commonly referred to as "Topping," takes place. This initial stage of crude oil processing involves breaking down the crude into various fractions based on their boiling temperatures. The process utilizes a fractionation column, which operates at pressures close to ambient levels (approximately 1 bar relative pressure).

Fractionation columns exploit the fact that the boiling temperatures of liquids on the trays increase from top to bottom. Each tray allows for the extraction of specific fractions—such as gasoline, kerosene, and diesel—through lateral cut withdrawals. Typically, a topping column features 3 to 5 lateral cut withdrawals and 2 to 3 pump rounds.
In the demo, the focus was on the area associated with gas compressors sourced from the head of the Fractionation Column. Within the Topping 1 area, there are three compressors: two reciprocating and one centrifugal, along with all necessary auxiliary circuits.

2.2 Inspection Hardware

The robot considered is the ANYmal D legged robot developed by ANYbotics, Figure 2. Robot's datasheet reports the ability to climb stairs up to 45, a step height of less than 230 mm and a minimum run of 210 mm. The maximum walking speed is of 1.3 m/s. The robot size is 886 × 540 × 908 mm in a standing configuration meaning that it may require sufficient space to move around and perform tasks. It weighs about 56 kg and can carry a payload of 10 kg. Two onboard computers (CPU Intel core i7 8850H, 16 GB RAM and 240GB SSD) provide power for complex optimization and vision tasks, while a router is installed, enabling Wi-Fi communication.
The system is sealed against dust and water ingress (IP67) and the battery ensures about 2 hours of autonomous operation. Several sensors are available: a LIDAR unit (903 nm wavelength), a thermal camera (336 x 256 pixels), a zoom camera (20x ratio with 4k resolution at 30 FPS), a directional microphone (384 kHz at 16 bit), 6 depth cameras, and a spotlight [6].
The Baker Hughes team has expanded the capabilities of the robot by integrating the FLUKE SV600 and the OGI camera.
The FLUKE SV600 is an acoustic imager equipped with a 64-digital MEMS microphone array for the detection of gas leaks. This sensor was mechanically integrated onto the robot using a 3D printed support, while the electrical integration was accomplished through a POE injector connected to the robot 48v power port.
A motion amplification camera sensor is a type of imaging sensor that enhances the visual information it captures by amplifying the motion or vibration present in the scene. This can be particularly useful in applications where small movements or vibrations need to be detected and analyzed, such as in robotics, machine condition monitoring, or vibration analysis. The integration on a legged robot allows for more precise and sensitive inspections, enabling the robot to detect and respond to even the smallest movements or vibrations in its environment.
The motion amplification camera sensor has been integrated on a legged robot with a dedicated custom mount, that has been designed and prototyped. The mounting bracket is installed on the robot payload. This provides a high degree of dexterity, the sensor orientation, roll, pitch, yaw, can be controlled and programmed according to the desired inspection tasks. During the autonomous inspection carried out by the robot, the data acquired by the emission monitoring sensor are streamed and

integrated into the Baker Hughes robot fleet management and asset monitoring systems

Mapping and localization are performed by merging 3D point cloud information from the LIDAR sensor and depth camera. Employing an Iterative Closest Point (ICP) based localization method, the robot determines its current position and orientation with respect to a previously recorded map. A pose graph is used as a map representation to define where the robot can move within the 3D point cloud of the environment [5]. ANYbotics has developed a set of software packages for controlling the robot and defining the autonomous mission based on the Robot Operating System (ROS), version 1 (noetic). The software (release 23.04) is installed on an operator PC with Ubuntu 20.04 as operating system.

Fig. 2: ANYmal D Robot in standing mode in Sarlux plant

2.3 Planning of the work

Before starting the robotic inspections is most important pre-work to plan all the activities in the most effective, efficient, and safe way. Specifically, the collaboration has been characterized by the following preliminary phases:

- First an examination of the area of interest, performed manually by operators, to identify critical points for robotic navigations and inspections, assessing the feasibility of Sarlux requirements;
- All plant staff were informed of the presence of the robot on the site, to allow everyone to work in complete safety and in compliance with all Sarlux plant procedures;
- On a second phase, when all the machines have been identified properly, an analysis of the P&ID (Piping and Instrumentation Diagram) has been carried out by a team of technical experts, identifying in detail the single components that are susceptible to malfunctions and maintenance procedures;
- A 3d mapping of the environment is required for safe robotics autonomous navigation. A first scan has been performed by teleoperating the robot around

the environment and a second high resolution scan has been carried out with an industrial grade 3d scanner;
- Finally, the robotics missions have been conducted in coordination with Sarlux plant planning;

2.4 Execution of the Experiments

All the measurements were concentrated on the machines and the lubricant oil circuit, being part of the auxiliars circuit of the compression system
A total of 10 inspection points were defined, consisting of thermal, RGB, and auditive inspections Specifically, the inspection points included:

1. Oil Level Gauge visual inspection through an RGB camera
2. Oil Visual Level inspection through an RGB camera
3. Detection of the manual valve position through an RGB camera
4. Gas Exhaust vent inspection through an RGB camera
5. Heat exchangers inspection through a thermal camera
6. Steam tracing inspection through a thermal camera
7. Hot condenser circuits inspection through a thermal camera
8. Cylinder valve covers inspection through an acoustic inspection
9. Electrical motor inspection through a thermal camera
10. Gas Detection through an acoustic camera

As regards the testing of gas and liquid detection sensors, low pressure steam condensate discharge circuits were examined, to conduct measurements in compliance with all safety and environmental protection requirements.
All data was recorded, ready to be analyzed in the next phase of the work.

2.5 Data Analysis

Several missions were executed, and data were collected, marking the beginning of the second part of the pilot phase. This phase focused on training AI models to extract valuable insights from the mission results. By training computer vision (CV) and AI models, we developed algorithms that enabled the robot to analyze the collected data and provide actionable information for each inspection point. Specifically, we trained a plugin for each of the 10 inspection points defined earlier, allowing the robot to determine the level of the valve in the level gauge, the temperature of the motor, and identify any anomalies.
The trained plugins and the robot were then integrated into a comprehensive platform, enabling seamless data collection, analysis, and visualization. This integration marked a significant milestone in the pilot project, as it demonstrated the potential of autonomous inspection robots to enhance plant safety and efficiency. The integrated platform, which we will refer to as the "Robot Fleet Management System," is a Baker Hughes proprietary platform

designed to simplify and optimize the monitoring and inspection process in energy plants using a fleet of robots and sensors.
The system follows a plugin-oriented approach, where each functionality is implemented as a plugin that can be individually enabled and configured based on specific monitoring requirements.

3. Results

Our study yielded promising results, demonstrating the effectiveness of the autonomous legged robot in navigating complex industrial environments and enhancing plant safety.
The robot successfully traversed challenging terrains and accessed hard-to-reach areas, collecting and processing data from various sources, including gas detectors, vibration analysis sensors, and thermal imaging cameras.
The successful training of these AI models marked a significant milestone in the pilot project, demonstrating the potential of autonomous inspection robots to enhance plant safety and efficiency.
The motion amplification technology allowed for remote measurements to be integrated directly into the robot, enabling the definition of missions and data acquisition on all axes, and the flexibility of measurement points and visualization was a key feature of the system, allowing for adaptation to specific inspection needs
Figure 3 shows the result of the vibration analysis, obtained after applying motion amplification algorithms on the area shown. As can be seen the frequency of the reciprocating compressor (10 Hz) is correctly captured.
The integration of the robotic system with different inspection sensors and the development of custom algorithms for specific inspection tasks also proved to be effective, highlighting the potential for this technology to transform plant inspection and maintenance practices across the energy industry and beyond. The integration of the FLUKE system for gas quantification is ongoing, with a low technology level (TRL) for this project, and the development of custom algorithms for specific inspection tasks was effective, highlighting the potential for this technology to integrate and optimize plant inspection and maintenance practices. Figure 4 reports to a measured water steam from a purge (being part to a low-pressure water steam condensate circuit) during inspections, showing the effectiveness of the autonomous inspection capabilities.

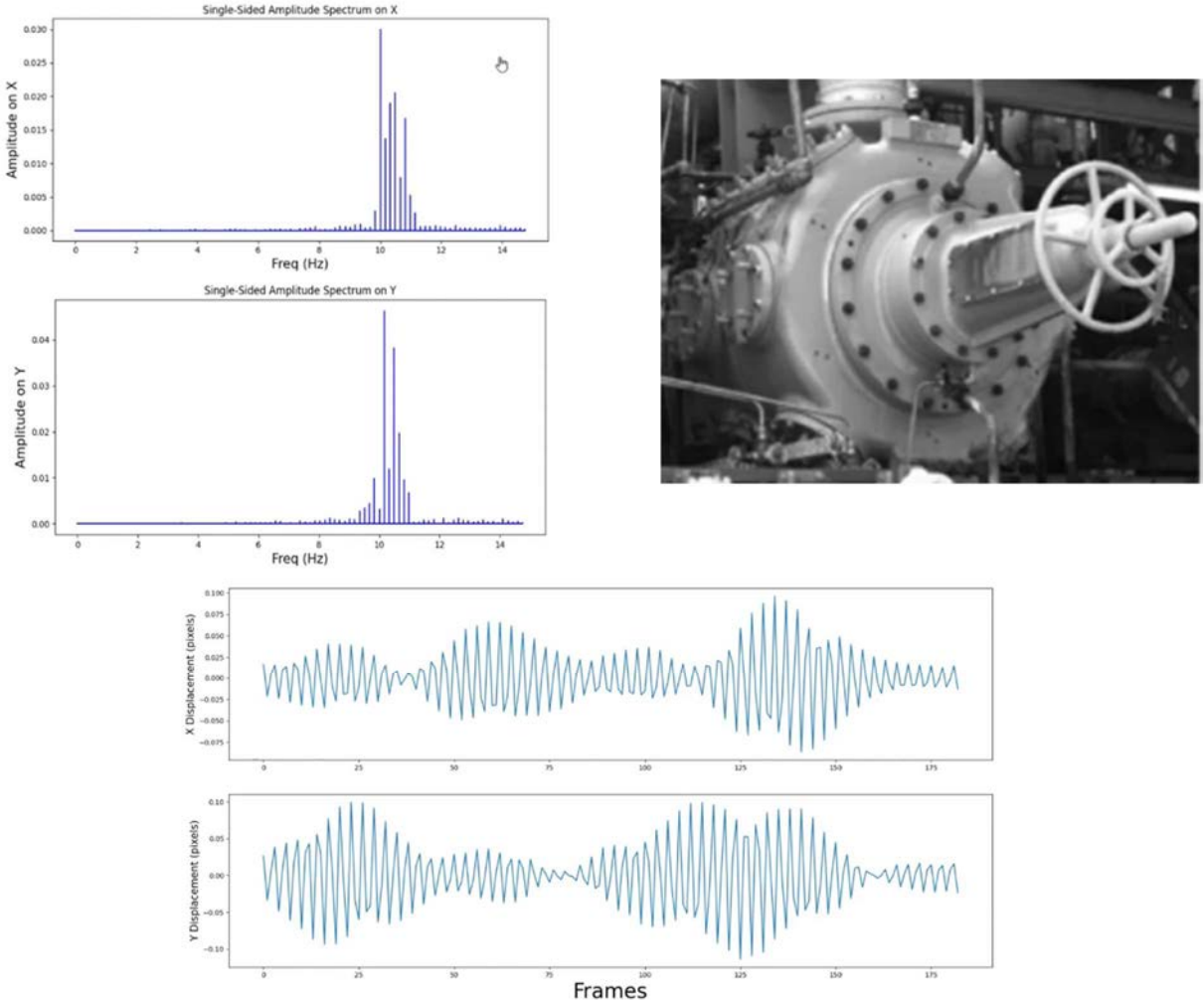

Fig. 3: The top-left figures show the vibration frequencies measured during acquisition of the area shown (top-right figure). Bottom plots show the vibration displacement in x-y coordinates (in camera reference frame).

Fig. 4: Figure shows the acquisition of a Fluke sensor integrated on the robot, capturing a low pressure water steam

Real-time data analysis enabled immediate identification of potential issues, facilitating proactive maintenance, and reducing the risk of equipment failure. The reduction in human exposure to hazardous environments can lead to enhanced overall safety for plant personnel.

4 Conclusions and future work

The successful deployment of the autonomous legged robot in the Sarlux refinery has marked a significant milestone in the development of this technology. The robot's ability to navigate complex environments, collect and process data, and provide actionable insights has demonstrated its potential to enhance plant safety and efficiency. The integration of the robotic system with existing plant management systems and data analytics platforms will be crucial in scaling up the technology to accommodate larger industrial facilities and more complex inspection tasks.

The primary objective of this project was to evaluate the feasibility and effectiveness of adopting autonomous inspection robots at the refinery site, specifically focusing on the T1 zone where two operational compressors produced by Baker Hughes are located. The robotic inspection system can validate the data acquired by iCenter and expand its capabilities by inspecting elements not covered by existing smart sensors. Additionally, the project scope included the development of a comprehensive data management system that enables the robot to collect, process, and store data from inspection points while providing real-time feedback to operators.

Future work will focus on improving the robot's navigation and mapping capabilities, enabling it to efficiently navigate complex environments and create accurate maps of the facility. Additionally, we will work on seamlessly integrating the robotic system with existing plant management systems and data analytics platforms, as well as developing custom algorithms for specific inspection tasks and integrating them with the robotic system.

Furthermore, we will expand the robot's sensor capabilities by integrating additional sensors and technologies to enhance its inspection capabilities. This may include the integration of advanced sensors, such as gas detectors and vibration sensors, to enable the robot to detect and classify anomalies in real-time.

We will deploy the robotic system in real-world industrial settings to further test and refine its capabilities and conduct thorough cost-benefit analyses to evaluate the economic viability of the technology in various industrial settings. In the future, Baker Hughes is planning to integrate the robotic system with the iCenter, the advanced data analytics platform, to provide a comprehensive and seamless solution for plant operators. This integration will enable real-time data analysis, predictive maintenance, and improved decision-making, further enhancing the value proposition of the robotic inspection system.

The successful development and deployment of this technology has the potential to revolutionize the way plant inspections are conducted, enabling plant operators to

identify potential issues before they become major problems. By reducing the risk of equipment failure and improving plant safety, this technology has the potential to save lives and reduce the economic costs associated with plant downtime. We believe that this technology has the potential to transform the energy industry and beyond, and we look forward to continuing to develop and deploy this technology in the future.

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Cobots: making friends with the ‘monster’ machines

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Abstract:
In modern manufacturing there has been a change from traditional industrial robots to co-operative robots, collaborative robots (Cobots) and Automated Guided Vehicles (AGVs). These new machines interface closely with workers without the conventional machine guarding.
Traditional machine safeguarding and previous types of risk assessment techniques are no longer applicable.
Horror movies and the media sometimes portray these new robots as ‘monsters’ who are seeking to attack and control humans. In the workplace, these machines can assist in reducing the physical burden of manual tasks on workers and advantage the business by allowing more efficient production.
Health, Safety and Environment managers and teams need to keep informed about new technologies, the benefits and risks, so that they may facilitate the safe introduction of innovative equipment.

Manufacturing businesses need new approaches from design, procurement, commissioning and assessment in the working environment. Of course, the safety team has a critical role to re-invent existing safety procedures to fit the modern manufacturing equipment.

International standards provide clear guidance and testing methods to ensure safety of people working with cobots and new robots. The author will explain how to integrate these safety standards into existing safety management systems to achieve safety for workers.

Andrea and her team have worked with global manufacturers including GlaxoSmithKline (GSK), Pfizer and Toyota Motor Corporation Australia.

1 Introduction

Traditionally, robots have been installed behind safety fences with elaborate interlock devices and procedures for entry to keep people separate and safe.
However, changes in automation of industrial processes are continuing at an increasing rate. The recent rush to perfect; driverless cars, trucks, planes and trains is an example.

These automated (robot) machines in factories can be broadly categorized as below:

- Industrial robots (traditional).
- Automated guided vehicles (AGVs) which are restricted to set pathways.
- Co-operative robots which do not share space or time with people.
- Collaborative robots (cobots) where people and robots may work in the same space at the same time.

Progressive companies that pursue continuous improvement and efficiency are increasingly introducing more automated processes.

Each jurisdiction has their own laws for safety of machinery, but to ensure common high standards for cobots and Automated Guided Vehicle (AGV) businesses should apply best practice standards for installation and operation of new automated equipment.

The objective of this paper is to familiarise participants with the key safety standards for the Design, Procurement, Commissioning, Operation and maintenance and modification of cobots and AGVs.

2 Background

The term “Zero Access” is considered the physical guarding concept of first intent for machinery. This means to prevent human body parts such as arms or fingers from touching harmful parts. Of course, this is not possible or appropriate for cobots and AGVs.

Therefore, businesses must ensure high levels of safety by alternate means for cobots and AGVs. This is usually achieved using safety-rated sensors and control systems and or limited force and speed of movement.

Futuristic Images of Robots

Science fiction has created many scary machines and frightening future-world scenarios involving disobedient or secretive robots, or more likely malevolent controllers.

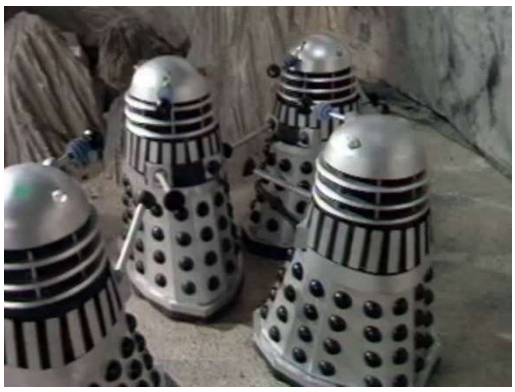

Fig. 1: Image from early science fiction TV series, Dr Who (1974).

Humorous History of Robots

Back in 1942 the famous science fiction author Isaac Asimov created the three laws of robotics in order:

1) Don’t harm humans;
2) Obey orders; and
3) Protect yourself [1].

Asimov explained the order of these laws is important because a robot protecting itself must only do this after complying with the first two laws.
Another author, Osamu Tezuka, formulated an expanded set of ten (10) principles for robots for his 1988 series Astro Boy. I particularly liked a couple of the new rules including:

a) Robots shall not leave the country without a permit; and
b) Robots must not alter or conceal their identity [2].

Clearly, the Astro Boy robots were expected to be very advanced and able to operate independently.

Evolving Technology

A speaker on a radio science program recently made the comment that cockroaches are more intelligent than our current breed of robots.
He said current robots are so stupid that if you placed one in the forest it would quickly get lost, fall over and die. Whereas a cockroach would scurry for cover, forage for food and thrive.
The science program speaker explained our goal is to first develop robots as smart as cockroaches, then rats, and then dogs. But they are cautioned to develop robots as smart as monkeys because monkeys know they are not human and are likely to disobey us.
However, technology is changing fast. Up until now all industrial robots were fully isolated in the workplace with extensive guarding and fencing with complex interlock procedures to enter robot compounds.
These old-fashioned robots typically performed tasks which were too heavy or dangerous for humans.

Fig. 2: Traditional style of robot “locked” in a fenced compound, Kuka.

Collaborative Robots

Many progressive companies are now introducing collaborative robots (cobots) to perform intricate and repetitive tasks alongside human workers.

Fig. 3: Human and the YuMi® collaborative robot, working together without cage or fence.

These robots often have superior; “eye-sight”, dexterity, patience and infallible accuracy and reliability. All the things us normal humans do not have.
Therefore, cobots will increasingly be seen working alongside us, and possibly as our quality supervisor in future generations.
Collaborative robots working side-by-side with people must have specialized risk assessments and multiple levels of presence sensing and power limiting devices to minimize the risk of harm for the people in their vicinity.

Key safety principles for cobots

Below is a table which provides an overview of the primary safety systems for normal operation and for various types of machinery interventions, including for cobots and AGVs.

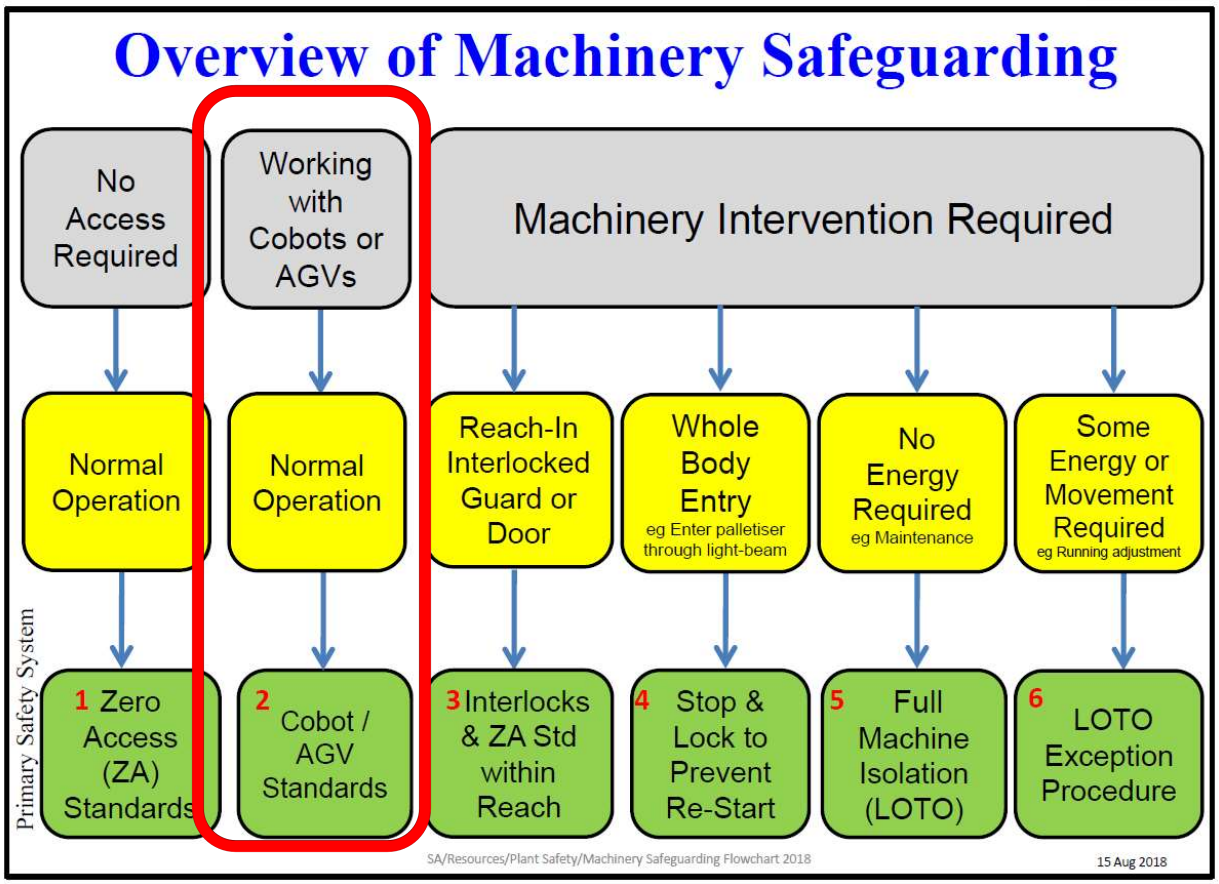

Fig. 4: Overview of machinery safeguarding, Safety Action Pty Ltd. The primary safety system for cobots and AGV is outlined in red.

Note that safety control measures for item 4 'Stop & Lock to Prevent Re-Start' is not complete machine isolation or lock-out tag-out (LOTO), as required by many company policy but may be an agreed local procedure for machine. For example, an operator placing personal lock on eye beam to prevent re-set and starting while in palletising robot for brief intervention.
Key Safety Principles for Cobots & AGVs

1. Sensors are to detect personnel or obstructions in the collaborative workspace.
2. Stop automatically within sensor range, or inherently safe e.g. force and speed limited.
3. Emergency stop button readily accessible for people in vicinity.
4. Use restricted to trained and authorised personnel e.g. access by key or PIN.

5. Can only switch to non-collaborative mode when sensors confirm no person is in the collaborative workspace.
6. All control systems and safety devices are safety-rated e.g. PL”d” (Cat.3).
7. Awareness briefings provided to all personnel in proximity including visitors.
8. Only one source of control can command a cobot or AGV at any one-time e.g. operator control panel or remote control.

Remember, Cobots and AGVs can move suddenly unless under manual control or correctly shut down and isolated with Lock-out and Tag-out (LOTO).
Some advice for cobots & AGV safety:

a. Operators are only to conduct tasks for which they are trained and covered by documented operating procedures.
b. Only trained and authorised personnel are to conduct maintenance or repairs.
c. Establish a documentation file for each cobot / AGV, with clear responsibility for maintaining it and storage location.
d. Select a competent integrator ideally at design stage.
e. Confirm general work area suitable for cobot/AGV use.
f. Cobot collaborative workspace to be clearly marked eg line marking.
g. AGV routes to be clearly marked, particularly at busy intersections.
h. All controls to be clearly labelled.
i. Danger zone marked and safety controls in place for AGV load pick-up or drop-off points where sensors turn off to dock.
j. Emergency stop devices to be at least PL”d” (old Cat.3).
k. AGVs are to be capable of detecting specified “test pieces” placed in their path.

3 Control Systems & Safety Devices

Cobots and AGVs operate near people and therefore the control systems and safety devices need to be highly reliable with fail-safe design.
Alternatively, cobots and AGVs can be inherently safe by design. For example, cobots can be designed to be force and speed limited where people can manually stop movement or not be harmed or trapped by accidental contact.
However, it is more difficult for AGVs to be force limited due to the loads they typically need to carry. Therefore, AGVs have some different safety requirements including ability to stop safely without load tipping over, and separate precautions for pick-up and drop-off points where the personnel sensors need to be turned off to dock the AGV.

The key principles for safety-related control systems include:
- No single fault can cause loss of safety function.

- Single or foreseeable faults are detected by the system at or before next demand.
- Stop function stops all movement before striking a person/obstruction in path and cuts power to actuators.
- Emergency stops and safety-rated sensor devices to typically be at least PL”d” (previously called Cat.3 level).
- Cobots to have hard-stops or safety-rated soft axis movement limitation.
- Any fault of the Safety Rated Monitored Stop (SRMS) stop function to result in a category 0 stop. For example uncontrolled stop with immediate removal of power to actuators.
- Pendants and enabling devices to have an emergency stop button.
- SRMS always active when an operator is in the co-workspace.
- AGVs capable of detecting personnel in path and safely stopping within range of sensor and without causing load to overturn.
- AGV may start automatically after a minimum of 2 second delay from when a person steps out of its path.
- AGV to sound audible warning for at least 2 seconds before starting and operate in speed-limited mode (e.g. max. 0.3m/s) for at least 5 seconds.
- AGVs to have stop buttons readily accessible on each side, including when load over-hang.
- AGV to emit distinctive audible warning signal when moving with personnel detectors off e.g. docking at pick-up or drop-off point or charging station.
- AGV brakes to:

a) Hold vehicle at maximum gradient and load;
b) Maintain stability of AGV and load including during emergency braking.
a) Activate if power interrupted; and
b) Activate automatically if AGV loses control of speed or steering.

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7 Images

Figure 1: Dr Who robots
https://m.imdb.com/title/tt0811228/mediaviewer/rm1932806656/
Figure 2: Kuka industrial robot https://www.kuka.com/en-my/products/robotics-systems/ready2_solutions/kuka-ready2_rivet
Figure 3: YuMi® photo gallery
https://new.abb.com/products/robotics/robots/collaborative-robots/yumi/dual-arm

UAV-Based Overturning And Collision Risk Assessment Of Ground Vehicles: An Overview

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Abstract

The use of unmanned aerial vehicles (UAVs) has significantly transformed workplace safety practices, offering efficient and cost-effective solutions for monitoring and inspection. This review examines the diverse applications of drones across industrial settings, focusing on their role in assessing risks related to ground vehicle overturning and collision. UAVs equipped with RGB cameras, LiDAR sensors, thermal, and multispectral imaging technologies have proven highly versatile in capturing high-resolution data. This capability enables both visual monitoring and structural assessments, ultimately improving safety by analysing ground stability, terrain slopes, and potential geotechnical hazards that could lead to vehicle accidents. The review classifies drone applications into three main categories: visual monitoring and inspection, image-based analysis, and artificial intelligence (AI)-powered image processing. These applications span industries such as construction, infrastructure maintenance, and environmental monitoring, where drones provide actionable insights to identify risks and ensure safety compliance. A key factor in drone efficacy is proper flight planning, which ensures adequate coverage, optimal resolution, and efficient data collection for subsequent analysis. Emerging trends, such as AI integration, are driving advancements in automated hazard detection, decision-making, and predictive analytics, reducing reliance on manual processes and improving safety outcomes. This study underscores the growing role of drones in workplace safety and highlights the potential for interdisciplinary innovations to expand their capabilities and address evolving industrial safety challenges.

1 Introduction

The adoption of drones (UAV) has enabled terrain mapping and environmental monitoring using cameras and LiDAR at a fraction of the cost of airplane-based services or satellite imagery. Additionally, drones' ability to operate at lower altitudes ensures higher-resolution data capture, which is critical for detailed analyses. These advancements have allowed the possibilities for both research institutions and businesses to utilise drones in various sectors, including construction, infrastructure inspections, and industrial operations. Among the most prominent applications are video and image capture and terrain stability assessments [1].

The integration of high-resolution cameras, thermal cameras, multispectral cameras, stereoscopic (also known as depth) cameras, and LiDAR sensors expands the versatility of drones, offering a wide range of low-cost and highly flexible possibilities that can also be employed for safety purposes in many different types of workplaces. These tools

also can help in enhancing the situational awareness of workers, reduce risks, and provide actionable information for any kind of ground operations in real time.
This study aims to explore the use of drones in workplace safety, particularly in monitoring and inspecting infrastructure. The research identifies key technological and methodological trends, emphasizing their implications for improving safety standards.

2 Materials and Methods

2.1 Bibliographic research

To identify the state of the art regarding the use of drones for workplace safety, a bibliographic search was conducted on Scopus Database, focusing on studies published between 2014 and 2025. The following query was used:

Logic	Keyword
	((road OR bridge OR environment) AND safety AND (uav OR uas)
AND NOT	(crop OR food OR energy OR cell* OR reliability OR flight OR aircraft OR aviation OR antenna* OR planning OR disaster OR security OR pressur*)
LIMIT-TO: publication year	From 2014 to 2025
LIMIT-TO: subject area	Engineering OR Computer Engineering OR Agriculture
LIMIT-TO: Document type	Articles
LIMIT-TO: language	English

Table 1 - Scopus search parameters

The database query aimed to isolate studies focusing on drones in safety-related applications, particularly in construction sites, engineering applications or agricultural applications while avoiding at the same time other sectors or misleading subjects. These exclusions were necessary to filter works that were related to research topics within the scope of the subject areas fields but not fit for the purpose of this review: these cases are, for instance, energy management, flight planning, aviation reliability, crop protection, food supply chain or disaster management. The Scopus search returned 11 relevant research works which have consequently been analysed to classify their approaches into three macro-categories that consider the purpose of the activities and the technologies that have been exploited:

- **Visual Monitoring and Inspection**: Using drones equipped with RGB cameras to provide real-time or recorded visual data.
- **Image-Based Analysis**: Utilizing drones to collect data for post-processing, including crack detection and terrain modelling.

- **AI-Powered Image Analysis**: Employing machine learning algorithms and neural networks to identify hazards, such as unstable terrain or water accumulation, in work sites.

The studies were further evaluated based on the technologies employed, flight planning strategies, and data analysis methods. This systematic approach provided a comprehensive overview of the applications and their potential for improving safety, with the purpose of exploring the possible benefits related to the use of Digital Elevation Models (DEMs) and Digital Terrain Models (DTMs) to enhance any existing capabilities for map-based risk analysis. These models, in fact, provide detailed representations of terrain geometry, making them critical for assessing slopes, elevations, and potential geotechnical hazards in construction sites and other industrial areas. The bibliographic research was therefore oriented to understand if the reliance on these geospatial tools would improve the accuracy of risk detection methods and terrain stability analyses.

2.2 Digital Elevation and Terrain Models

Beyond the use of RGB cameras and LiDAR, Digital Elevation Models (DEMs) and Digital Terrain Models (DTMs) have emerged as essential tools in geospatial data analysis: their use is often combined with UAVs or any sort of UAV-collected data. These models, being based images that have pixel size in the range of few square centimetres, offer high-resolution terrain representations that are critical for understanding elevation changes and slope dynamics. Such models can be generated using photogrammetry or LiDAR technology, providing detailed insights or indexes that can be used in geotechnical analyses that may be eventually used as bas for safety assessments.

DEMs and DTMs have proven particularly valuable for assessing terrain stability and identifying risks associated with uneven surfaces, such as landslides, erosion, and slope failures. Authors intended to analyse their possible integration in studies focusing on UAV applications in construction and environmental monitoring, where their integration allowed for precise hazard mapping.

3 Results

The bibliographic search identified 11 studies showcasing different approaches to drone technology and its applications in post-processing, particularly in enhancing workplace safety and safety management tasks. These studies reveal three main lines of application, that can be listed as: visual real-time monitoring, image-based analyses, and advanced AI-powered image processing (both real-time and post-processing analyses). Among these research works, four articles have been further selected for a systematic methodology comparison and therefore their hardware, software and settings benchmarks are shown in Table 2.

Application field	SW Technologies	IA (typology)	Output
Crawler crane overturning [2]	Photogrammetry, detection	YES (3) Swin transformer, ResNet, HrNET, RegNet	Discrete risk map, 4 zones
Detection of crack [3]	Edge detection from grayscale	No	Length of crack on bridge
Construction safety inspection, hazard detection, accident prevention, and construction management [4]	Data processing of collected visual assets, creating a database of images and safety compliance indicators	No	Visual compliance regarding safety compliance
Environmental monitoring [5]	Inverse Ant Colony Optimization (IACO)	Yes, path optimization	maximize the area explored by UAVs

Table 2 - Comparison of methodologies employed by main research studies in the topic

A significant portion of the research highlights the use of drones for visual monitoring and safety assessment, particularly in construction sites. Equipped with RGB cameras, drones provide a practical, low-cost solution for conducting inspections of work environments. They enable the identification of abnormal and unsafe conditions, collision hazards against objects and obstacles, or other risks that might compromise safety in general and safety compliance to regulations. Observers can analyse footage either in real-time or after the drone's flight, facilitating proactive management of workplace hazards. This approach has proven particularly effective in construction sites, where studies have demonstrated how drone inspections can prevent accidents, optimize risk detection, and improve workflow management [4]. While most attention has been focused on construction, drones are also deployed in other contexts, such as airports [6] and railways [7], where they help detect foreign objects, obstructions, or damages.

For image-based analysis, drones are employed to collect data that undergoes advanced processing to extract detailed information about the monitored environment. This category includes applications such as structural monitoring [8] [9], where drones inspect infrastructure for potential defects. For instance, research has demonstrated the ability to identify cracks and fissures in bridges using grayscale images. By detecting sudden changes in pixel intensity, the images can reveal areas of structural weakness and even measure the dimensions of these cracks with precision [3]. In addition to structural monitoring, drone data can be used to assess terrain

stability and identify geological risks [1]. The combination of RGB and LiDAR data allows for the creation of orthophotos and digital terrain models, which offer a comprehensive view of the site. While this is not always the primary objective, such models are a valuable addition in geotechnical studies, enabling detailed analysis of terrain or infrastructure irregularities [10]. In the reported studies the use of LiDAR and photogrammetric data would enable comprehensive assessments of harsh terrain conditions and slopes, enhancing traditional image processing tools with geospatial parameters that help determine critical parameters for hazard detection.

Finally, drones have been paired with artificial intelligence (AI) to perform automated image analysis, offering a cutting-edge approach to workplace safety [11]. In this context, neural networks and machine learning algorithms have been used to detect hazards and risky areas directly from the images captured by drones. For example, orthophotos of construction sites can be processed to identify unstable soil, excavations, or water accumulation, factors that could compromise the stability of heavy equipment such as cranes [2]. By automating these processes, AI-based systems reduce the risk of human error, enhance detection accuracy, and enable faster decision-making, significantly improving safety in complex environments. Integrating DEM and DTM data into AI-powered risk assessment workflows would enhance the decision-making processes: for instance, Machine Learning (ML) algorithms trained on geospatial datasets that include terrain models could easily predict unstable areas and assess risks linked to specific elevation profiles or gradients.

UAV-based research works display versatile tools for capturing high-resolution data essential for safety assessments, but since these are based on orthophotos their possible success in applications related to safety relies on a combination of appropriate flight planning, sensor configuration, and data analysis methods. These factors would ensure the collection of accurate, high-quality data that can be utilised to monitor risks, optimize safety measures, and improve compliance standards in industries such as construction and infrastructure maintenance. Other configurations should also include payload analyses, but in the systematic review no significant differences have been detected in such aspects.

Further analyses and benchmarks have therefore been conducted by authors on the hardware configuration of the UAVs and their flight plans, together with camera specifications and any other useful setting that can represent the specifics according to the expected outcome and on the specific focus of each research activities that employed them. The results of this hardware benchmark are shown in the following table 3.

Research focus	**Outcome**	**Camera and UAV settings**
Research developed a crawler crane overturning prevention method using Swin Transformer and UAV images to detect dangerous zones and create a driver safety risk map.	Mean Average Precision values for bbox and segmentation: “Detection” (bboxAP, segmAP) "Unhardened" (0.968, 0.973). "Pit" (0.814, 0.814) "Water" (0.669, 0.632)	Flight height 70m FOV 84° Aspect ratio 3:2 Resolution 3648*5472
Evaluation of cracks and fissures with the use of a UAV provided length and thickness parameters	The Wilcoxon test showed no significant differences between ImageJ and field measurements for crack thickness and length, confirming accuracy (p-Values 0,355 for thickness and 0,861 for length).	28 mm focal length, Resolution 5472*3648, shutter time 1/8000, 0,735 mm/pixels
Application of UAS for safety inspection on construction sites, focusing on visual asset collection (photos, videos) to monitor and analyze safety compliance	Missed inspections ranged from 8% to 27%, with highest values in building sites with less safety management processes	camera 12.76 MP, Resolution: 4000×3000, Flight height 60m
Use of UAV swarms equipped with built-in sensors like GNSS, accelerometers, and microphones for data acquisition.	99% exploration coverage	Any (urban)

Table 3 - UAV configurations and outcomes

4 Conclusions

The application of drones in workplace safety spans diverse working environments and emerging technologies are rapidly making them vital tools across industries. Among the sensors employed, RGB cameras remain the most commonly used due to their ability to capture high-resolution images at a relatively low cost. However, there is an increasing reliance on specialized sensors such as LiDAR for specific applications, including terrain modeling and slope monitoring.

A critical factor in successful drone operations is flight planning, which ensures adequate coverage and appropriate Ground Sampling Distance (GSD) based on the distance between the drone and the target. Accurate planning is essential to meet the desired resolution and to optimize data quality for subsequent analyses. The incorporation of Digital Elevation Models (DEMs) and Digital Terrain Models (DTMs) into UAV-based safety assessments represents a significant advancement, contributing to more accurate terrain evaluations and enhancing risk analysis for vehicle overturning. Research related to collision avoidance systems based on UAVs is, however, still limited to the analysis of field background with little or no assessment of dynamic obstacles or interferences among field activities.

Future research should further explore the integration of geospatial tools with AI-driven systems or sensors with embedded AI to develop predictive models for hazard identification and accident prevention, including collision avoidance. Real-time operations, autonomous supervision capabilities, and predictive analytics are consequently expected to be the primary focus of future UAV safety applications related to purposes such as limiting interferences and providing predictive information for accident prevention.

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Occupational back-support exoskeleton development: a 5-year journey

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Abstract
Manual labor is still strongly present in many industrial contexts (such as logistics), involving onerous tasks and non-ergonomic working conditions. Work-related musculoskeletal disorders are indeed still a major problem. In particular, the lower back is one of the most affected human body regions. We propose a 3D-printed occupational back-support exoskeleton with backbone-inspired kinematics to solve such an issue. Such a design results in a personalized and transparent exoskeleton. To assist the operator, two versions of the exoskeleton are proposed: a passive exoskeleton and an active exoskeleton. While the passive version assists with elastic elements storing energy and releasing it to relieve the back from the lifted load, the active version adopts motors to actively assist the user. In the former case, a simple, reduced size and weight design is achieved. In the latter case, a machine learning-based control strategy is developed to assist the user in the lifting task, employing machine vision for the detection of the target objects, and enhancing the assistive performance of the device. Customizable gain tuning is also possible, employing, *e.g.*, human-in-the-loop or active preference learning methodologies for a personalized human-exoskeleton collaboration. In this paper, we provide a complete overview of our developments in the field in the last five years, pointing out the current and future directions for further developments and transfer of the proposed devices to the industry.

1 Introduction

In industrial settings, workers often perform physically demanding tasks that involve repetitive lifting, bending, and prolonged static postures [1-3], all of which can strain the musculoskeletal system. These strenuous activities are prevalent in sectors such as manufacturing, construction, and warehousing, where manual labor remains essential despite advancements in automation. Over time, repetitive loading of the spine and surrounding musculature places workers at a heightened risk for musculoskeletal disorders (MSDs), particularly in the lower back region [4]. These injuries are not only debilitating for the workers themselves, often leading to chronic

pain and mobility issues, but they also impose significant economic burdens on employers and healthcare systems through increased medical costs, lost productivity, and worker compensation claims.

In response to these challenges, collaborative robots [5] and occupational exoskeletons [6] have been proposed. In particular, back support exoskeletons are emerging as a promising ergonomic solution to address lower back pain injury issues. By supporting the user's body mechanics, exoskeletons can help reduce the physical strain experienced during high-risk activities, alleviating the biomechanical loads on the lumbar region [7]. Studies have shown that properly designed exoskeletons can potentially reduce muscle fatigue and lower the incidence of work-related injuries, improving both worker safety and job satisfaction [8]. Furthermore, by enhancing ergonomic conditions, exoskeletons may contribute to a more sustainable workforce, as workers can maintain their physical health over a longer career span. However, while the potential benefits of back-support exoskeletons are significant, they also pose unique design and implementation challenges. Ensuring comfort, adaptability, and ease of use for a diverse range of body types and movement patterns is essential for successful adoption in workplaces. As research and development in exoskeleton technology advances, it is crucial to assess both the ergonomic benefits and practical limitations of these devices in real-world settings to optimize their impact on industrial occupational health.

This paper aims to provide an overview of the developments of our back-support exoskeleton in the last five years. The main design principle of our device is based on a 3D-printed occupational back-support exoskeleton with backbone-inspired kinematics. Such bio-inspired kinematics aims to implement a personalized and transparent mechanism, capable of following the natural motion of the human back (*i.e.*, enhancing transparency). This mechanism has been employed in two exoskeleton versions: pBLEX (passive Back-bone Low-back EXoskeleton) and aBLEX (active Back-bone Low-back EXoskeleton). While the passive version (pBLEX) assists with elastic elements (*i.e.*, storing energy and releasing it to relieve the back from the lifted load) and it is characterized by a simple, reduced size/weight design, the active version (aBLEX) adopts motors to actively assist the user and it is instead characterized by the possibility of employing advanced (*e.g.*, machine learning-based) control strategies to enhance and customize the active assistance of the user in the lifting/handling tasks. We provide a complete overview of our developments in the field in the last five years, pointing out the current and future directions for further developments and transfer of the proposed devices to the industry. The development timeline is shown in Figure 1, where four prototypes are highlighted: the first designed device, where we first proposed the backbone-based kinematics [9], the optimized passive device (in terms of weight, size, and structural performance) [10], the first design of the 3D-printed cycloidal actuator integrated with the active

exoskeleton [11], and the last version of the active exoskeleton equipped with a human-robot interaction controller [12].

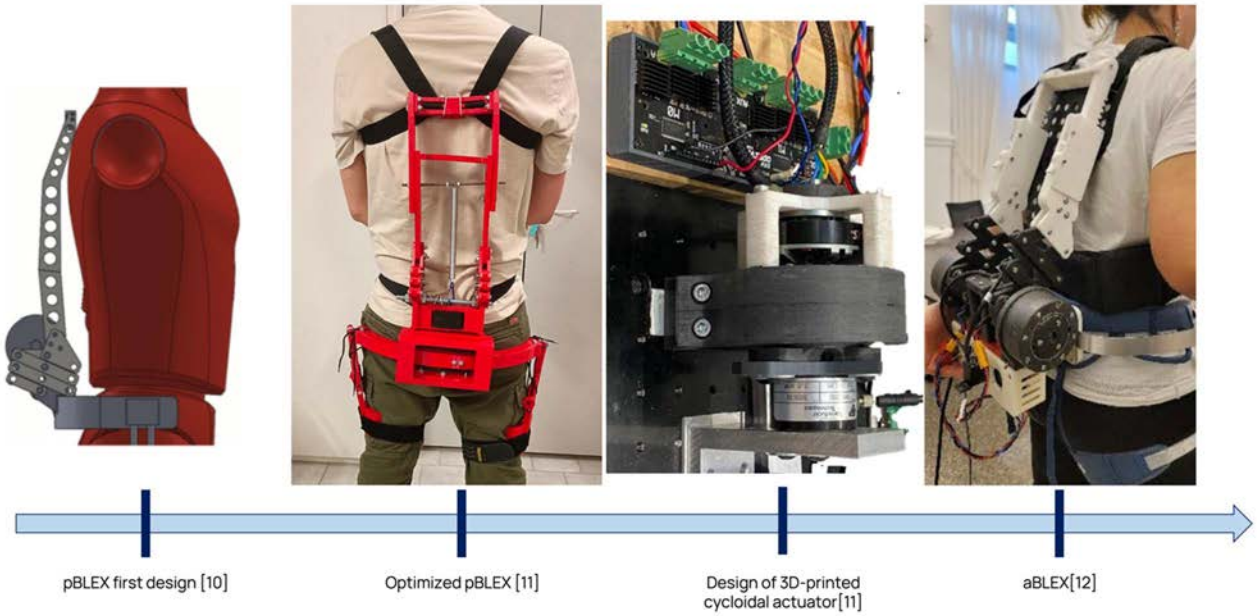

Fig. 1: development timeline for the backbone-based kinematics occupational exoskeletons.

The paper is organized as follows: Section 2 introduces the backbone-based kinematics of the exoskeletons, Section 3 delves into the developed passive devices, Section 4 describes the active exoskeleton, and Section 5 draws conclusions.

2 Backbone-Based Kinematics

The main feature of the proposed occupational exoskeletons developed in the last five years (both passive and active devices) is the employed backbone-based kinematics [9] (Figure 2). The exoskeleton kinematics has been designed to achieve transparency. To this end, the vertebrae motion has been modeled by acquiring the user motion data with the Vicon System, placing markers in the correspondence of each vertebra. The exoskeleton end-point (*i.e.*, connected to the user body) should indeed follow the reference vertebra motion (the T2 in our study).

Based on this modeling, a single-degree-of-freedom scissor hinge mechanism has been implemented for the exoskeleton kinematics. Such a mechanism (as shown in Figure 2) allows to follow the reference vertebra motion. To customize and optimize the device, the parameters of such a mechanism have been tuned to minimize the tracking error as in [9]. This approach is extremely interesting since it can accurately

describe the complex motion of the spine during relevant movement with a single parameter to be controlled.

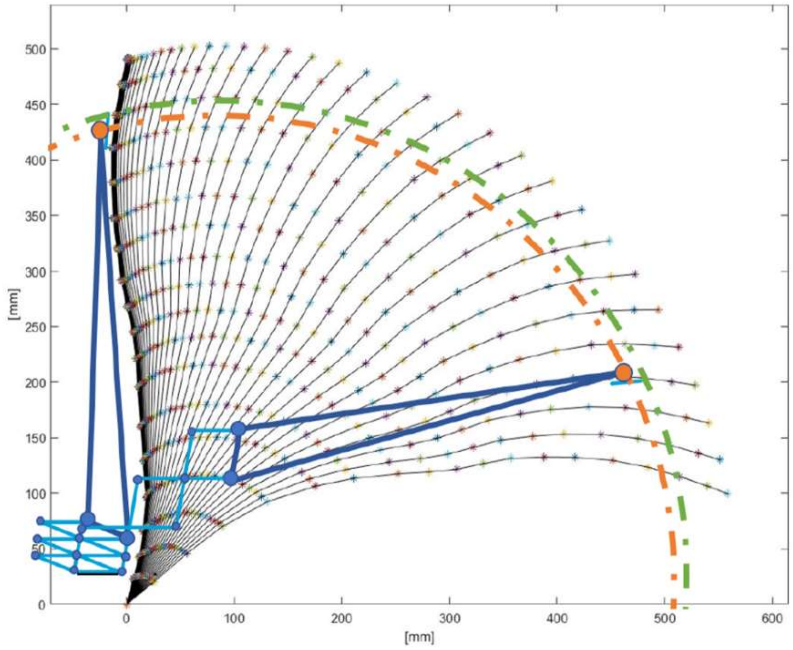

Fig. 2: Backbone-based exoskeleton kinematics [9].

3 Passive Exoskeleton (pBLEX)

Based on the backbone-based kinematics outlined in Section 2, a passive device has been designed – pBLEX –, optimized, and fabricated [10]. Such an exoskeleton is characterized by passive elements assisting the operators in the relevant movements such as bending, squatting, load lifting, etc. (Figure 3). The elastic elements store energy to be released when lifting objects. In such a way, the stored energy relieves the operator's muscles from the lifted load.

Fig.3: Passive exoskeleton with an elastic element(s) - *i.e.*, actuation spring - for energy storing/releasing [10].

The proposed exoskeleton has been preliminary tested [13] to evaluate its performance in assisting users in lifting tasks. In particular, we observed a decrease in the mean absolute value of muscle activity, including the erector spinae, during payload manipulation tasks, whole wearing pBLEX. This reduction occurred without compromising task performance, as measured by task time and joint range of motion.

4 Active Exoskeleton (aBLEX)

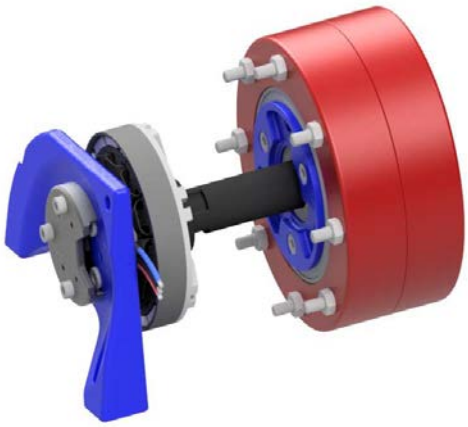

Fig. 4: 3D-printed cycloidal actuator [11].

The active exoskeleton – aBLEX – has been designed to be as lightweight as possible. For that reason, a 3D-printed cycloidal actuator (Figure 4) has been designed,

manufactured, and integrated into the active device [11]. Employing the same kinematics as the passive device, the active exoskeleton has been designed and fabricated [12] (Figure 5).

Fig. 5: Active exoskeleton [12].

Collaborative machine learning-based controllers are currently under development, starting from the interaction controller developed in [12]. Such a control framework implements i) a low-level optimal position control, ii) an external torque observer (to estimate the interaction between the human and the exoskeleton), iii) an admittance controller, and iv) a human-in-the-loop approach for the optimization of the control gains. Machine learning-based approaches use machine vision to detect packages to be lifted, operating the exoskeleton accordingly for the lifting task execution [14, 15]. The human-robot interaction dynamics will be modeled using Neural Networks, and an MPC will be developed for online control optimization [16, 17]. Preference-based optimization [18] will also be employed to implement a user-centered control tuning methodology [19].

5 Conclusions

We have developed two prototypes – pBLEX and aBLEX –, both based on a backbone 1DOF mechanism to support the user during potentially dangerous movements. We think that both solutions have advantages and disadvantages, and we are currently testing both with end-users in relevant environments, with encouraging results. Besides testing, which is aimed both at validating the concept and collecting feedback to drive future developments, we are working on two improvements. In particular, the scissor hinge mechanism has quite a relevant friction when moved, and we are

planning to design a different mechanism that can track the same measured kinematics. Secondly, we plan to include a bio-inspired module, which aims to support posture more than muscles. With this back-support exoskeleton, we aim to provide a useful device to the manufacturing and logistic sectors (e.g., for manual handling tasks), improving the working conditions of the workers and their quality of life.

6 References

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Robotics in pressure equipment inspection: a review towards full autonomy

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Abstract
Monitoring pressurised equipment presents significant safety challenges due to hazardous fluids and complex access requirements. Traditional inspection methods often lead to delays and pose risks to personnel. This paper reviews ca.100 studies on inspection technologies, particularly robotics, from 1989 to 2024, highlighting their advantages over direct visual inspection, such as reduced reliance on highly skilled operators and shorter inspection times. Despite their promise, automated systems face limited adoption due to a lack of standardized regulations. This review critically evaluates advancements in robotic systems and deep learning for surface defect detection, exploring key areas like image-based inspection and infrared thermography. It identifies challenges, including the need for large training datasets and environmental constraints. This paper concludes by outlining autonomous robotic platforms enhanced with Cognitive Mechatronics and AI, integrated with advanced measurement tools and Virtual Reality. These innovations promise to enhance inspection precision, reduce operator risk, and improve overall safety and efficiency.

1. Introduction

The inspection and maintenance of pressure equipment—often installed in challenging environments and containing toxic or hazardous fluids—pose significant technical and safety challenges. These tasks frequently require specialized cleaning processes to prepare the equipment for inspection, adding complexity and operational risks. Personnel conducting visual inspections face hazards arising from both the inherent dangers of the equipment and the constrained environments in which they operate. To mitigate these risks, strict adherence to legal and regulatory safety requirements is essential. The adoption of automated robotic systems, capable of remote operation and equipped with advanced inspection technologies, offers a promising avenue for enhancing safety and reducing the likelihood of accidents. Verifying the integrity of pressure equipment typically involves internal and external visual examinations, often supplemented by ultrasonic thickness measurements. Additional inspections may be necessary if visible damage is identified during initial

assessments. Visual inspections are classified as direct, conducted without intermediate tools between the operator's eye and the equipment, or remote, employing technologies such as photography, video recordings, or automated systems integrating image processing.

Despite their potential, the use of robotic and automated systems for visual inspections of pressure equipment remains limited. Regulation and adoption of these technologies are still in their infancy. Current applications primarily involve drones equipped with high-definition and thermal imaging cameras, which are generally restricted to inspecting externally accessible components. Challenges in accessing internal structures—due to narrow openings, non-removable obstacles such as pipes and coils, and complex geometries—hinder broader implementation. The inspection process is a critical precursor to the maintenance of pressurized equipment, yet it presents substantial safety challenges. Hazardous fluids and complex access requirements often necessitate extensive remediation, leading to delays and increased risk exposure for personnel. Robotic systems, with their potential to address these issues, represent a vital area for further research and development

This paper reviews 90 key studies on inspection technologies (robotics in particular) for pressure equipment from 1989 to 2024, highlighting the advantages compared to the inherent limitations of direct visual inspection, such as the need for highly skilled operators, prolonged inspection times – economically impacting the activity with extended downtimes-, and significant safety hazards.

Despite the potential of automated systems, their adoption remains limited, primarily due to the lack of standardized regulations that define the minimum requirements that automated systems must satisfy to ensure the correct detection of discontinuities of interest. However, advancements in robotic systems, visual sensors, and automation hold considerable promise.

1.1 Scope of the review

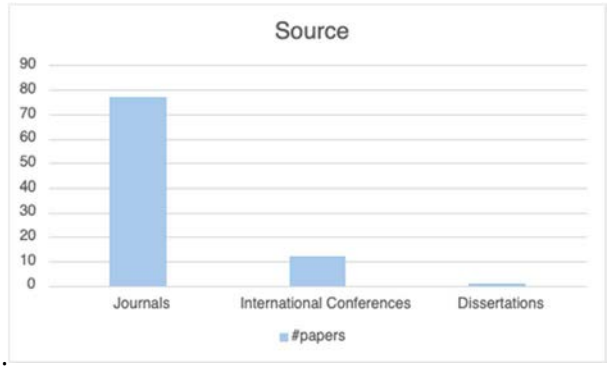
The proposed review aims to explore robotic solutions for inspecting pressure equipment, emphasising advancements in deep learning for surface defect detection and robotics applications for inspection and maintenance. This critical review of approximately 100 papers assesses their potential to provide guidelines for enhancing robotics to improve safety and operational efficiency in areas such as image-based defect detection, big data analysis for monitoring, uncrewed vehicles, and infrared inspection thermography.

The main contributions of our review include a bibliographical analysis of papers on robotic solutions for inspecting pressure equipment and hazardous environments since 1989, highlighting the evolution of these solutions over time. From this analysis, the review provides comprehensive insights into the proposed approaches and discuss the key challenges and gaps identified in the literature. Finally, it outlines the potential for inspection tasks conducted by autonomous or semi-autonomous

robotic platforms equipped with cognitive mechatronics (CM) and artificial intelligence (AI).

1.2 Presentation of the reviewed papers

In order to conduct the present review, the following four research questions were defined to serve as guidelines in searching and selecting relevant papers:
RQ1: What methodologies are commonly used in the inspection of pressure equipment and other hazardous environments?
RQ2: What type of approach is more commonly used for the detection of defects in this type of equipment?
RQ3: What are the current robotic solutions used to inspect pressure equipment and other hazardous environments?
RQ4: What are the future challenges, and limitations in the inspection of pressure equipment and other hazardous environments?
From these research questions, a broad search was conducted in Google Scholar. This search engine was chosen since it provides quick access to a vast repository of academic content that is linked to other scholarly literature platforms, such as ScienceDirect. The keywords used in this search were: 'robot', 'pressure equipment', 'inspection', 'cleaning', 'pipelines', 'in-pipe', resulting in 224 academic papers from 1989 to 2024.
The resulting papers underwent an assessment based on the following eligibility criteria: a) inclusion of peer-review process; b) relevance to the topic; and c) institutional accessibility. After this evaluation, 90 papers were selected. A shared Mendeley folder was created to facilitate team collaboration and to maintain a bibliographical database containing publication details (Author(s)-Year-Title-Source). To understand the variability within the selected papers, analyses were conducted on the evolution of the topic's publication over time and the main sources or publishers. The critical review of these papers focused on the main objectives of each study, the methodologies employed, identified limitations, and conclusions drawn. The results of this evaluation are presented in Section 2, while Section 3 provides a summary of the current solutions, challenges and gaps.
The 90 papers selected for this review cover a period of 25 years, from 1989 to 2024 [1-90]. 85,6% (n=77) of papers reviewed were published in international journal, while 13,3% (n=12) corresponded to a publication in international conference; one dissertation (1,1%) on the topic was also considered (Figure 1a). From 1989 to 2014, publications related to robotic inspection of pressure equipment were scarce, with one or two each year, said number increased from 2015 on, reaching a peak in 2024 (Figure 1b).

a. 

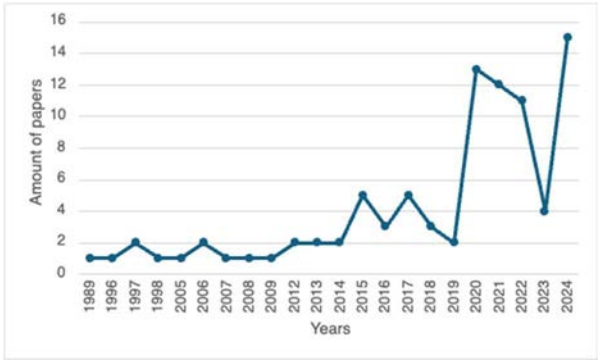
b. 

Fig. 1 – Presentation of the reviewed papers. a. Number of papers by source. b. Number of papers by Year.

2 Organisation of Inspection Solutions

In order to analyse the selected papers, they were grouped by their main topics: Pressure Equipment Inspection, Defect Detection Approaches, and Robotic and Autonomous Systems for Inspection (Table 1).

	Pressure Equipment Inspection	**Defect Detection Approaches**	**Robotic and Autonomous Systems for Inspection**
Reference	[1, 8, 9, 14, 17, 19, 21, 24, 26, 29, 32, 39, 49, 52, 53, 55, 59, 63, 66, 67, 77, 80, 84, 90]	[2, 6, 12, 13, 22, 23, 25, 27, 34, 35, 40, 42, 43, 45, 54, 57, 58, 68, 69, 75, 81, 82, 83, 87]	[3, 4, 5, 7, 10, 11, 15, 16, 18, 20, 28, 30, 31, 33, 36, 37, 41, 46, 48, 50, 51, 56, 60, 61, 62, 64, 65, 70, 71, 73, 74, 76, 79, 85, 86, 88, 89]

Table 1 – References grouped by main topic.

Papers grouped in the category 'Pressure Equipment Inspection' focus on challenges in pressure equipment and regulatory compliance for applicable technologies. They propose solutions for structural integrity and damage repair, such as glass fibre- and carbon fibre-reinforced polymers to reduce stress and restore structural integrity [1]. Solutions like laser welding, hot isostatic pressing (HIP), and ultrasonic (UT) inspection ensure material quality [29]. For high-pressure applications, such as penstock pipes, steel of precise thickness meets fracture assessment standards [90].

Enhanced fabrication techniques, advanced materials, and integrity assessment within manufacturing frameworks significantly improve performance and safety [17]. Several studies highlight the effectiveness of acoustic emission (AE) analysis in assessing fracture distribution and structural integrity. AE analysis effectively detects fractures and corrosion, and when combined with phased array UT, monitors crack growth in welded joints [24, 49, 55]. Moreover, fractal analysis of AE signals offers more accurate defect location and severity [66]. AE monitoring of maraging steel pressure vessels provides high-stress environment guidelines. Magnetic Barkhausen noise analysis assesses stress distribution and detects surface and subsurface defects [84]. AE analysis has also been applied in harsh marine environments [8], particularly for strain real-time monitoring in multi-purpose offshore platforms.

Continuous and standardised monitoring in hazardous environments is emphasized. Computational load assessments for International Thermonuclear Experimental Reactor (ITER) port plugs improve operational safety by standardizing monitoring protocols [32]. For in-vessel maintenance [19], a robotic deployer for ITER's confined spaces integrates AI to support inspection, repair, and payload handling. The ASME/FFS-1 standard is recommended for evaluating storage tank integrity through real-time visual inspection and UT thickness measurements [67].

Big data integration with non-destructive testing (NDT) techniques such as UT, magnetic particle, and penetrant testing enhances defect detection [52]. Stress analysis approaches for oil tanks [80] prevent structural failures. Leak detection in pipelines is addressed with real-time transient modelling and continuous pressure monitoring systems [21], while condition-based monitoring (CBM) for high-pressure high-temperature equipment in remote areas minimizes downtime and improves reliability [63]. Underwater equipment inspection employs eddy current testing and simulations via CIVA software to improve accuracy [39]. A risk-based inspection (RBI) optimises maintenance by prioritising resources. Studies in Italy [14] propose flexible inspection intervals tailored to risk levels while applying RBI to petrochemical plants [53] reduces costs by extending inspection intervals and enhancing safety.

The 'Defect Detection Approaches' category includes advanced methodologies for identifying defects in industrial components, focusing on machine learning (ML), thermal imaging, and visual inspection. The use of deep learning and AI-powered solutions is central, with real-time applications such as convolutional neural networks (CNNs), generative adversarial networks (GANs), and attention-based models [6]. An artificial neural network (ANN) trained on public datasets predicts solar energy output [12], indirectly flagging defects or inefficiencies in photovoltaic (PV) systems. Deep learning for civil structures [34] explores CNNs, U-Nets, and vision transformers (ViT), using transfer and active learning to address data scarcity and improve reliability. Automated visual inspection (AVI) with CNNs and ViT [40], combines supervised and semi-supervised learning for robust defect detection in binary and multi-class classification tasks. Similarly, a CNN-based system for automated flange defect detection in pipelines [43] improves accuracy by leveraging image resizing, normalisation, and augmentation. Autonomous inspection of PV modules with uncrewed aerial vehicle (UAV) based thermal imaging enhances hotspot detection and thermal fault diagnosis [54], while when using CNNs [82] improves accuracy in anomaly detection. Computer vision approaches have been applied to manufacturing inspection [57], where clustering analysis of diverse datasets enhances model robustness and generalization.

In NDTs, several studies aim to improve detection precision. Vibration-based acoustic modulation (VAM) paired with ANNs [13] achieves 96.7% accuracy in classifying bonding defects through vibration response analysis. Aerial infrared thermography (aIRT) using UAVs with thermal cameras [23] detects hotspots and cracks in PV systems. For wind turbine blades [27], methods like radiography, eddy current, and

UT emphasise the need for standardized blade inspection protocols and cost-effectiveness solutions, with advanced signal processing techniques providing superior results [45]; UT, radiography, and AE can provide information for internal defects and real-time monitoring [25]. For PV systems, UAVs combined with infrared (IR) imaging provide enhanced results in advanced algorithms for fault categorisation [58]; while the addition of geometric calculations effectively detects panel deviations and shading. Combining electroluminescence (EL) imaging, IR, and AI-based methods improves scalability and efficiency [2].

Hybrid approaches integrate traditional methods with emerging technologies like internet-of-things (IoT), UAVs, and automated routing to enhance coverage and efficiency. Examples include decentralized task assignment and energy-efficient routing algorithms for UAVs and uncrewed ground vehicles (UGVs) inspection in PV plants [22]. SCADA-based IoT systems [42] enable real-time performance analysis, detecting early signs of defects or inefficiencies and supporting preventive maintenance. Studies on environmental factors affecting PV plants [35] identify cleaning frequencies preventing defects and energy loss, while water-based and water-free cleaning prevent performance degradation and defects [87], highlighting robotic cleaning as an innovative maintenance strategy. Other innovations include a two-stage adaptive augmentation strategy to reduce false positives [68]. Mask R-CNN applied to ultrasonic TOFD images [81] combines UT with deep learning automation for high-accuracy defect segmentation and classification in welding seams. Terrestrial scanning combined with web-based visualisation tools [83] enhances defect detection on curved and flange-end surfaces.

The ‘Robotic Systems for Inspection and Monitoring’ category explores the development and application of autonomous navigation and robotic systems. An optical inspection system for autonomous underwater vehicles (AUVs) combines a pan-tilt unit with high-resolution laser-based scanning [3]. Floating wind turbine inspections integrate remotely operated vehicles (ROVs) for underwater components and UAVs for aerial inspection, coupled with IoT to enable real-time data monitoring [88]. The FlatFish AUV [4] provides a cost-effective alternative to ROVs and divers for continuous monitoring. Repeated close visual inspections [5] using sonar, cameras, and doppler velocity logs (DVL) demonstrate effective 3D reconstructions in shallow water trials, with potential for offshore operations. UAV systems are widely employed in PV inspections, using digital and thermal cameras to detect defects [51]. A customised drone equipped with IR and visible light cameras offers rapid, cost-effective inspections [60], UAV-based inspections are also recommended in concentrated remote solar power plants [20] for scalable and automated maintenance. For offshore oil and gas platforms, robotic systems with NDTs and AI integration are explored [73], proposing ROVs and AUVs to identify corrosion, cracks, and structural anomalies.

Robotic wall-climbing systems feature dead-reckoning navigation with sensor fusion and extended Kalman filters for axial and circular motion precision [50]. A structure-

climbing robot [64], combining vacuum fixtures and pneumatic muscles for movement across inclined and vertical surfaces, demonstrates stability and adaptability to challenging environments. Other designs include a robot equipped with scanning suction cups and wireless communication for vertical building inspections [85], similar to the suction-based robot developed for cleaning the steep glass roof of the Louvre pyramid [46]. A robot with UT scanning for tank and wall inspections [74] combines autonomous scanning with accurate path-following, while a passive support mechanism [76] ensures stability for tank inspections of varying diameters. Confined space inspections benefit from crawler robots, such as those in ITER's vacuum vessels [41]. Tele-operated systems address nuclear plant decommissioning challenges by performing tasks in radiation-intensive areas. Robotic cleaning of PV installations is crucial in arid regions [33, 70, 86], where the use of an autonomous dust-cleaning robot with rotating helical brushes and UT sensors [7], and the integration of an optimized low-energy navigation system [65] are proposed. Other systems include a portable robot with microfiber brushes and multiple environmental sensors to maintain panel efficiency [10] or a dual-brush robot controlled via a smartphone app [71], improving energy production but lacking AI for optimised navigation.

Robotics are combined with solar-powered UAVs operating in remote areas [37], and visual inspection integrated with automated trifocal analysis to improve efficiency without pre-calibrated cameras [15]. Transient chaotic neural networks (TCNN) and genetic algorithms are used in wind farms to optimize patrol paths [16]. The application of robotic solutions in particular cases provides innovative systems such as UGVs equipped with soil sampling tools and terrain estimation systems for tailings inspection in challenging terrains [62]; robots equipped with magnetic wheels and multi-sensor arrays for internal inspections of pipelines and tanks [28]; a cost-effective robot for detecting thin-wall flaws using UT probes [36]; a robotic cleaning systems designed for building-integrated PV panels [48]. For nuclear decommissioning, telerobotic systems with enhanced machine vision [11] improve safety and cost-effectiveness. A robotic deployer supports autonomous underwater operations in ITER reactor maintenance [18], while a ground-based robot equipped with cameras and sensors for electrical substation inspections [56] enables automation. The solution of a robot integrated with IoT sensors to inspect renewable energy installations enables real-time monitoring [61], while an adaptable robotic system for precision measurements in vehicle testing can be transferred to tank and pipeline inspections [79]. In the case of welding inspection [89], a robotic system using X-rays in defect detection emphasises precision and automation.

3 Discussion

In the previous section, the main contributions to the inspection of pressure equipment, defect detection, and robotic solutions were outlined. In this section, the

answers to the research questions proposed in Section 1.2 are presented, considering approaches, main solutions, limitations, and challenges.

RQ1: *What methodologies are commonly used in the inspection of pressure equipment and other hazardous environments?*

NDT methods [13, 24, 27, 39, 45, 55, 66, 77, 86, 87] such as UT, radiographic, and AE testing, are proposed for defect detection without causing damage to the equipment, while AI and ML techniques enhance defect detection and predictive maintenance through models such as CNNs, GANs, and mask R-CNN [6, 12, 34, 40, 42, 43, 52, 57, 61, 69, 81, 82, 83, 88]. CBM is proposed to trigger maintenance of the equipment only when needed based on real-time data [53, 54, 56, 77]. The RBI approach prioritises inspections based on the risk associated with different equipment components [14, 53]. Robots, including AUVs, ROVs, and UAVs, are used to inspect hard-to-reach or dangerous areas, offering high precision and the ability to operate in hazardous environments; these are often combined with AI and IoT [3, 4, 5, 18, 19, 28, 31, 41, 59, 73, 88]. Several papers combine traditional inspection methods with advanced technologies, mainly AI, to optimise monitoring and maintenance [15, 16, 22, 37, 48, 56, 74, 79]. Finite element analysis is utilised for simulating stress distribution and evaluating the structural integrity of components such as pressure vessels and pipelines under material degradation or external forces [1, 33].

RQ2: What type of approach is more commonly used for the detection of defects in this type of equipment?

In the case of defect detection, the most commonly employed techniques are NDTs; UT, AE, IRT, radiography, eddy current testing, and fractal analysis. AE testing is widely used to detect cracks, corrosion, and defect propagation in pressure vessels, pipelines, and high-pressure environments [24, 55, 66, 84]. UT, including phased array UT testing and ultrasonic TOFD imaging, is effective for detecting internal defects in welded joints and assessing stress distribution [39, 45, 81]. IF thermography identifies thermal anomalies, such as hotspots and cracks in PV systems and pressure equipment [2, 23, 58, 69]. Radiography, effective for visualizing internal structures, is employed for composite blade inspection and pipe corrosion detection [13, 27] and frequently applied to detect surface and near-surface defects in reactor components and storage tanks [39, 62].

RQ3: What are the current robotic solutions used in the inspection of pressure equipment and other hazardous environments?

Robotic solutions include AUVs, ROVs, wall-climbing robots, UAVs, and crawler robots. AUVs and ROVs are used for underwater inspections in offshore platforms and pipelines. Examples include FlatFish (AUV) for high-resolution 3D modeling and ROVs equipped with NDT tools [4, 73]. Wall-climbing robots, equipped with magnetic wheels, vacuum systems, and pneumatic muscles, are used to inspect vertical structures such as storage tanks and pipelines [50, 64, 85]. UAVs with thermal cameras and advanced navigation systems inspect PV systems, wind turbines, and confined spaces [51, 58, 69, 88]. Crawler robots, specialized for confined

environments, are utilised to inspect high-radiation areas in nuclear reactors, such as ITER vacuum vessels [41, 59].

RQ4: What are the future challenges and limitations in the inspection of pressure equipment and other hazardous environments?

The future challenges and limitations mentioned in the reviewed papers include: a) the scalability of AI models, that need improved generalization across datasets and variability in defect types that can only be achieved by augmenting the available annotated datasets [6, 34, 40, 57, 83]; b) the adaptation of robots and sensors to extreme environments, current challenges that robotic systems have to face in settings with high radiation, deep underwater, desert climates, or pressure equipment [8, 18, 86]; c) standardisation and regulatory compliance, currently there is a lack of standardised protocols for NDTs, robotic inspections, and AI-based defect detection [25, 27, 39], therefore the compliance of regulations on hazardous environments is still a challenge [53, 67]; d) energy efficiency, autonomous robots and UAVs require energy-efficient designs for long-term operation [22, 65, 70].

4 Conclusions

A review of the state of the art reveals the necessity for a robotic solution compliant with international safety regulations in high-pressure environments. This solution must meet the demand for an autonomous system capable of conducting visual inspections using advanced sensors, integrating AI and ML to enhance reliability and scalability. We propose a system based on autonomous or semi-autonomous robotic platforms equipped with CM, AI, advanced sensors, and VR/AR interfaces. The goal is to develop a fully autonomous solution compliant with ATEX directives. Key components include a self-propelled robot, such as a Robotnik Vogui [91], a supporting frame and positioning arms for precise placement, and a wall-climbing robot operated via a winch system equipped with inspection sensors. These sensors comprise a laser scanner for high-precision 3D mapping and defect detection, a thickness sensor for structural integrity assessment, and two cameras: hyperspectral for detecting corrosion or contamination, and RGB for capturing high-resolution images. Data from these sensors will be analyzed using AI models to detect defects and anomalies. This information will be communicated to the operator through a human-machine interface (HMI) featuring a digital twin of the pressure equipment for intuitive operation. A multimodal interface combining VR and AR will provide immersive visualization and enable remote control, emphasizing intuitive and efficient teleoperation.

The system is designed with a modular architecture to ensure scalability and flexibility, enabling adaptation to various types of pressure equipment. The goal is to acchieve accurate defect detection using multimodal imaging and advanced sensor data with low latency for real-time teleoperation and feedback. Additionally, the system aims to ensure robust, safe, and efficient operations in pressurized environments. One key challenge lies in ensuring compliance with ATEX safety

regulation. Magnetic and eletric solutions, such as those proposed for other wall-climbing robots [50, 85], are not in line with these regulations, and the same can be said of the sensors mounted on the robot. To achieve a fully ATEX-compliant system, the inspection robot will utilise pneumatic actuation, and the sensors will be encapsulated. The proposed system represents a cutting-edge solution for the inspection and maintainance of pressurized equipment, combining advanced robotics, sensors, and user-centered interfaces to improve safety and efficiency.

5 References

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Marker-based area-of-interest detection for safe human-robot collaboration using an eye-tracking wearable device

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Abstract
Human-robot collaboration (HRC) is becoming an increasingly researched topic because it enables the creation of more versatile and human-centered work environments, thus improving the well-being of workers. One of the challenges of HRC is ensuring the safety of the operator when he/she shares the same workspace as the robot and performs potentially hazardous operations with the end effector. This work presents an integrated framework for monitoring human concentration in HRC scenarios using the Neon Pupil Labs eye-tracking device, equipped with a front camera and two rear cameras to capture the motion of the pupils. A marker-based area-of-interest (AOI) delimiting the end effector is defined, and a real-time algorithm continuously checks the relative position between the operator's gaze and the AOI while performing the assigned task. A hazardous condition, due to a lack of concentration of the worker, is identified when the gaze goes outside the AOI. In this case, a proper safety protocol can be implemented to adequately protect the operator, stopping the collaborative activity.

1 Introduction

Human-robot collaboration (HRC) is one of the main development lines in the context of industrial robotics. This approach is characterized by a change of paradigm from traditional robotics because it involves a shared workspace between the human operator and the robot rather than a separation of the two by means of safety fences or other equipment. This would allow to combine the benefits of the presence of human operators, in terms of flexibility and ability to adapt to varying working conditions, to the benefits of robots, in terms of precision of the manufacturing process and reduction of work-related diseases of the musculoskeletal system ([1], [2], [3], [4]). A shift towards human-centered manufacturing framework is therefore being observed [5], and this comes with a number of new challenges to ensure the safety of the workers.

The problem of guaranteeing that, on the one hand, no impacts with the robot may harm the operator and, on the other hand, the collaborative activity is ergonomically suitable is often approached in the literature ([6], [7], [8]). However, [9] reviews a number of studies in the field of HRC, and observes that numerous collaborative activities do not employ standardized safety actions, and [10] points out a research

gap in exploring robot behavioral characteristics concerning the human safety factor of the operator.
This work aims at closing this gap, introducing a novel approach to monitor the concentration of the human operator during the HRC activity, thus improving the level of safety of the application. In particular, the article presents an algorithm that, by means of a wearable eye-tracking system, is able to determine if the worker is looking towards the end effector. If this is not the case, some risk-reduction strategies can be employed, such as stopping the robot or preventing the actuation of the end effector.

2 Experimental setup

The HRC application considered in this study is a collaborative drilling activity, in which the end effector of a collaborative robot is manually guided by the operator to the desired drilling position, and then actuated to perform holes in an assisted way. In this manner, the operator musculoskeletal system undergoes much less effort, because the robot takes on the tasks of both holding the weight of the drill and of keeping the drill tip aligned and applying the force needed to perform the hole.

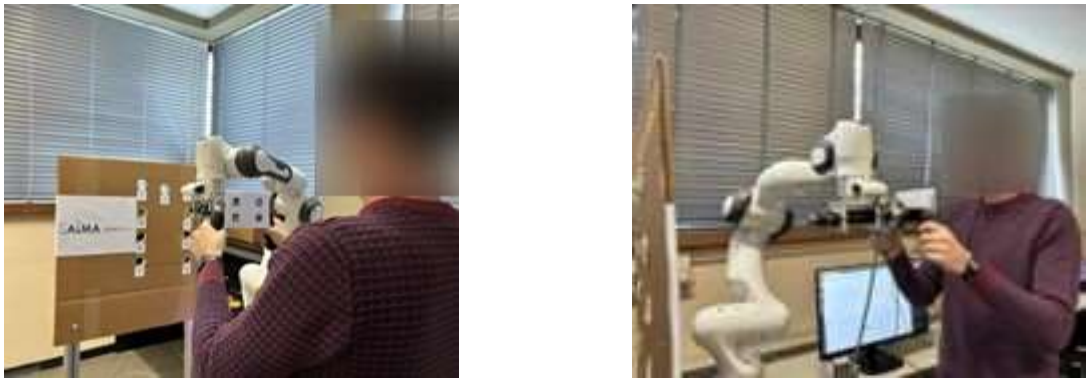

Fig. 1. HRC drilling activity considered in the article.

The experimental setup consists of the following components:

- The Franka Emika Panda robot, a seven-degree-of-freedom collaborative robot that can receive joint position, velocity or torque references from the command interface and has an internal proprietary controller capable of closing the control loop to follow precisely these references;
- The Neon Pupil Labs smart glasses, an eye-tracking device equipped with a front camera and two rear cameras framing the operator's eyes, which is connected with a USB cable to a mobile phone to transmit the data;
- The mobile phone companion device of the smart glasses (OnePlus 10 Pro), transmitting the eye-tracking data via Wi-Fi;
- A custom end effector structure, which is connected to the terminating flange of the Franka Emika Panda, and whose parts are:

    - A pneumatic drill to perform the holes;
    - A six-axis Schunk Axia-80 force/torque sensor, to measure the force that the operator applies on the end effector;
    - A metal structure connecting the last link of the robot to the drill and to the force/torque sensor;
    - A 3D-printed handle grabbed by the hands of the operator to perform the manual guidance.
- A workstation PC receiving the data from the eye-tracking mobile phone via Wi-Fi and controlling the robot via Ethernet connection and the C++ libraries provided by the developers of Franka Emika Panda.

The robot controller works with an admittance control scheme [11], which is based on the principle of making the end effector behave like a virtual body with user-defined inertia and damping parameters in response to the force and torques applied by the user. If those parameters are chosen as low (but not too low to avoid instability), the operator can move the end effector in a smooth and effortless way.

The safety functionality proposed in this work is obtained in two steps: 1) identifying the region of the end effector within the image provided by the front camera of the Neon Pupil Labs device; 2) checking that the gaze (i.e., the position at which the operator is looking within the scene captured by the front camera, estimated by a Pupil Labs proprietary algorithm based on the rear camera data) is within the end effector area.

The second feature is directly provided from the Pupil Labs libraries, while for the detection of the end effector region the algorithm described in the next section is used. Trying to identify the whole end effector would be a very hard task, because it is a complex and irregular structure that is seen from very different perspectives during the HRC activity. As a consequence, it was chosen to use fiducial markers placed on the end effector, simplifying the problem as the detection of a planar Area of Interest (AOI) consisting of four markers (Fig. 2).

Fig. 2. Planar AOI with fiducial markers mounted on the end effector: (a) front view; (b) lateral view.

3 AOI detection methodology

The proposed algorithm for AOI detection uses the ArUco fiducial markers as the way to identify the area, since they are recognized tools in computer vision for effective object pose estimation and detection thanks to the application of several techniques, including adaptive thresholding, contour extraction, polygon extraction, binary thresholding, and bit lookup ([12]).

In the considered case study, however, it is rather frequent that the ArUco library is not able to detect the markers in the first place. This can be due to several causes, such as motion blurring or rapid movement of the head of the operator with respect to the AOI. If one or more of the four ArUco markers are not detected, the Optical Flow algorithm is used as an alternative to detect their position. This technique tries to estimate the displacement of a pixel of an image from a frame to the next one (flow) based on the brightness constancy assumption, i.e., the hypothesis that the intensity of the pixel representing a point of the 3D scene will be the same as the pixel representing the same point in the next frame. Under this assumption, the flow is found considering a window of pixels around the point of interest according to the Lucas-Kanade well-established method ([13]).

Then, based on the positions of the markers in the 2D scene (estimated by ArUco or Optical Flow) and on the intrinsic parameters of the camera (distortion and focal length), the pose in the 3D environment of the markers in the camera frame can be estimated with an algorithm proposed by Muñoz ([14]). In this way, it is possible to find the plane that best interpolates the four 3D points and to compute the area of the quadrilateral obtained from the projection of these points on the interpolating plane. Theoretically, this area should be equal to the real geometric area of the region in Fig. 2. If the estimated area and the real area differ for more than a threshold value (chosen as 30% of the real area), the ROI estimation is considered as an outlier, otherwise it can be used to check the concentration of the worker on the end effector. This verification on the value of the area is necessary because the detection, especially if performed with the Optical Flow method, can sometimes lead to outliers because some other object in the scene was mistaken for a marker or because the estimation of the flow was hindered by some condition such as blurring or too rapid relative motion between the operator and the plane of the markers.

In conclusion, the AOI can be classified as correctly estimated if the estimated area is within the tolerance value, as outlier if it is outside of the tolerance value or as missing if neither ArUco nor Optical Flow provided a result. If the area is correctly estimated and the gaze is within the AOI the actuation of the end effector is safe, while in all other cases an appropriate risk-reduction strategy must be implemented.

4 Experimental results

Two sets of tests were performed to assess the validity of the proposed approach for the considered HRC application: in the first one the operator was instructed to avoid rapid motions of the head, and to try to follow the end effector with his eyes while

moving to the different drilling positions; in the second case, instead, he was instructed to purposedly moving his head more quickly and abruptly, though always trying to maintain his sight on the AOI. Three tests were performed for both these cases.

Fig. 3 shows the results of the tests of the first type. The charts show the percentage of the total number of frames of the tests in which the AOI was 1) detected correctly with ArUco, 2) detected correctly with Optical Flow (at least for one of the four markers), 3) detected (either with ArUco or with Optical Flow), but with an estimated area value outside of the tolerance, and therefore classified as outlier, 4) not detected. It can be observed that, under these testing conditions, the AOI is almost always detected correctly with the ArUco method. Fig. 4 shows two frames from the video captured during the tests. The AOI is correctly identified within the 2D image provided by the front camera of the Neon Pupil Labs device, the area is estimated with good precision (the real value would be 37.5 cm^2), and in the cases shown in the figure also the gaze is within the AOI.

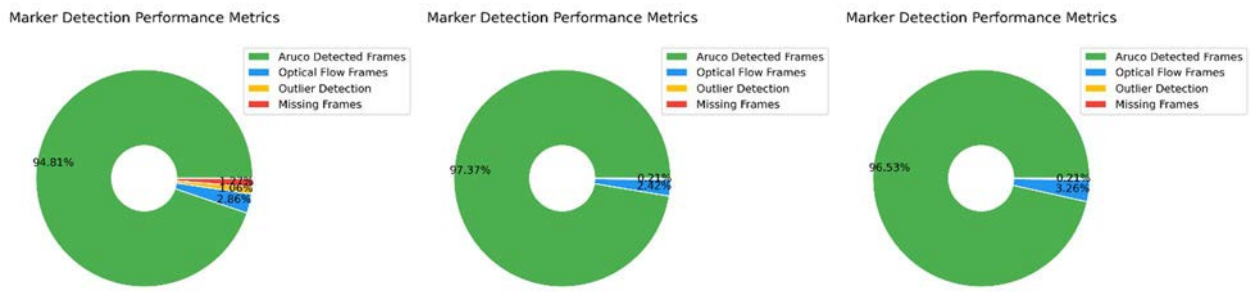

Fig. 3. Results of the three tests in situation 1 (no rapid head movements).

Fig. 4. Frames from the tests in situation 1, showing a correct detection with the ArUco method.

Fig. 5 shows the results of the tests of the second type. In this case, a much higher rate of frames detected with the Optical Flow method can be observed. This is an expected consequence of the more rapid head movements, that prevent direct detection with the ArUco library. It is also positive that the rate of outlier detection is

low, as this indicates that also the Optical Flow is providing a good estimation of the markers' points in the 3D scene. There are also some missing frames, which are due to the cases in which either the operator's head position is such that the front camera is not even framing the AOI, or there is so much motion blur that even the Optical Flow method cannot provide acceptable estimation of the flow. Example frames for all these situations are also shown in Fig. 6.

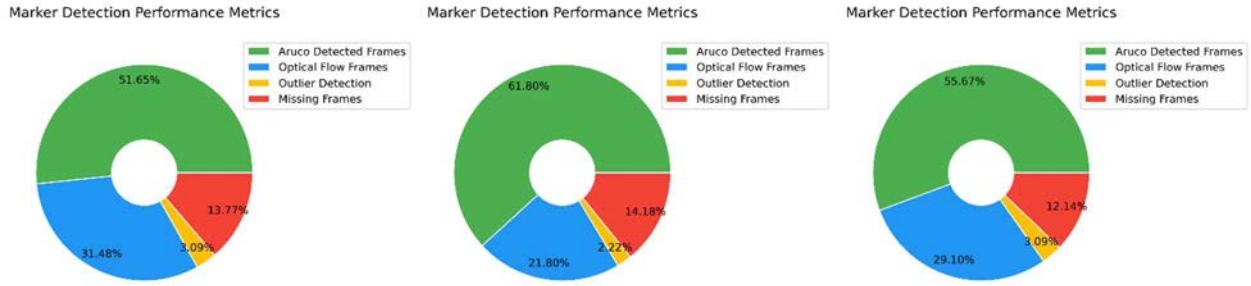

Fig. 5. Results of the three tests in situation 2 (rapid head movements)

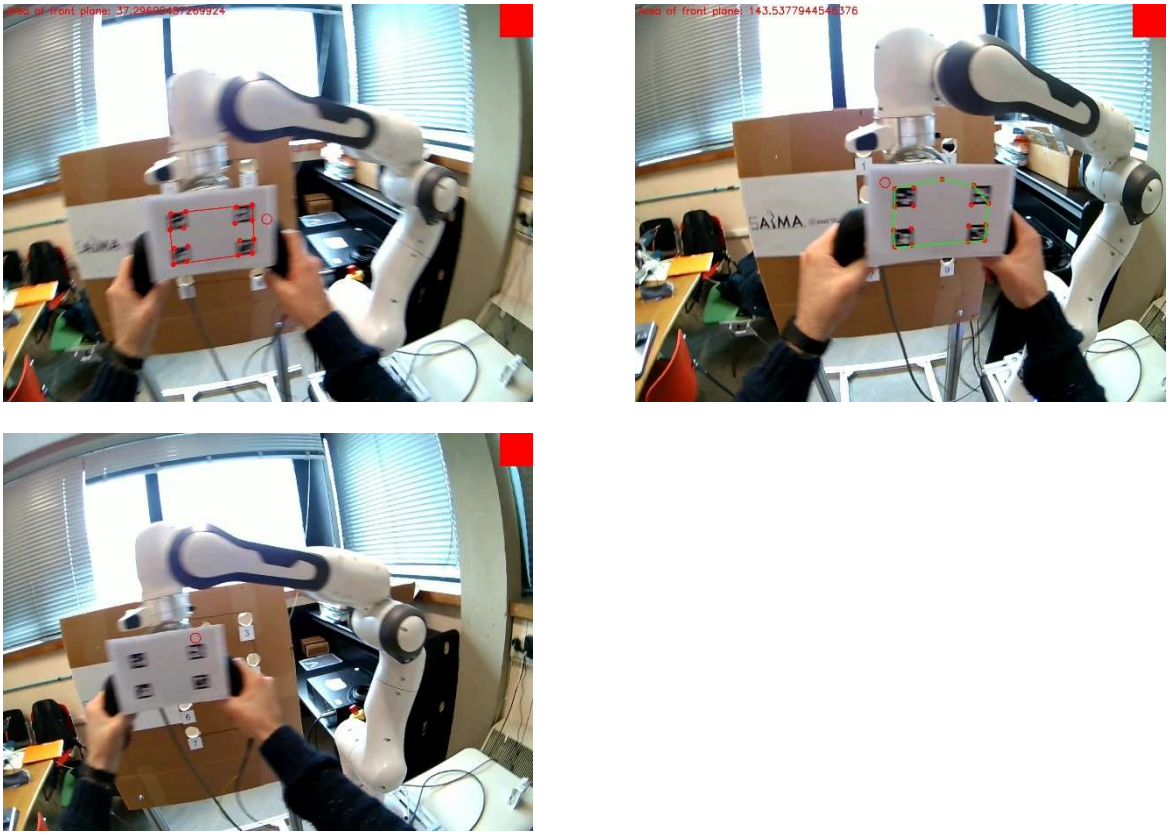

Fig. 6. Frames from the tests in situation 2, showing a correct detection with the Optical Flow method, an outlier detection with the Optical Flow method and a missed detection.

5 Conclusions and future developments

In conclusion, the preliminary tests presented in this work have shown that the developed method for AOI detection is effective in the relevant testing conditions and

can be applied online to check if the concentration of the worker is on the end effector, thus enabling the development of safer HRC applications.
More rigorous tests will have to be conducted as a future development, in order to assess the accuracy of the proposed algorithm in a more systematic way, due to the intrinsic lack of repeatability of tests conducted with human operators.
Additionally, it can be observed that in some cases, such as the first one in Fig. 6, the AOI is correctly detected and the gaze is outside the area, but still it is in the zone of the end effector, meaning that the operator is actually concentrated on the activity, and the implementation of a risk-reduction strategy would not be needed under this circumstance. It will therefore be necessary to look for a way to identify completely the end effector. The study presented here was useful to demonstrate that using a commercially-available technology it is possible to identify one planar AOI: in the future it will be beneficial to study a way to detect the whole end effector region based on the position of several planar AOIs.

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Vision based safety algorithm in human-robot cooperation

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Abstract
Human robot cooperation is a growing paradigm in industrial production as it allows efficient semiautomated production, which is most relevant to ensure customized production cycles for small batches or even single pieces.
Within this context several approaches can be considered in order to reduce the risk that a contact between the robot and the operator can cause any kind of damage for men. The existing standards imposes mass, speed and force limitation and provide detailed information about the maximum allowed force that can be exchanged between man and robot in each part of the body. An additional approach aims to eliminate any kind of risk by avoiding contact through the use of visual feedback to modify in real time the trajectories of the robot according to the motion of the operator. This approach can be applied both to anthropomorphic and mobile robots, as well as to the assembly of the two systems.
The paper introduces the layout designed within the ISACOB project to develop a robotic cell where this kind of algorithms are implemented. The algorithm is based on the use of virtual potential, and several configurations were developed in the project to ensure safe operation in a production environment where man and a mobile robot share their workspace. The paper introduces the applied methodologies and shows some preliminary results.

1 Introduction

The industrial sector is undergoing a significant transformation, driven by the advancements of the Fourth Industrial Revolution, commonly referred to as "Industry 4.0". One of the key innovations emerging from this revolution is collaborative robotics, which is set to optimize factory operations. The core aim of collaborative robotics is to move robots beyond the safety cages that traditionally separate them from human workers, facilitating direct human-robot interaction. This shift marks a major evolution in industrial robotics, as it allows for the combination of robots' precision, speed, and repeatability with the adaptability and problem-solving abilities of humans.

Because of potential sharing of the workspace between humans and robots, collaborative robotics is regulated by standards. The ISO/TS 15066 provide safety measures according to two approaches: Power and Force Limiting (PFL) and Speed and Separation Monitoring (SSM). PFL ensures safety by combining risk assessments with measures to limit forces, torques, and velocities, preventing harm during human-robot contact. SSM, instead, relies on maintaining a safe distance between the operator and the robot.
Politecnico di Torino, in collaboration with INAIL, is developing systems —specifically sensors, algorithms, and methods for their integration— with the aim of applying collaborative robotics according to SSM guidelines [1]. These systems involve real-time robot control algorithms that not only ensure the safe distance between human and robot but also adapt robot trajectories to the operator's preferences. The algorithms use data from a vision system, which includes depth cameras for tracking the operator's movements in space.
A highly relevant case study, the disassembly of electric car batteries [2], was chosen for the development of the system. Indeed, an analysis of the entire disassembly process showed that the robot can potentially perform several tasks, including unscrewing and removing simple components, while others require the presence of humans, such as disassembling and manipulating more complex parts [3], [4]. In addition, due to the size of these types of batteries, it was necessary to consider a robotic system consisting of a manipulator mounted on a mobile base. In this way, the robot can reach every part of the battery and operate in parallel with the operator, so as to speed up the disassembly process.
The purpose of this article is to summarize the methods and tools developed so far, to point out what has been achieved and what still needs to be improved. Starting from the case study, the collaborative system and the algorithms that ensure safety according to SSM are presented. However, the results obtained by considering the case study have broader significance, as they can be implemented in a generic collaborative robotics application.

2 Collaborative robotic system

A model of the collaborative robotic cell is shown in Fig. *1*. The work area was designed to be compatible with the dimensions of a 2017 Chevrolet Bolt battery, whose footprint is 1x1.6x0.17 m. The robotic system consists of the 7-degree-of-freedom Franka Emika manipulator, mounted on a Tiago mobile base from PAL Robotics. A vision system like the Kinect depth camera by Microsoft can be used to track the operator's movements.

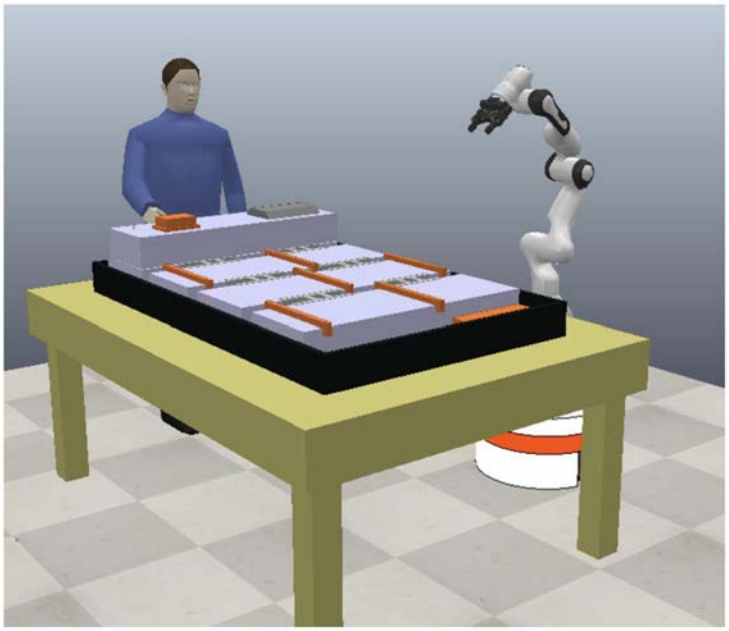

Fig. 1 – Layout of the collaborative robotic cell for EV battery disassembly

2.1 Algorithms for safe human-robot collaboration

In order to make human-robot collaboration possible, particularly in workspace sharing, real-time collision avoidance algorithms were designed for the mobile base and the anthropomorphic manipulator to meet the provisions of ISO/TS 15066. This standard requires that under shared workspace conditions, where there is no contact between the human and the robot, a minimum distance is guaranteed as a function of the speed of the human and the robot, as well as the robot's reaction time and its maximum acceleration. This minimum distance is defined as:

$$d_{min} = (v_{m\perp} + v_{r\perp})T_r + \frac{v_{r\perp}^2}{2a_s} \quad (1)$$

where $v_{m\perp}$ and $v_{r\perp}$ denote the velocity of the operator and robot, respectively, along the direction of minimum distance, T_r the reaction time of the robot, and a_s its deceleration. As an example, the quantities of interest are shown in Fig. *2*; in this case, the robot link and the operator arm are approximated with spheres and cylinders to facilitate the calculation of the minimum distance direction.

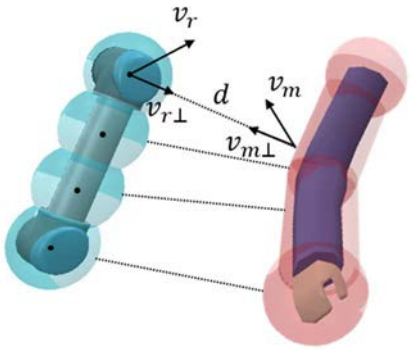

Fig. 2 – Analysis of human-robot distances and velocities

The idea behind the algorithms presented in this section is based on the inversion of the minimum distance equation (1), so that it is possible to determine the maximum allowable robot speed that complies with the regulations, according to the actual distance between the robot and the person:

$$v_{i\perp,max} = -a_s T_r + \sqrt{(a_s T_r)^2 - 2a_s(v_{m\perp} T_r - d)} \tag{2}$$

where $v_{m\perp} = 1.6\ m/s$ as required by the standard in case the operator's velocity is not known. In addition, T_r and a_s are constants, since they are characteristics of the robot. The only variable is d, which is possible to calculate by knowing the configuration of the robot and the posture of the person, the latter measured by body tracking software.

It is assumed that, in the real case, a set of vision sensors will make the human operator's pose information available. It is also assumed that the guidance algorithms for the mobile base will allow the pose of the mobile base to be known with an accuracy of less than 10 mm, while the pose of all links of the anthropomorphic robot is known by combining the pose data of the mobile base with the rotation angles of the joints received in feedback from the controller.

Mobile robot navigation

To develop the guidance algorithm for the mobile base, it is essential that the system can guide the base to its working position in the battery disassembly cycle, orient it appropriately, and avoid collisions with the human operator and its surroundings i.e. the table on which the battery is placed.

One of the most effective navigation algorithm for real-time collision avoidance is the artificial potential field [5]. Since the mobile robot moves on the ground, a two-dimensional treatment of the problem is sufficient. Let $\boldsymbol{p}_b$ be the generic position of the mobile base. The final position $\boldsymbol{p}_a$ is associated with a quadratic, i.e., attractive, field defined as:

$$U_{goal} = \frac{\sigma}{2} |\boldsymbol{p}_b - \boldsymbol{p}_a|^2 \tag{3}$$

Where σ is the intensity of the attractive field.
To define the virtual potential fields associated with obstacles, such as the operator the work surface, simple geometries are considered: the table is modelled as a rectangle, while the encumbrance the man is approximated to a circle, the center of which is placed on the axis of the operator's torso. This simplified representation also keeps computation time down and makes the algorithm compatible with the use of sensors typically installed on board the platform, such as LIDARs and cameras.
The virtual potential field associated with the operator is defined as:

$$U_{person}(x,y) = K_m e^{-\frac{\gamma_m}{2}((x_b-x_m)^2+(y_b-y_m)^2)} \tag{4}$$

While the one related to the table is:

$$U_{table} = K_t \sum_{i=1}^{4} \frac{1}{1+e^{-\gamma_t(A_i(x_b-x_t)+B_i(y_b-y_t)+C_i)}} \tag{5}$$

where the coefficients K denote the field strength and γ is a parameter that defines the decay [6]. The coefficients A_i, B_i and C_i allow the shape of the obstacle to be modeled. The subscripts b, m and t, refer to the moving base, man and table, respectively.
Finally, the velocity sets for the robot $\boldsymbol{v}_b$ and ω_b, which are linear velocity and the angular velocity respectively, are calculated considering the direction opposite to the gradient of the total potential field, obtained from the sum of all contributions:

$$\boldsymbol{v}_b = -\nabla(U_{tot}), \qquad \omega_b = k\theta \tag{6}$$

where k is an appropriate gain while θ is the error between the desired direction, defined by the gradient, and the robot's current direction [7].

Robotic arm collision avoidance
As for the robotic arm, the three-dimensional problem should be considered. To make collaboration more effective, it is not appropriate to use a cylindrical representation for the human. In addition, the actual geometry of the anthropomorphic robot may be relatively complex, and taking this into account precisely would slow down the calculation of distances between human and robot, effectively making it impossible to control the robot in real time. Thus, it was decided to approximate the human and robot by capsules, i.e. cylinders joined by spheres at the base, like [8]. In Fig. *3* the robot and operator are shown with their simplified geometries.

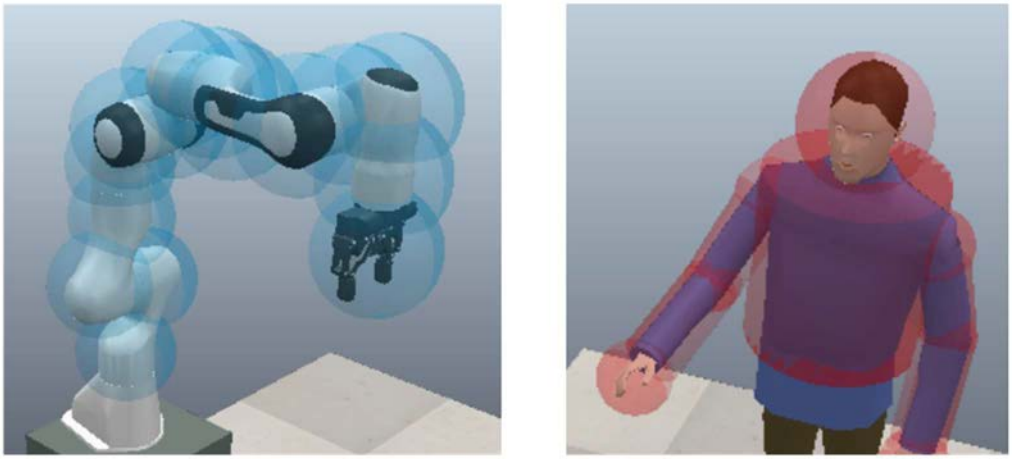

Fig. 3 – Representation of robot and human by means of spheres and cylinders

The footprint of the manipulator robot is approximated by a series of spheres arranged along its kinematic chain. The pose of each sphere can be calculated as a function of the q_i coordinates of each joint and the position of the moving base on the floor. In particular, the position of the sphere is referred to the coordinates of the highest joint placed before the sphere itself, starting from the base.
Let ${}^{b}A_i$ be the matrix that defines the pose of the i-th sphere with respect to the reference system at the movable base, and let ${}^{0}A_b$ be the matrix that defines the pose of the movable robot with respect to a fixed reference system, chosen as the reference for the work area. The pose of the generic sphere with respect to the fixed system can be written as ${}^{0}A_i = {}^{0}A_b {}^{b}A_i$. The velocity of each sphere $\boldsymbol{v}_i$ is calculated as:

$$\vec{v}_i = \vec{v}_b + \vec{\omega}_b \Lambda \vec{p}_i + {}^{0}A_i {}^{b}J_i \dot{q}_{fb} \tag{7}$$

where $\boldsymbol{p}_i$ is position of the sphere and ${}^{b}J_i$ is the Jacobian matrix calculated with respect to the moving base.
The control logic of the manipulator is the multiple link collision avoidance algorithm presented in [9]. A repulsive velocity is applied to each link to the point of minimum distance from the human. The repulsive velocity is defined on the maximum speed considerations from ISO/TS 15066. Specifically, the direction of the repulsive velocity coincides with the direction of minimum distance from the operator, while the modulus is chosen as:

$$v_{rep,i} = \begin{cases} v_{i\perp} - v_{i\perp,max} & se \quad v_{i\perp} \geq v_{i\perp,max} \\ 0 & se \quad v_{i\perp} < v_{i\perp,max} \end{cases} \tag{8}$$

In which $\boldsymbol{v_{i\perp}}$ is the component of the velocity $\boldsymbol{v_i}$ of the sphere along the direction of the minimum distance calculated according to (7).
In a real application, the motion of the person is tracked by a vision system, as Kinect V2, to compute the minimum distance between the person and the robot.

3 Test in simulation environment

To evaluate the effectiveness of the algorithms, tests were conducted in a simulation

environment. The robotic system, consisting of the mobile base, manipulator, operator, work surface, and battery, was modeled in CoppeliaSim for visualization and in MATLAB for computation. The computational part involves deriving the distances and commands for the robots based on the control logic described. To visualize the robots' and operator's movements, MATLAB sends position data to CoppeliaSim at each simulation step. Fig. *4* shows the calculation scheme in the Matlab environment and the whole system in the Coppeliasim visualization environment.

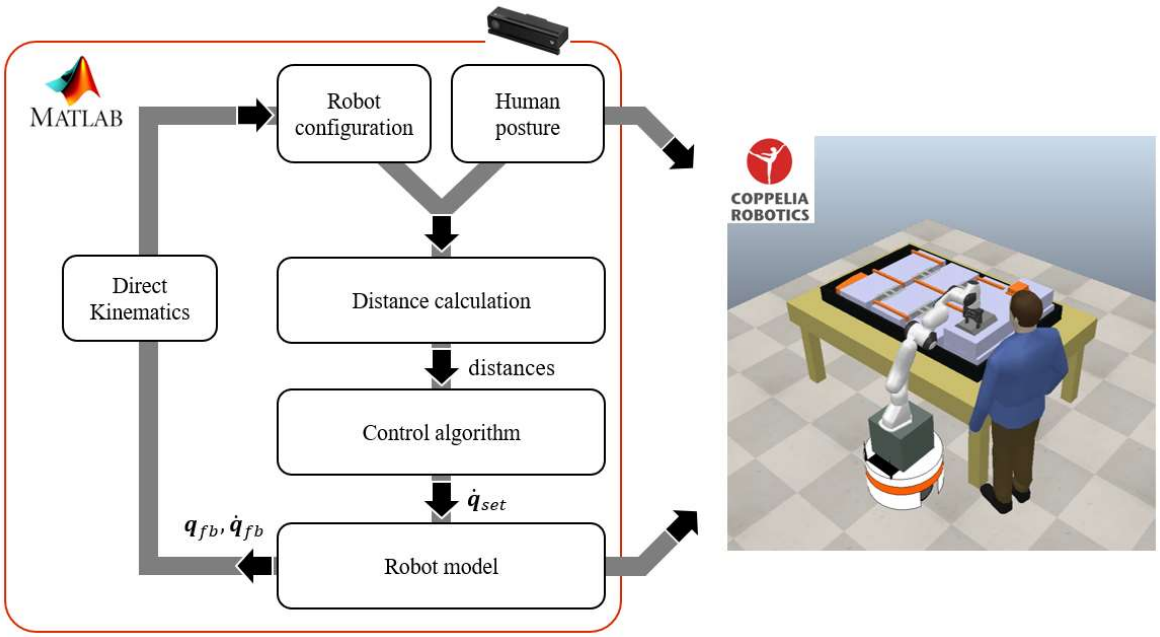

Fig. 4 – Computation of control algorithm in Matlab and visualization in Coppeliasim

Since the mobile robot exploits artificial potential fields, the fields of each element of interest, i.e., the target point and obstacles, the latter consisting of the work surface and robot, were calculated. An example of a representation of the potential fields of all elements, as well as the potential field resulting from the sum of these elements, is shown in Fig. *5*.

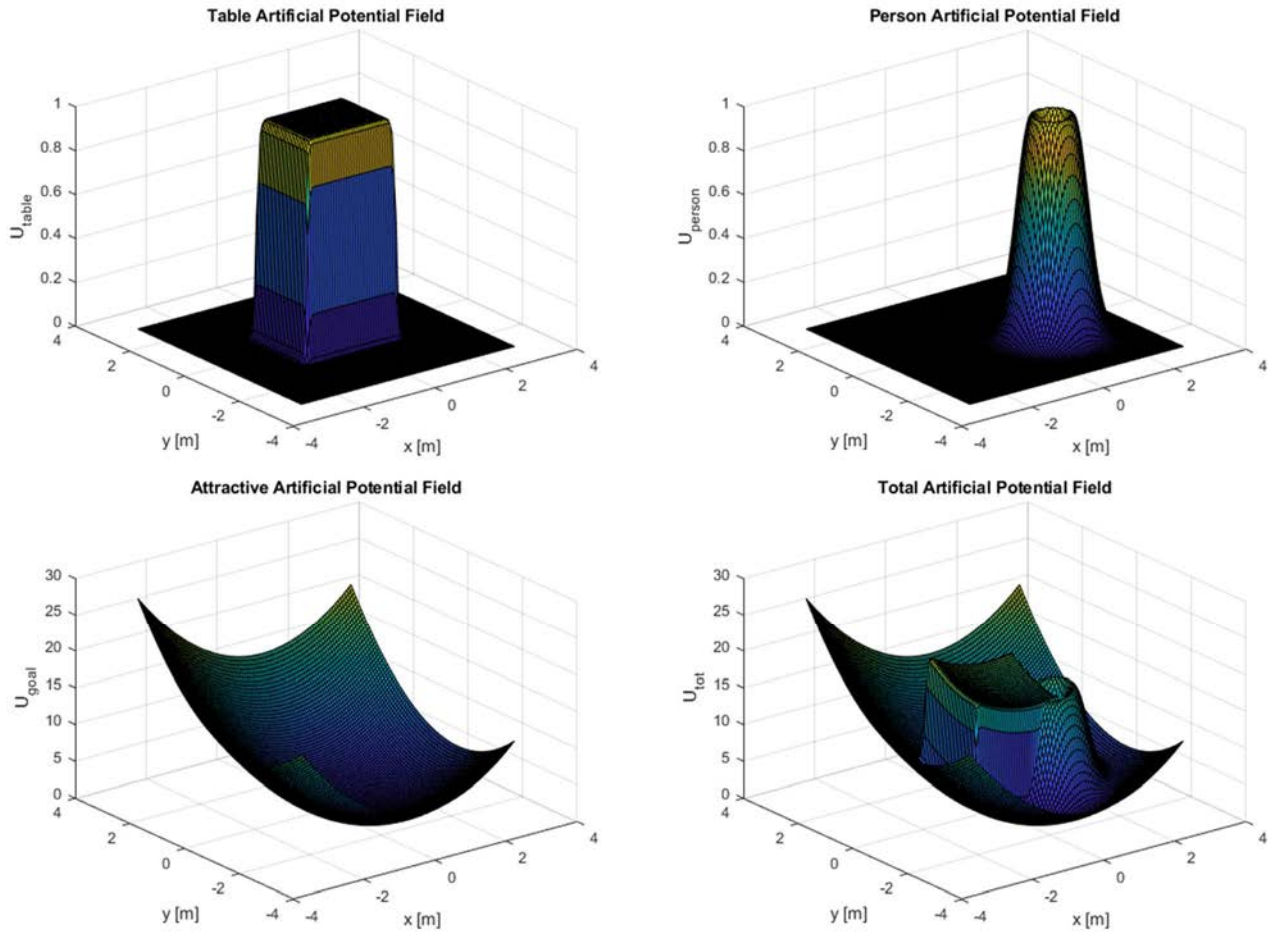

Fig. 5 – Sum of potential fields of the principal elements of the collaborative robotic cell

Two representative tests of two typical scenarios are considered:

a) The mobile base follows a path that intersects the area occupied by the operator and ends its movement at a point where the robotic arm operates, where there is potential interaction with the human operator.
b) The moving base remains in a fixed position while the robotic arm performs tasks, sharing the work area with the human operator.

Some significant frames of test (a) in the CoppeliaSim environment are shown in Fig. *6*. The motion of the person in CoppeliaSim is the one of a person recorded using Kinect V2 cameras in laboratory. The robotic system moves from the start position to the end position, moving around the table and the operator, and the robotic arm reaches the final position on the work table. The two robots move according to the algorithms explained in the previous sections.

Frames relative to different simulation instants in the Matlab computational environment are shown in Fig.7. The footprint of the robot is approximated with spheres arranged along the kinematic chain, which enclose the actual footprint of the robot. The operator is represented by a light blue skeleton, whose points represent

those of interest in the upper body. To make the images easier to read, the capsules which represent the robot's approximation have been hidden. The working table is shown in blue. The minimum distances, in the time instants relative to the frames, between each link and the operator are shown in magenta. As can be seen, the distances are monitored throughout the simulation.

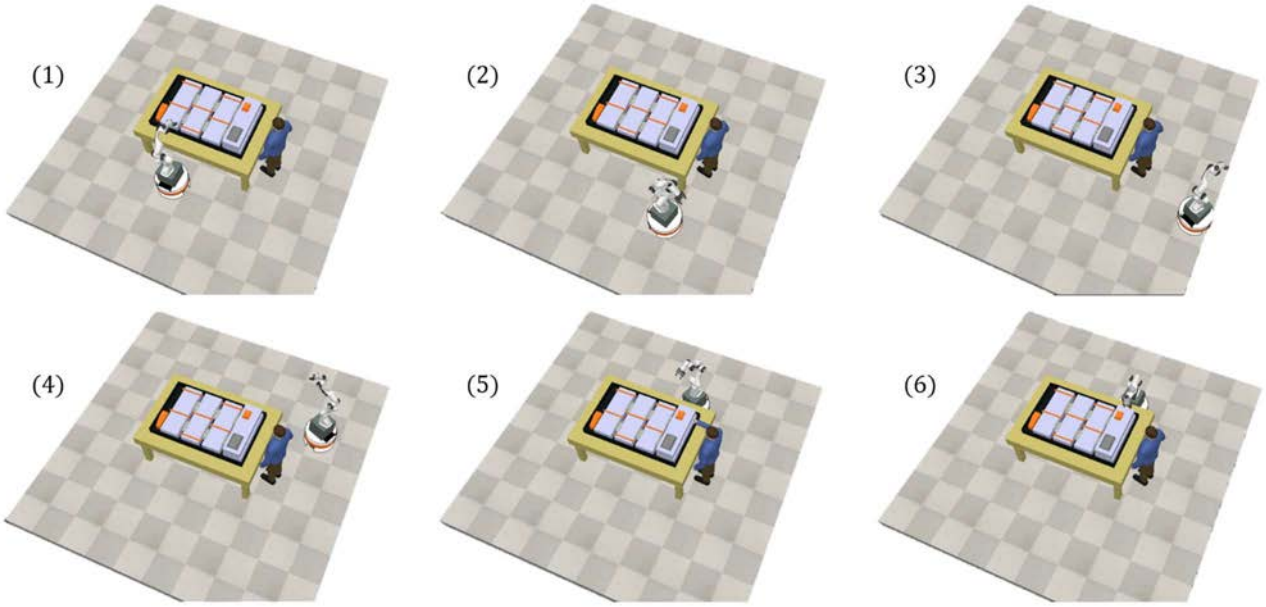

Fig. 6 – Simulation frames of test (a) in CoppeliaSim.

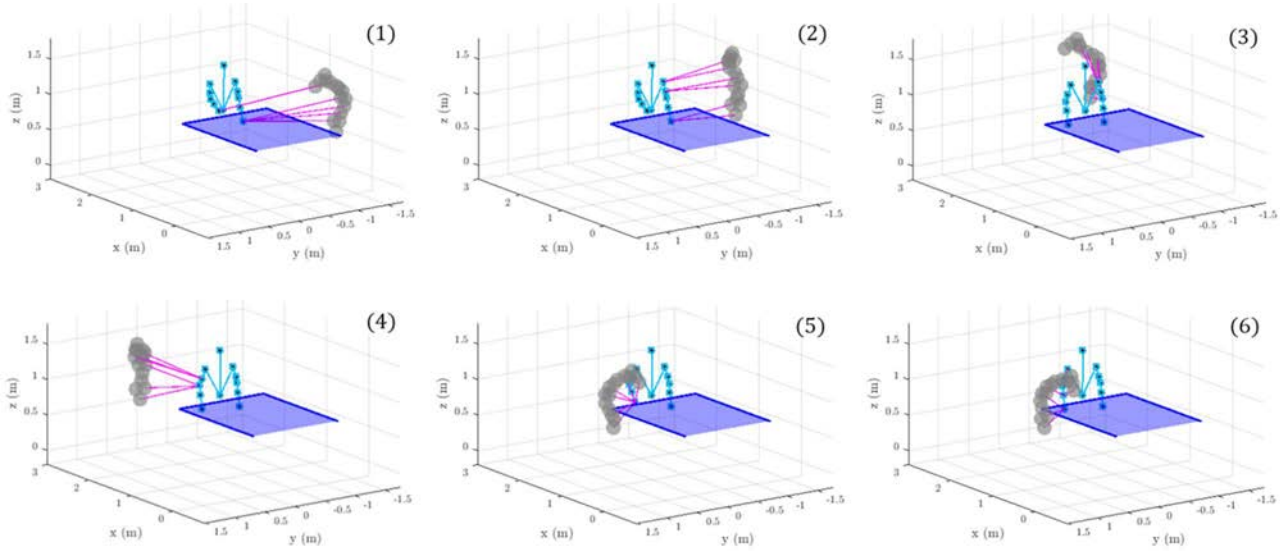

Fig.7 – Computation frames of test (a) in Matlab

Fig. *8* shows five frames of test (b) in the CoppeliaSim environment. In this test, the robot Tiago remains stationary while the robot Franka's EE moves to reach a point on the worktable. However, as the dummy moves, its right arm intercepts the robot's path. As a result, the robot deviates from its trajectory to avoid the collision.

Fig. 8 – Simulation frames of test (b) in CoppeliaSim

4 Development of the experimental setup

The experimental workbench is currently being set up, which required the construction of the prototype of the robotic system and the design of the workbench. The prototype is shown in Fig. *9*a, in which the main components are highlighted. An aluminum frame is placed between the movable base and the arm, which houses a battery and allows the manipulator base to be positioned level with the work surface. Fig. *9*b shows the Chevrolet Bolt 2017 battery. For safety reasons, it is chosen to test the algorithms with a 3D printed replica of a battery section, so that the removal of some components, such as screws and bus bars, can be tested. Finally, Fig. *10* Fig. *10* shows the work area, with the operator, robot, table, and battery. The vision system is being set up and will be positioned so that the area can be viewed from different points of view.

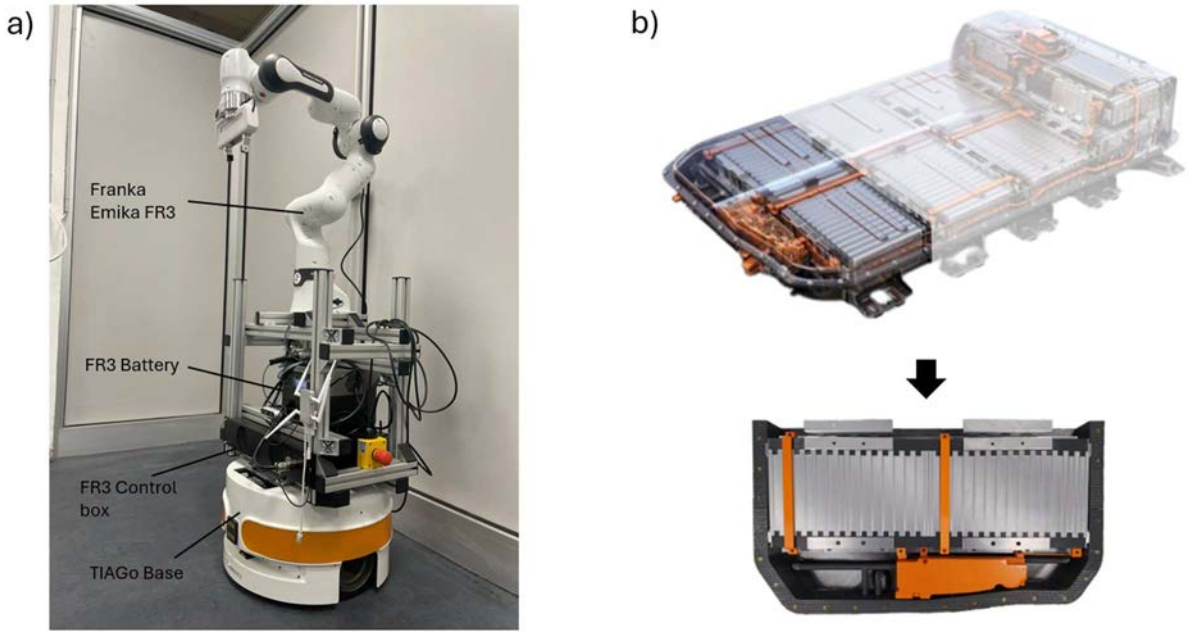

Fig. 9 – a) robot assembly; b) Chevrolet Bolt Battery and 3D printed replica.

Fig. 10 – Experimental Setup for collaborative disassembly

5 Conclusions and future works

The algorithms developed so far allow a robotic system consisting of a mobile robot and a manipulator to move autonomously and safely in a shared workspace with an operator. Safety has been managed taking into account aspects related to the collaborative robotics standards. To demonstrate the effectiveness of these algorithms and to show an application that can benefit from human-robot collaboration, the disassembly of an electric car battery was considered, which results in the need for human and robot to share the workspace. As an example, two representative manoeuvres were considered, one related to the mobile robot moving around the table, the other related to the manipulator and the human working on the same part of the battery. The control logics are based on previous work already experimentally validated in other applications, either on the manipulator or on the mobile robot alone [5], [10]. In this work, however, the whole system has been considered. In addition, a first experimental setup is presented, where only the tuning of the vision system is missing. Again, this is to integrate an element that has already been used in previous work. The next steps will be to complete the test bench with the vision system and to define a set of operations to be performed on the battery in order to validate the results with a view to industrial application.

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Occupational exoskeletons: a new challenge for safety disciplines in the workplace of the future

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Summary
Work-related musculoskeletal disorders (WRMSDS) arising from biomechanical overload are associated with physical and organisational risk factors related to manual handling of loads or activities that require static and/or incongruous postures maintained for prolonged periods of time. The traditional approach to mitigating these risks involves the implementation of preventive measures aimed at reducing potential harm as much as possible through improved workplace design, proper organisation of work activities or the selection of the best work equipment to be provided to the worker.
Recently, especially in some manufacturing sectors such as the automotive industry, new technologies are being used to assist the worker in reducing physical strain. Hence the growing interest in new wearable assistive devices, also known as exoskeletons, which are proposed as an effective and innovative solution to support the musculoskeletal system and reduce muscular stress in the regions of the body most frequently affected by overload. Although their potential benefit in the prevention of WRMSDS seems clear, it is necessary to analyse all the possible implications in order to understand what critical issues might arise by virtue of this choice.
In order to initiate an in-depth study in the regulatory field on the topic of general wearable devices, in 2024, the first technical report UNI/TR 11950 [22] was published on: Safety and health in the use of occupational exoskeletons, with the aim of providing indications regarding the types of exoskeletons suitable for the work environment, with the intention of providing criteria to guide the design and the selection phase, also in terms of the well-being and comfort of the user.

1 Introduction

The risk of biomechanical overload is inherent to all activities that involve significant physical effort, such as tasks involving lifting, carrying loads, pulling and pushing, or the performance of activities in which we are required to perform a high frequency of gestures, especially in prolonged non-neutral postures. Such working conditions are responsible for the continuous increase in WRMSDS and the resulting costs for the community in terms of insurance compensation [15].

The idea of supporting human activities in manual tasks, in addition to the possibility of automating or mechanising specific individual tasks, using high-end technologists (robots or co-robots), is not a recent one.
Over the last few years, devices designed to be worn, commonly known as exoskeletons, have been increasingly introduced in various occupational contexts (e.g. automotive, logistics,...). automotive, logistics,...) wearable devices, commonly known as exoskeletons, have been increasingly introduced in various occupational contexts (e.g. automotive, logistics,...) in order to reduce stress , so they are now perceived as a valuable tool to prevent the onset of WRMSD, especially in occupational contexts where the tasks to be performed do not have a direct spatial relationship with a specific workstation or are not standardised.
In the coming future, according to current market statistics, wearable devices will increasingly represent a constant presence in many of the occupational scenarios. With this in perspective, it will be important to highlight the critical issues that need to be overcome, the needs that must be fulfilled and the requirements that exoskeletons must have in order to both maximise user benefits and minimise potential negative impacts.

2 Exoskeletons in the professional context

An exoskeleton is a wearable external structure that can enhance the wearer's physical capabilities [12]. It is a technology that can specifically increase the capabilities of a subject engaged in the performance of a task in terms of strength, speed, agility, power and motor coordination.
From a functional point of view, exoskeletons are classified as active or passive systems (Figure 1 and Figure 2).
In the former type, movement assistance is provided by a complex integrated system of motors[1]/actuators[2]/sensors/software. These are systems that, in some recently developed models, are able to modify the amount of support to be provided to the worker on the basis of information on gestural behaviour collected by on-board sensors. In a closer sense, active exoskeletons make it possible to extend the force developed by the user.
Based on the definitions given in the technical report draft standard ISO/CD 18646-4 [9], the wearable robot (exoskeleton) can be considered as a device that can reduce the load, particularly in the user's lumbar spine, due to its capacity to generate an assistance torque to integrate or increase personal capabilities while in close connection with the user (Figure 3). This category of exoskeletons is used in various fields, from the rehabilitation of patients with motor disabilities [13], in the military [11] or in sports [17].

[1] They are generally electric motors; in some cases they are pneumatically driven
[2] These are devices that convert energy from one form to another, so that it acts in the physical environment rather than human beings

Unlike their predecessors, exoskeletons of the passive type support human movement, using the restoring forces generated by a system of springs, shock absorbers and other elements. In this case, it is the user's own movement that generates the energy (force) that is subsequently released to assist the user.
Regardless of their type, the use of exoskeletons is nowadays perceived and considered, sometimes only intuitively, as a suitable alternative to reduce biomechanical overload, especially for those cases in which the solutions provided by ergonomic practice do not demonstrate to be resolving or entirely feasible. In recent years, the landscape of this type of device has been populated with both prototypes intended for development and research, as well as commercial products.

Fig. 1: Examples of lumbar support robot **(**Source: XoTrunk – INAIL/Italian Institute of Technology (IIT) project on collaborative exoskeletons

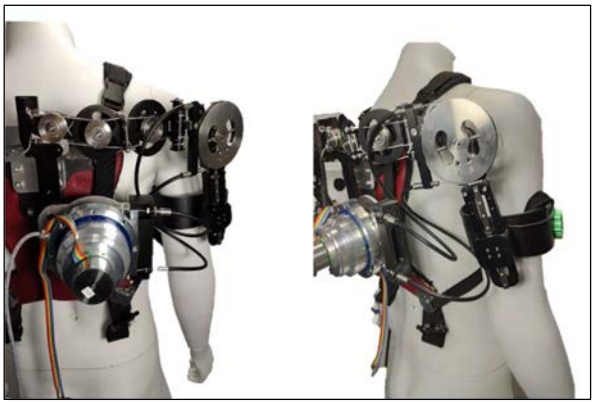

Fig. 2: Example of occupational upper active exoskeleton (Source: Park, Ortiz & Caldwell, 2018)

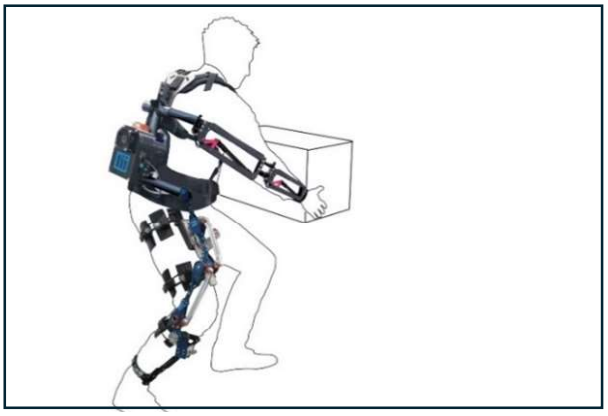

Fig.3: Concept of occupational full body active exoskeleton (Source: INAIL/Italian Institute of Technology (IIT) project on collaborative exoskeletons

3 The exoskeleton and human-centred design (HCD)

For some time now, the technological component of the robotic type has been firmly established in production environments to replace humans in tasks considered to be demanding or unsafe; however, it is necessary to maintain a clear division of the operating space allocated to it in order to guarantee the safety of operators. By using technologies based on 'protections' offered by advanced software, it is now possible to remove this 'physical' barrier, enabling the mutual sharing of the same operating space between man and machine. This is why there is an increasing use of advanced assistive technologies, including occupational exoskeletons, especially in those production contexts equipped to respond effectively to the demands and principles of Industry 5.0. Despite the high level of interest shown in this equipment, its large-scale deployment is still far from being completed. One of the main disincentives is the tendency of designers to adopt prototype design styles developed according to a robot-centric conception, predominantly oriented towards taking care of aspects that oversee production efficiency, with only a marginal focus on health and safety issues. In addition, there is the lack of a supporting body of legislation that could direct the design of these devices to respect the physical and cognitive characteristics of the potential user[3]. In this perspective, the large scale introduction of exoskeletons will imply the need to completely reconsider the approach with which to assess the risk associated with the working load, since the current analysis models provided by the technical standards, in particular those indicated in the UNI ISO 11228 suite mentioned in Annex XXXIII of Legislative Decree 81/2008, are not designed to assess the risk when handling operations are performed while wearing the exoskeleton.

To respond to this need, the technical report UNI/TR 11950 - 'Safety and health in the use of occupational exoskeletons designed to facilitate work activities' was recently published by the UNI/CT 042/SC 01/GL 16 group [22][4] . This is a first important contribution that deals with the topic of occupational exoskeletons in a wide-ranging manner and intends to provide indications on the general guiding principles to be followed in the design, considering the possible criticalities that affect this type of device starting from the description of the different types of exoskeletons available.

It is also necessary to completely rethink the approach by which workload-related risks are assessed, since the current analysis models provided by the technical standards, and in particular those indicated in the UNI ISO 11228 family of standards cited in Annex XXXIII of Legislative Decree 81/2008, are not structured to assess the risk when handling operations are performed when wearing an exoskeleton[5].

As far as research is concerned, the studies conducted so far have focused mainly on the analysis of the surface electromyographic signal of the main muscle groups

[3] The technical standards released on the safety of collaborative robots, such as ISO/TS 15066 [8] for example, focus solely on the characteristics of the control systems to be used in robot cells.

[4] In close coordination with the UNI 'Ergonomics' and 'Machine Tools' Commissions

[5] In this sense, the need to design holistic models that take into account the complexity of human-system interaction must be considered in the future.

involved in the execution of a particular work gesture, with or without an exoskeleton. These are pilot studies, mostly conducted in the laboratory on volunteer subjects, initiated to analyse the effectiveness of the various devices and to understand the possible methods of use in the industrial context and the potential effects of long-term use of exoskeletons.
Lastly, there is a lack of consolidated 'field' data on users' perceptions of the usability and acceptance of exoskeletons, which are difficult to extrapolate tout court from analyses conducted in a controlled context such as that of the laboratory: these are fundamental aspects for the definitive deployment of collaborative robotics and exoskeletons in production environments.
Mention was made earlier of the step change that the design process needs to make in order to facilitate the deployment of exoskeletons in the workplace. This evolution can ultimately only take place if the designer's eye focuses his attention on the end user who would like to make use of these wearable technologies, as the one who has specific needs, determined not only by his physical, sensory and psychological characteristics, but also by the need for a product to be usable and accessible in order to be used effectively. This change in perspective requires an in-depth analysis of how the product interacts with the user, in the light of their experiences, preferences and expectations. In terms of design, this results in the development of objects that are complex from a technological point of view but easy to use, intuitive and comprehensible in their handling[6]. The design of exoskeletons does not escape this scheme.
The synergic relationship between designer and end-user is the basis of what is known as Human-Centred Design (HCD). Designing according to HCD logic therefore means developing effective, efficient, satisfactory and acceptable solutions for as wide a range of users as possible, analysing all possible constraints and feedback received from those who use the product. Forgetting or disregarding certain elements may mean excluding some of the people potentially affected. For this purpose, reference can be made to the standard UNI EN ISO 9241-210 [20], which defines the framework and basic concepts to be followed for the design, development and implementation of human-centred interactive systems. Systems designed with the HCD method ensure improvement at different levels (effectiveness, efficiency, satisfaction in the first place, but also competitiveness and sustainability.
On the subject of HCD design, some recent publications [16; 18; 10], analysing the degree of acceptance in relation to the use of wearable technology, have highlighted the importance of considering issues relating to pleasantness on a par with those relating to safety and comfort of use.

[6] Such products are perceived to be different and better than those of competitors even at higher costs

4 Design aspects of exoskeletons

Studies conducted with regard to their prolonged use in the workplace have highlighted a number of critical issues determined by the fact that wearing an exoskeleton modifies motor behaviour [3; 5; 6][7]. Attention must therefore be paid in the initial stage to all potential conditions of discomfort that may occur at the points of contact between the user and the device itself, bearing in mind that even a minimal level of discomfort could undermine user acceptance. [1;2].

A correct design of a wearable exoskeleton starts with the selection of an appropriate kinematic structure to be given to the device. Even before dealing with the control systems of a device, it is necessary to ensure that the mechanical structure is wearable quickly[8], that it does not affect the ease of operation of the various controls (transparency), and that it does not reduce comfort in the long run by limiting or preventing the user from assuming postures at will. In order to design and develop an exoskeleton, it is important to start with a detailed analysis of the functionalities of the joint district to which one intends to provide support, in the knowledge that, however accurate the reconstruction may be, human biomechanics is so complex that it cannot be assimilated to that of a conventional serial-chain robot. Once the model has been defined, it will be possible to simulate its functionality in order to understand whether, and to what extent, the device is truly compatible. In this regard, giving the exoskeleton a morphology similar to that of the human being could make it possible to overcome, or at least minimise, those critical conditions that arise when the coupling between the exoskeleton and human anatomy does not allow movements to be performed naturally. Taking advantage of the current potential of technology (sensors, computing capacity, etc.), the exoskeleton could also be equipped with sensors capable of perceiving the subject's movements in advance, in a sort of self-learning system that allows the actuators with which it is equipped to respond to the various solicitations appropriately and without delay, recognising voluntary movements from random or unintended ones. Another nodal point is the need to provide the exoskeleton with a number of degrees of freedom in movement sufficient to allow smooth movement of body segments under conditions of varying speed and acceleration [23].

Lastly, the need to limit the weight and bulk of the exoskeleton must be taken into account, considering the increase that would result if the number of elements (joints, actuators, motors, batteries, etc.) were to be increased in order to improve its functionality.

In this scenario, it becomes important to think about how to manage the exchange of information acquired by the sensors at the expected human-machine contact points (feedback).

[7] With possible redistribution effects of the strain on other joint districts, which are normally little or not at all involved during manually performed work tasks

[8] Including undressing.

5 Design features of a safe working exoskeleton

We have previously discussed the need to use the HCD approach, given the complexity to be expected of the exoskeleton, in light of the critical issues listed above. In the first phase of the HCD process, knowledge of the context of use (characteristics of the workplace; type of handling/handling required) in which to introduce the exoskeleton is fundamental. For this purpose, useful elements[9] for the design can also be deduced by reading the UNI ISO 11228 series [21], in the ISO 11226 standard [7] and in the ISO/TR 12295 technical report [7], focusing on the risk factors that contribute to the definition of the various risk indices.

The next step in this design approach is to specify the requirements to be given to the device in order to meet the user's needs, with reference to: the anatomy and sex of the potential users; the degrees of freedom to be provided to accompany movement; the conditions of dressing and undressing[10]; the shape and size, weight and materials used Intuitiveness of use of the various components (e.g. cognitive resources required); the conditions at the interface points during use; to the effects on physiology determined by organisational aspects (e.g. the right balance between activity and inactivity); to the aesthetic appearance of the working exoskeleton.

The last step in the HCD process is the assessment of the gap between the design context and user requirements, an analysis that requires the active participation of users repeated as often as necessary.

The following points outline the most salient technical, managerial and environmental aspects to be taken into account for a correct qualitative assessment of the device when making a choice between different models already on the market.

5.1 Weight and footprint

The weight and size of the device have a direct influence on its perceived comfort. When selecting, it is advisable to opt for the lightest and most compact solutions possible, compatible with the intended use, in order to minimise fatigue conditions and the risk of interference and impact with the components and instruments present in the workplace.

5.2 Fit, adjustability and degree of assistance provided

Fit and adaptability are two key factors to consider when choosing the most suitable device for one's situation, as they have a direct impact on the wearer's perception of comfort and influence the correct use of the exoskeleton. The devices should be chosen to support as wide a range of subjects as possible in terms of anthropometric dimensions: multiple sizes should therefore be considered.

The adjustment devices developed by the designer must be easy to apply and be such that they maintain the same settings even after many hours of use. The level of

[9] Frequency of the required gesture, weight moved, geometries, duration of the task, age and sex of the user,...

[10] Considering these aspects in possible emergency situations

assistance provided must also be controllable at the user's request, according to the needs of the moment. Lastly, all the dressing/undressing operations of the device should be simple to carry out independently and in a time suited to the needs of the workstation and the type of work organisation.

5.3 Materials: breathability, hygiene and environmental conditions of the workplace

The choice of materials significantly influences the exoskeleton's ability to support the wearer in performing the required tasks. This particularly concerns the materials chosen for the parts of the exoskeleton that come into direct contact with the wearer. Removable covers and washable fabrics are preferable because they make it easier to clean the exoskeleton.

5.4 Potential critical mechanical issues in use and emergency situations

Attention should be paid to models that show good compatibility of the exoskeleton's fastening systems with the user's work clothes and that guarantee the user the possibility of having total control over the device itself, even when it is not in use but is worn in the rest position.

5.5 Suitability to the work environment

Particular attention must be paid to verifying that the movement of the individual parts of the device can take place without causing impacts within the workplace. It is then essential that the exoskeleton is structured in such a way that the operator has total control over the device itself and is able to deactivate, on demand, the mechanical parts and to quickly release, in the event of an emergency, the active parts of the exoskeleton in order to be able to secure himself without his movements being hindered.

6 Conclusions

Exoskeletons can support workers effectively in the performance of certain specific tasks, reduce stress caused by biomechanical overload and ultimately help to prevent disorders of the musculoskeletal system. However, for a number of reasons, mainly related to the lack of knowledge of the long-term effects of the use of these devices, the practical resolution of the technical issues and ii possible problems of usability and user acceptance, the widespread use of exoskeletons in the professional field is less than it could be. In this perspective, a user-centred design (HCD) approach, because of its characteristic of involving users from the earliest design phases, could prove to be the appropriate tool to ensure that in production environments, activities subject to biomechanical overload are increasingly supported by exoskeletons.
All the indications given in this article represent suggestions to be considered in the design or choice of the most appropriate devices that are able to synergistically combine terms such as usability, acceptability, pleasantness and effectiveness,

expressed in terms of productivity with a careful look at the prevention of the risk of exposure to biomechanical overload.

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Results of the DEGS1 study on allergic sensitisation to wheat flour and prevention of occupational respiratory allergies

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Abstract

Introduction: Occupational respiratory allergies have a high socio-economic relevance. Baker's asthma is an occupational disease under German social insurance law. Those affected are often no longer able to carry out their work for health reasons. Inhalation of wheat flour (WF) and rye flour dusts are the most common cause of occupational asthma. In general population, however, WF is a food allergen.

Methods: Representative blood samples (n=7,024) of DEGS1 (German Health Interview and Examination Survey for Adults) were analysed for specific IgE antibodies (sIgE) against WF and 50 other common allergens.

Results: The prevalence of sIgE-sensitisation to WF (WF positive) is 5.6%. Younger people (18-29 years) are more frequently affected (8.6%). Polysensitisations (≥20 allergens) is significantly more frequent in WF-positive (70.6%) than in WF-negative study participants (1.8%).

The prevalence of bronchial asthma / allergic rhinitis is significantly higher in WF positive (25.2 % / 49.4 %) than in WF negative (7.3% / 13,3%) participants.

Discussion: Baker's asthma is probably often a kind of “continuation of the atopic march in working age”, which begins in childhood and develops from a pre-existing respiratory allergy and sensitisation to WF.

Conclusion - Primary prevention: Occupational counselling for young people with allergic respiratory diseases (asthma, rhinitis) should take place as early as possible and before choosing a career.

Conclusion - Tertiary prevention in the workplace: Comprehensive measures to reduce flour dust in the workplace are necessary. This includes innovations such as low-dust, hydrothermally treated flours. Frequently occurring non-occupational allergies (pollen, house dust mites, animal epithelia) must also be taken into account in individual prevention.

1 Introduction

1.1 Allergic respiratory diseases as widespread diseases

The lifetime prevalence of bronchial asthma and allergic rhinitis (e.g. hay fever) in the German general population is 8.6% and 14.8% respectively [1]. Allergies to

pollen from grasses, trees and herbs, house dust mites and epithelial cells from animals (e.g. cats, dogs, horses) are common.

1.2 Occupational respiratory diseases

In an occupational context, allergic respiratory diseases are usually caused by organic occupational dusts. In addition to flour dusts, these include grain and animal feed dusts, wood dusts, dusts from various foods, animal epithelia, feathers, dusts from mites and other storage pests, enzymes and mould-containing dusts [2].
These are usually IgE-mediated respiratory diseases. Specific IgE antibodies (sIgE) against the respective triggering occupational substances can usually be detected in the blood.
According to the 'United Airways' concept, allergic rhinitis is regarded as a precursor to bronchial asthma. In the case of allergic occupational asthma, the changes in lung function (obstruction) and symptoms (e.g. breathlessness, cough, asthma attacks) correlate closely with exposure to allergens at the workplace. With complete allergen avoidance, the disease is usually fully reversible.

1.3 Flour dust is the most common cause of occupational asthma (baker's asthma)

Inhalation exposure to flour dust in baking production is the most common cause of occupational asthma in Germany [2]. Baker's asthma and rhinitis is an occupational disease under German social insurance law (Berufskrankheit 4301) [2]. Those affected are often no longer able to carry out their work for health reasons. The disease has a high individual and socio-economic relevance. Baker's asthma is therefore particularly suitable for exemplary considerations for primary prevention and for individual prevention (secondary and tertiary prevention) in the workplace. sensitisation to flour is the immunological prerequisite for baker's asthma and rhinitis. Specific IgE antibodies (sIgE) in the blood against wheat and rye flour can usually be detected diagnostically.

2 The "German Health Interview and Examination Survey for Adults" (DEGS)

2.1. General information on the DEGS study

The "German Health Interview and Examination Survey for Adults" (DEGS) is a nationwide longitudinal study carried out by the Robert Koch Institute (RKI) within the framework of a continuous health monitoring programme. The aim of this study is to provide representative data on the health status of adults in Germany on a regular basis, to calculate trends in the development of health indicators and to gain insights into the development of health during life. The first wave of data collection (DEGS1) was carried out from November 2008 until December 2011 and comprises health interviews and physical examinations as well as blood and urine sampling [3].

2.2. Results on sensitisation to wheat flour (sIgE)

Wheat is a staple food and a food allergen in the non-occupational context. The general population is an important reference group for occupational groups from baking production with aerogenic exposure to flour dust.

With our DEGS study of 7,024 blood samples, we have conducted and published one of the world's most comprehensive studies on sensitisation to wheat flour. The most important results are [4]:

- The prevalence of sensitisation (sIgE) to wheat flour is 5.6%. Younger people (<29 years: 8.6%) are more frequently affected than older people (>50 years: 2.8 to 3.4%) (Figure 1).

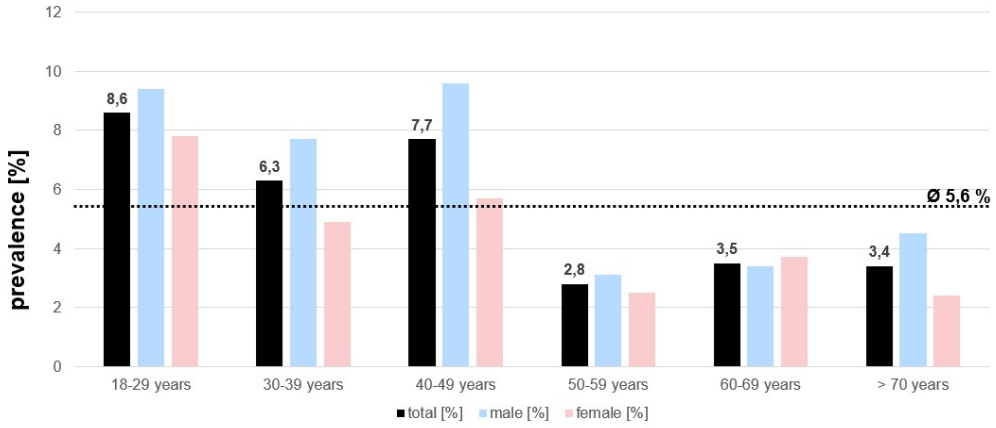


Fig. 1: Prevalence (%, weighted) of sensitisation (sIgE) to wheat flour in the German adult population (n = 7,024) stratified by age and gender [4].

- sensitisation to wheat flour is strongly dependent on total IgE (tIgE), which is usually elevated in atopic diseases (Figure 2) [4].

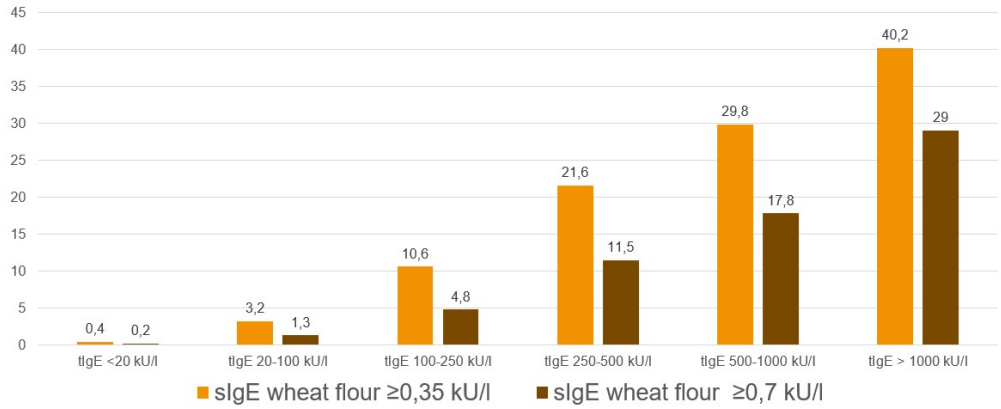


Fig. 2: Prevalence of sensitisation to wheat flour (sIgE) [%] in relation to total IgE (tIgE) [4]

- Sensitisation to WF is usually associated with pronounced polysensitisation (Figure 3 and 4). Polysensitisations (≥20 allergens) were present in 70.6% (WF positive) respectly 1.8% (WF negative) (Figure 4).

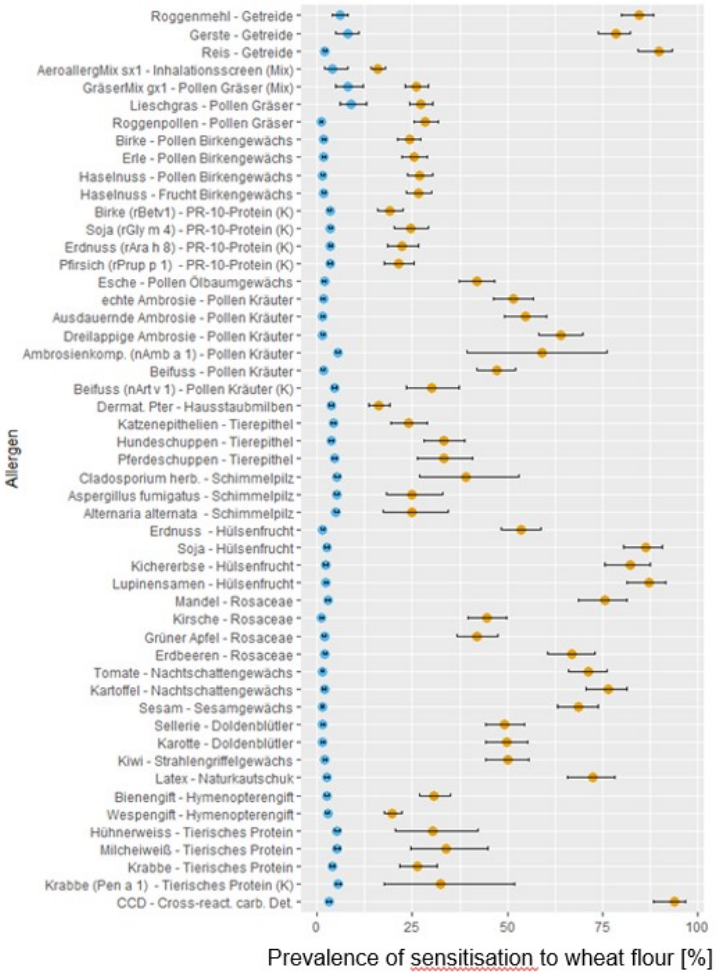


Fig. 3 shows the relationship between wheat flour (sIgE) and 50 other allergens (sIgE): The prevalence of wheat flour sensitisation [%] with positive sIgE (blue) and negative sIgE (orange) against the respective allergen in the list [4]

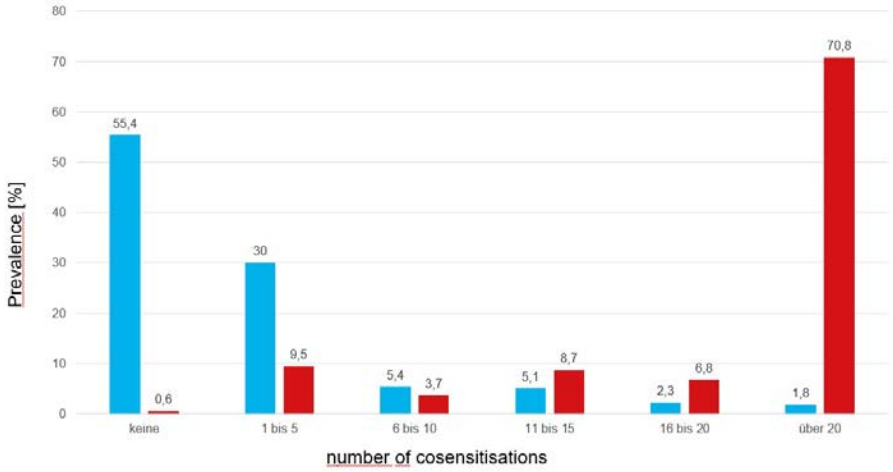


Fig. 4 Number of Cosensitisations in wheat flour sIgE-negative (blue) and wheat flour sIgE-positive (red) persons [4]

- The lifetime prevalence of bronchial asthma / allergic rhinitis is significantly higher in WF-positive participants (25.2 % / 49.4 %) than in WF-negative participants (7.3 % / 13.3 %), although there is no occupational exposure to flour dust in the general population [4].

2.3 Discussion

Many people with baker's asthma and baker's rhinitis fall ill during their first few years of work. Pre-existing non-occupational allergic respiratory diseases from childhood and adolescence are the rule [2,4]. Baker's asthma is probably often a kind of 'continuation of the atopic march in working age' that begins in childhood. There is much to suggest that it often develops based on polysensitisation and a pre-existing respiratory allergy [4].

3 Conclusion: Primary Prevention of baker`s asthma

Our results indicate that allergological occupational counselling for young people with bronchial asthma and allergic rhinitis should take place as early as possible before choosing a career. The significantly increased risk of developing an occupational disease should be explained at an early stage [2].

4 Conclusion: Tertiary prevention in the workplace

By minimising exposure to flour dust and other allergens (e.g. enzymes) in the workplace, good asthma control can often be achieved in conjunction with modern asthma therapy. However, baker's asthma cannot be cured causally. A change of occupation with strict allergen avoidance should always be considered, taking psychosocial and socio-economic factors into account. This is particularly important for employees at a young age or with severe bronchial asthma.

The STOP principle represents the order of priority in occupational health and safety. Allergen exposure in the workplace should be systematically reduced

according to this principle. Table 1 gives concrete examples of different measures in the baking industry.

S	**S**ubstitution	• substitution of enzyme dusts with liquid baking agents • flour substitution is naturally not possible
T	**T**echnical measures	• sealed silo system • air extraction at the flour inlet • the use of flours with low dust release as hydrothermally treated flour (picture 1) • low-dust cleaning (no compressed air, damp cleaning, special hoovers) • structural measures (e.g. separation of dusty areas)
O	**O**rganisational measures	• intra-company transfer to low-dust areas (e.g. confectionery, baking oven, packaging, delivery)
P	**P**ersonal measures	• low dust working techniques • personal protective equipment (e.g. Half face masks) • Drug therapy for asthma • Regular medical check-ups

Table 1 Examples of S-T-O-P measures in the baking industry [4,5]

One example of innovative industry-specific solutions is low-dust, hydrothermally treated flours (HT-flour). This parting flours were first moistened and then dried. With the use of HT flours, a marked reduction in the respirable fine dust fraction can be achieved (Figure 6).

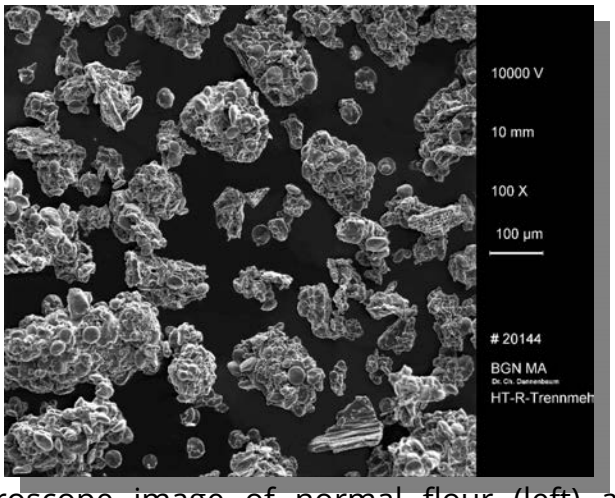
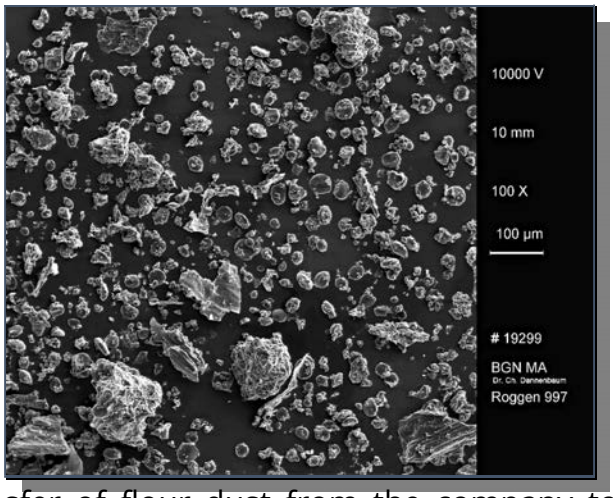


Fig. 6 Electron microscope image of normal flour (left) and hydrothermally treated flour (right) using the example of rye flour, which is also frequently used in German baking production



In addition, the transfer of flour dust from the company to private areas (e.g. through clothing) must be avoided.

In the case of common non-occupational allergies to pollen, house dust mites or animal epithelia (e.g. cat, dog), it is also important to ensure that exposure to allergens is minimised.

In summary, it can be stated that comprehensive measures to minimise allergens and good medical care are necessary for the tertiary prevention of baker's asthma in the workplace.

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Evaluating Firefighters' Physiological Responses in Wildfire Suppression Scenarios: A Wearable Technology Approach

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Abstract
Firefighters (FFs) encounter a complex array of stressors—from internal, psychosocial challenges to external, biogenic factors like extreme temperatures, strenuous activities, and exposure to hazardous chemicals—all impacting their health and performance. In wildfire scenarios, FFs face conditions that evoke strong fight-or-flight responses, underscored by fear and physical demands. Chronic stress in this profession, linked to a heightened risk of cardiovascular issues—the leading cause of line-of-duty deaths—underscores the critical need for continuous health monitoring in high-risk jobs. Traditional laboratory studies, with their simplistic stress evaluations, often fail to capture the nuances of real firefighting, and FFs' self-reported data often reflect individual biases and coping mechanisms. This study leverages wearable technologies to provide a multiparametric analysis of FFs' physiological responses, overcoming the limitations of traditional methods. FFs enrolled from the National FireFighter Corp participated in this study: the monitoring protocol was specifically designed to track deviations from baseline physiological states and to assess the acute impacts of varied stress levels on heart rate (HR), and respiratory rate (RR). Measurements were taken while FFs performed static tasks—such as standing while donning personal protective equipment—as well as during dynamic simulated wildfire suppression activities under elevated temperatures.
Preliminary results indicate that the integrated technologies effectively monitor and analyze the physiological impacts of firefighting. Despite minor difficulties during periods of intense activity, the system's performance was robust, providing crucial insights essential for developing targeted interventions aimed at enhancing FFs safety and health.

1 Introduction

Wildland firefighting is an exceptionally demanding profession, involving diverse tasks such as hiking, constructing fire lines, clearing brush, operating chainsaws, and setting controlled backfires [1], [2]. These tasks are performed under challenging conditions, including exposure to smoke, high environmental temperatures, and navigating steep terrains—all while wearing heavy personal protective equipment.

This profession primarily unfolds during the summer season when forest conditions are dry, amplifying the physical and environmental challenges.

The physical demands of wildland firefighting are comparable to those faced by other physically demanding professions such as soldiers, lifeguards, and structural FFs. Studies have shown that these professions require substantial physical endurance due to the nature of their tasks and the challenging environments in which they operate [3], [4], [5]. Specifically, FFs, both structural and wildland, must perform physically strenuous tasks under high thermal strain from proximity to fire, compounded by limited heat dissipation due to protective gear [6], [7]. In 2024, over 600 wildfires burned approximately 220 km^2 in Italy, as documented by the European Forest Fire Information System (EFFIS) [8]. This underscores the rigorous conditions under which wildland FFs operate, where real-world scenarios pose unique, unpredictable challenges.

Research on the physiological parameters of FFs has been predominantly confined to controlled environments and laboratories. Field studies on FFs' physiological responses are rare, and among these few, none have detailed the dynamics of what happens in each phase of fire suppression [9], [10], [11], [12]. Overexertion and stress led to over half of FF fatalities in 2023, largely due to sudden cardiac events, emphasizing the intense physiological burdens faced by FFs (NFPA) [13], [14].This highlights the severe physiological burdens FFs face, exacerbated by navigating difficult terrains, enduring high temperatures, inhaling smoke, and managing heavy personal protective equipment (PPE), weighing between 5 kg and 20 kg. The physiological demands on FFs necessitate a sophisticated understanding of their cardiorespiratory fitness and stress levels during operations. Continuous physiological monitoring is essential, enabling the categorization of HR into zones that reflect different intensity levels. These zones are crucial for assessing the stress and exertion experienced by FFs. High-intensity activities often push HR to or beyond the age-predicted maximum (HR_{APM}), aligning with the upper zones, which indicate severe physiological stress and high energy expenditure [15], [16], [17], [18], [19].

Effective management of these exertion levels according to HR zones allows for optimized work-rest intervals, enhancing safety and operational efficiency. Moreover, monitoring RR at critical times—specifically at the beginning and end of firefighting tasks—is also vital. An elevated RR at the onset can indicate initial stress responses and preparedness for intense activity [20], [21], while monitoring RR post-operation helps assess recovery status and potential strain from the activities performed [22], [23].

Tactical approaches to wildfire suppression, such as direct and indirect attacks, further intensify these challenges by varying the physical demands placed on FFs. Direct attacks involve confronting the fire up close, necessitating quick, vigorous actions and exposing FFs to intense heat and physical stress. Conversely, indirect attacks occur from a safer distance—often over 100 meters from the flames, focusing on isolating the fire's fuel source from remaining vegetation by constructing fire lines.

These barriers help prevent the fire's spread and, while reducing heat exposure, still demand significant physical labor and strategic planning, leading to unique physiological and recovery challenges [9], [11], [24].
These tactical differences in wildfire suppression highlight the complex and variable nature of the challenges faced by wildland FFs. Both approaches require extensive training and physical resilience, underscoring the need for continued research and development of supportive measures to enhance FF safety and effectiveness in these demanding environments [1], [10].
The distinction between these attack strategies and their physiological impacts has not been comprehensively evaluated in the context of actual wildfire scenarios. This study aims to bridge the gap in current research by testing wearable technology in challenging field conditions. Deploying this technology in real wildfire scenarios allows for continuous physiological monitoring, enhancing tactical decision-making and improving firefighter safety and effectiveness in both direct and indirect firefighting approaches.

2 Methods

2.1 Participants enrolment

Twelve wildland FFs from the National Fire Corps (CNVVF) of Rome participated in this study, conducted at the training school located at the Multifunctional Training Center in Montelibretti (Rome, Italy) on the 4th of September 2024. The FFs were organized into two heterogeneous teams, Team 1 and Team 2, with varying numbers of instructors to ensure each team had at least one instructor supporting the trainees. Specifically, Team 1 included two instructors and four trainees, while Team 2 was composed of one instructor and five trainees. Prior to the start of the study, the main anthropometric characteristics of the subjects were collected and are detailed in Table 1. Each FF was equipped with standard firefighting gear, which includes fireproof overalls made of 65% viscose, 30% aramidic, and 5% pararamidic, helmets, gloves, face neck shrouds, and mid-calf leather boots. Notably, only Team 1 was equipped with FFP3 masks during the data collection phases. Instructors specifically wore the Operational Helmet. Additionally, each participant carried various tools weighing between 3 to 20 kg necessary for their operational duties.

	Team 1	**Team 2**
Age [years]	34.5±15.7	33.7±12.6
Body Mass [kg]	79.2±8.5	72.7±6.7
BMI [kg·m^{-2}]	24.4±2.6	23.2±1.2
Height [cm]	180.2±8.6	176.8±6.7

Table 1 - Average anthropometric characteristics of Team 1 and Team 2 members, including age, body mass, height, and BMI mean ± standard deviation.

3 Experimental Design and Protocol

To measure the FFs' values of HR, RR, and level of activity during various tasks in wildfire suppression, data were collected using advanced monitoring equipment. The setup included a thoracic strap designed to track cardiac and respiratory parameters. This strap featured a respiratory strain sensor with a sampling rate of 25 Hz, electrodes for recording electrocardiograms at 250 Hz, and an accelerometer module that recorded movements at 100 Hz. External temperature was monitored using a standalone data logger equipped with a thermistor probe, which logged over 32,000 readings and offered a broad measurement range from -40 to 125°C. The probe provided high accuracy within specific temperature ranges, ensuring precise ambient condition tracking. To ensure the thermistor accurately captured the environmental conditions during the experiments, it was placed outside the subjects' jackets. The monitoring devices were regularly maintained to guarantee functionality, including recharging and refreshing the equipment, with data periodically downloaded from the memory cards of the devices.

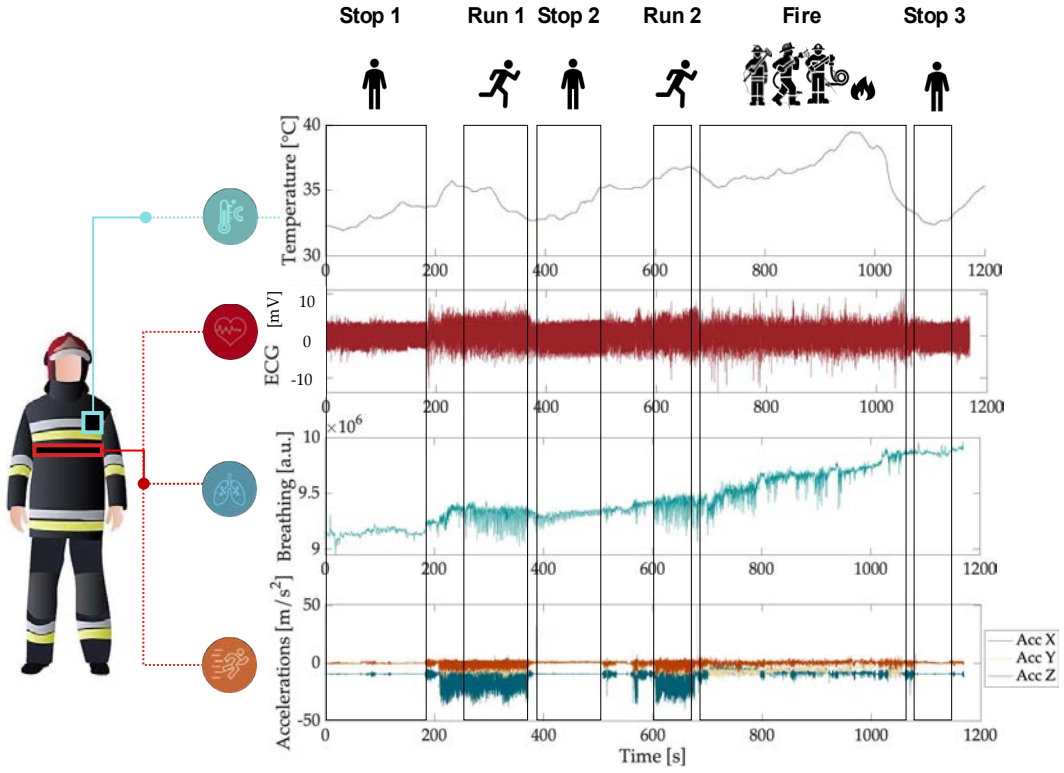

Fig. 1. Wearable monitoring systems placement on a FF during the protocol. The plots from top to bottom show temperature and ECG, respiratory, and acceleration (X, Y, Z axes) signals over ~1200 s. Distinct exercise phases are highlighted by outlined boxes.

The study's protocol consisted of six distinct phases: 'Stop 1' for baseline data collection at rest, 'Run 1' to elevate physiological stress, 'Stop 2' for recovery observation, 'Run 2' to simulate approaching a fire, 'Fire' for engaging in direct and

indirect firefighting tasks, and 'Stop 3' to assess physiological recovery post-suppression (Figure 1). It was thoughtfully crafted to realistically depict the demanding conditions of wildfire suppression, incorporating both direct and indirect firefighting tactics, as detailed in the 'Fire' phase of the simulation (Figure 2). This key segment of the protocol was designed to closely simulate the intense environment of an actual wildfire, challenging participants with tasks that required both direct and indirect methods of fire suppression. During the 'Fire' phase, participants were strategically assigned roles that corresponded to these tactics. The direct attack roles involved handling the hose for immediate fire suppression, designated as 'L1' for Team 1 and 'L2' and 'L3' for Team 2. These roles required participants to engage directly with the simulated fire, aiming to quickly reduce its intensity using the hoses. In support of the hose handlers, additional team members, 'S1' for Team 1 and 'S2' for Team 2, were tasked with providing hose support. These roles were crucial for the effective deployment and management of the firefighting equipment, ensuring that those handling the hose could maintain a continuous and efficient attack on the fire. Simultaneously, the indirect attack was simulated by participants designated as 'R1', 'R2', 'R3', and 'R4' in Team 1, and 'R5' and 'R6' in Team 2, who were responsible for using rakes to manage surrounding debris. This task is vital in real-world fire containment strategies, as it involves clearing flammable materials and creating firebreaks to prevent the spread of the fire beyond its existing perimeter. By incorporating both direct and indirect firefighting tactics into the simulation, the protocol provided a comprehensive view of the varied and critical roles within a firefighting team during wildfire suppression.

Fig. 2. FFs of Team 1 performing different tasks during fire suppression phase.

3.1 Data Processing

Raw data from the chest strap were processed in MATLAB 2024a to extract physiological, physical, and environmental parameters from the chest strap and the thermistor. The physiological signals from ECG and breathing sensors

underwent filtering to assess heart HR and RR. ECG signals were processed with a 20-30 Hz Butterworth bandpass filter to isolate QRS complexes for accurate HR measurement, while RR signals were also refined using a 0.1-0.7 Hz Butterworth bandpass filter to ensure reliable measurement.Physical activity was analyzed using data from an integrated triaxialaccelerometer, filtered between 0.1 and 0.8 Hz, and the Vector Magnitude Unit (VMU) was calculated.The VMU is derived by calculating the square root of the sum of the squares of the individual acceleration along the three axes. This value allows for a precise measure of movement intensity:

$$\mathrm{VMU} = \sqrt{\mathrm{x}^2 + \mathrm{y}^2 + \mathrm{z}^2} \quad (1)$$

The conversion from the acceleration value, expressed in m/s^2, to VMU in gravities (g) is then accomplished. To accurately capture the environmental conditions faced by FFs, temperature data were collected at a high frequency, recording every second to document the rapid temperature changes during active firefighting. This high sampling rate is crucial for tracking transient fluctuations that can critically impact thermal stress assessments. The thermistor was strategically placed on two FFs in roles closest to the fire. The choice of a one-second sampling interval aligns with the dynamic and quickly changing environment of firefighting, providing a continuous and detailed temperature profile essential for evaluating protective gear effectiveness and developing safer firefighting tactics.

4 Results

The mean values for RRs and HRs for each subject of each team during each phase are documented in Table 2.

	RR $_{mean \pm std}$ [bpm]						***HR $_{mean \pm std}$ [bpm]***					
Team 1	**Stop 1**	**Run 1**	**Stop 2**	**Run 2**	**Fire**	**Stop 3**	**Stop 1**	**Run 1**	**Stop 2**	**Run 2**	**Fire**	**Stop 3**
L1	10.8±3.0	27.6±24.5	13.7±2.7	15.6±4.5	14.6±7.0	17.6±0.7	-	-	-	-	-	-
R1	10.1±1.7	22.1±6.0	12.9±2.0	13.7±8.9	24.3±8.1	11.8±0.8	80.3±8.9	132.3±10.4	114.4±16.7	125.7±10.4	121.0±7.5	123.2±10.6
R2	12.5±3.5	22.2±6.6	19.3±5.9	25.8±11.4	20.6±9.4	18.4±5.9	81.3±6.6	137.9±16.2	127.5±14.1	129.6±14.9	145.4±6.2	145.9±6.9
R3	11.2±2.2	15.3±2.7	13.4±1.5	11.8±6.4	20.4±4.2	15.1±2.4	80.3±8.1	144.3±32.9	124.9±15.0	137.8±43.1	151.9±13.6	146.7±8.5
S1	15.7±7.6	22.3±1.8	15.8±6.1	24.0±1.4	15.5±6.9	10.7±2.3	87.1±7.2	135.2±15.7	124.5±13.1	137.2±17.9	138.8±6.7	140.6±5.0
R4	14.6±2.34	15.9±1.6	17.0±3.4	18.6±7.2	33.5±10.1	19.5±0.9	90.8±8.0	147.5±12.7	121.4±16.8	143.7±17.8	164.8±8.0	147.2±11.3
Team 2	**Stop 1**	**Run 1**	**Stop 2**	**Run 2**	**Fire**	**Stop 3**	**Stop 1**	**Run 1**	**Stop 2**	**Run 2**	**Fire**	**Stop 3**
R5	16.1±6.2	17.8±8.8	21.7±6.9	22.3±12.5	26.6±14.1	25.1±6.8	-	-	-	-	-	-
L2	15.4±5.1	26.6±7.4	22.2±2.2	17.5±6.1	15.1±7.6	16.4±7.9	97.8±7.7	144.5±10.1	125.0±17.7	140.0±12.3	141.5±7.0	130.2±5.7
S2	21.7±9.6	22.5±11.8	26.7±9.0	48.9±25.5	23.5±14.0	26.6±13.2	98.1±7.9	134.3±18.0	131.2±11.8	130.2±16.7	130.4±7.3	123.0±1.7
S3	17.3±6.8	20.3±10.6	26.1±6.0	18.9±11.6	16.4±11.0	21.1±6.8	91.9±3.9	139.2±12.5	106.9±13.1	138.5±14.6	129.7±13.5	114.2±6.7
L3	11.5±3.6	16.3±4.9	21.0±11.2	24.1±18.0	16.2±9.3	11.4±1.9	111.2±6.8	145.7±16.2	146.4±12.7	150.1±13.5	149.2±12.0	140.8±6.8
R6	17.9±4.1	22.6±3.8	20.7±2.2	31.7±2.8	26.8±11.4	18.3±6.0	130.0±3.2	152.2±12.3	162.0±8.4	161.1±7.9	170.7±4.5	164.4±4.3

Table 2 – RR and HR values expressed as mean ± standard deviation (std) calculated for all subjects over all the phases of the protocol. '-' indicates data were unavailable, and subjects L1 and R5 were excluded.

RR values typically fall into the following categories:

- *Bradypnea*: characterized by a slow breathing rate of less than 12 bpm (breaths per minute), indicating a state of relaxation or, in some cases, respiratory suppression.
- *Eupnea*: normal, unlabored breathing ranging from 12 to 20 bpm, reflecting a stable and comfortable state of respiration.
- *Tachypnea*: An elevated respiratory rate exceeding 20 bpm, often occurring in response to stress or increased physiological demand. This rate is crucial for enhancing oxygen intake and carbon dioxide expulsion.

During the recovery phases ‘Stop 2’ and ‘Stop 3’, a transition from tachypnea back to eupnea was typically expected as the body recovered. Monitoring these transitions provides critical insights into the effectiveness of the body's stress responses and recovery mechanisms, which are vital for designing training and recovery protocols. Notably, all subjects generally returned to a state of eupnea by the end of the simulation (phase ‘Stop3’), with average values falling within the normal breathing range of 12 to 20 bpm. However, subject S2 from Team 2 exhibited RR starting from 21 bpm and above even at the onset, indicating that the subject entered the protocol in a state of mild tachypnea. This condition may suggest either pre-existing stress or an initial heightened physiological arousal, potentially impacting their overall performance and recovery dynamics.

In terms of cardiac response, this study assesses the physiological responses of FFs during various tactical operations, focusing on HR as a measure of exertion and cardiovascular strain. The HR_{APM} formula establishes benchmarks for individual exertion levels during different firefighting activities: HR_{APM} = 220 bpm (beats per minute) - age. According to the American College of Sports Medicine (ACSM), exercising at 85% of HR_{APM}falls into the "vigorous" or "hard" intensity category. This intensity level is crucial for evaluating when cardiovascular effort suggests significant physiological stress. The threshold is calculated as 85% HR_{APM} = 0.85 · (220 bpm - age)[17].

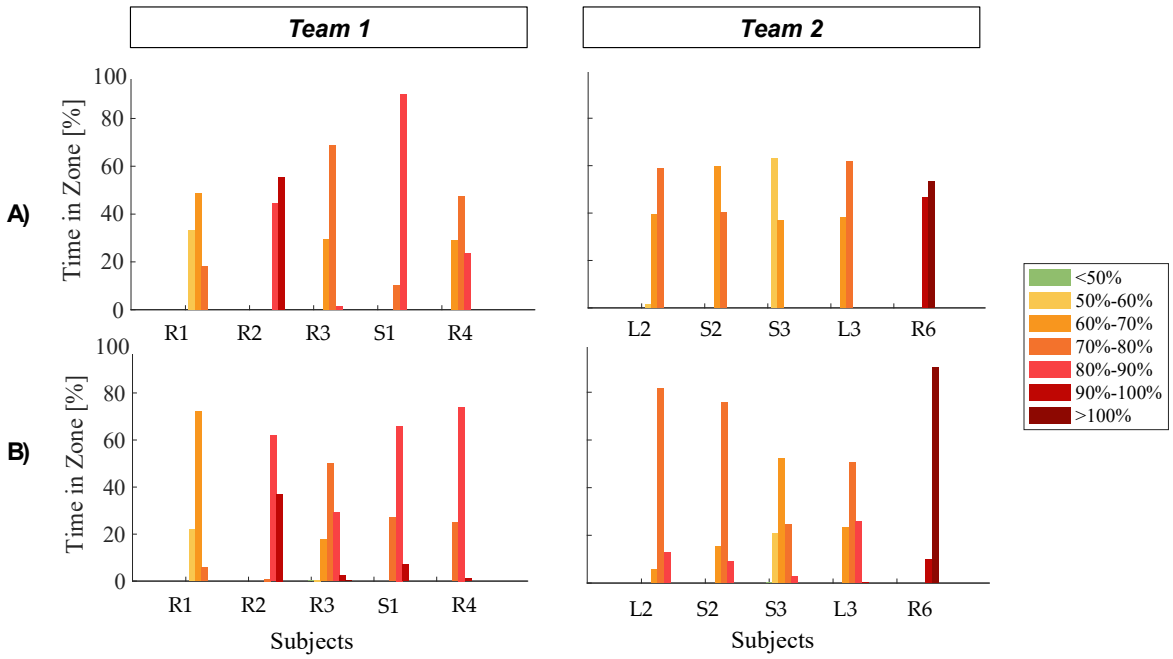

Fig. 3. HR zones from 1 to 5, with an added zone for <50% HRAPM and a zone exceeding the maximum age-appropriate heart rate (HR_{APM}).

For detailed analysis of exertion, the "Training Effect" methodology [25]categorizes HR data into zones, facilitating an understanding of the physiological demands and recovery needs associated with different firefighting tasks (Figure 3):

- **Zone 1**: <60% of HR_{APM}– Mostly restorative benefits, low intensity.
- **Zone 2**: 60-70% of HR_{APM}– Moderate intensity, suitable for most cardiovascular training.
- **Zone 3**: 70-80% of HR_{APM}– Targets improvement in efficiency and agility.
- **Zone 4**: 80-90% of HR_{APM}– High intensity; potential for overtraining.
- **Zone 5**: 90-100% of HR_{APM}– Very high intensity, maximum effort, used sparingly to avoid excessive stress.

Graphical representations illustrate the percentage of time each FF spends in each HR zone, underscoring the variability in cardiac exertion between direct and indirect firefighting tactics during the active fire suppression phase ('Fire'). It is particularly noteworthy to observe instances where FFs' HRs exceed the vigorous intensity threshold (>85% HR_{APM}– Zone 4).

Following the cardiac response analysis, accelerometer data sourced from chest straps provided further insights into physical activity levels, categorizing them into three distinct intensity categories based on VMU thresholds of 0.2 g and 0.8 g. These thresholds define the levels of exertion as follows:

(1) **Low Intensity (<0.2 g)**: are considered low intensity, indicative of minimal physical exertion observed during recovery tasks.

(2) **Moderate Intensity (0.2 g to 0.8 g)**: this range covers activities equivalent to standard intense walking or running, reflecting the typical demands of

most firefighting operations where maximal effort is not continuously required.

(3) **High Intensity (>0.8 g)**: categorized as high intensity, representing vigorous and sustained physical efforts. Such levels are usually required in emergency situations where rapid and intense actions are critical.

During the 'Fire' phase (beyond almost 50-60 % time), the variability in activity intensities was notably influenced by the specific firefighting tactics employed—direct and indirect attacks. This distinction provides valuable insights into the physical demands placed on FFs depending on their proximity to the fire and the nature of their tasks. In direct attack scenarios, FFs such as 'S1' in Team 1, and 'L2' and 'L3' in Team 2, who were engaged in handling hoses for fire suppression, encountered a different kind of physical exertion. Holding and maneuvering the fire hose, which involves substantial weight and requires considerable strength, predominantly resulted in moderate intensity activities. This task demands maintaining a controlled posture while managing the hose under high pressure, which is physically demanding yet does not typically lead to high accelerometer readings as the movements are more static but strenuously sustained.In these direct attack scenarios, the standalone temperature data logger worn by instructors 'S1' in Team 1 and 'S2' in Team 2 recorded temperatures that reached respectively maximum 39.5°C and 40.3°C, providing a detailed record of the extreme thermal challenges during active fire suppression. This underscores the intense conditions faced by hose handlers, who must balance the physical demands of managing high-pressure hoses with the environmental heat of direct fire engagement. Conversely, FFs involved in indirect tactics, such as 'R1' through 'R4' in Team 1, and 'R5' and 'R6' in Team 2, who used rakes to manage surrounding debris, frequently recorded high-intensity levels. Positioned further from the direct fire but highly mobile, these individuals often exceeded the 0.8 g threshold on accelerometers, indicating vigorous physical effort. The use of heavy tools like rakes—typically weighing between 1 to 2 kg—and the need to move rapidly to clear debris or create firebreaks, contribute to this high-intensity classification. Their continuous movement, coupled with the weight of PPE, significantly adds to the physical load.

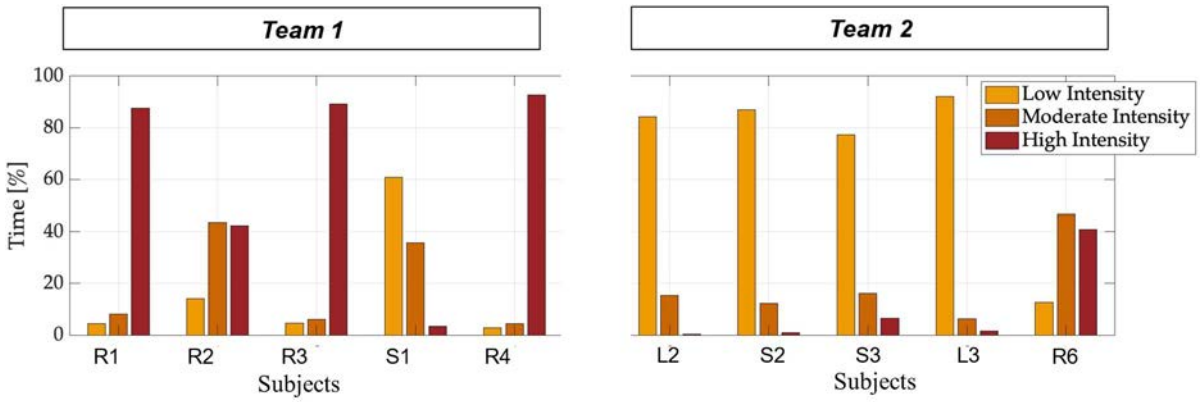

Fig. 4. Percentage of time spent in Low, Medium, and High intensity activities for Team 1 and Team 2.

5 Discussions and conclusion

In the study of wildland firefighting dynamics, the intense and variable physical demands across different firefighting tactics were closely examined. Particularly during the 'Fire' phase, FFsengaged in direct attacks showed a tendency to maintain heart rates within the ACSM-recommended targets. These roles, which often involve minimal movement but require resilience to high temperatures due to close proximity to the fire, demonstrated the critical balance of cardiovascular exertion needed in high-risk environments.

Conversely, in indirect attack scenarios, FFs such as 'R2' and 'R6' were significantly challenged, with their heart rates frequently surpassing the ACSM's Zone 5 and entering Zone 6. These roles demand extensive movement around the fire perimeter to draw fire lines and handle heavy equipment like rakes, contributing to sustained high-intensity activities. Notably, these subjects maintained high activity levels in terms of VMU for at least 40% of the fire suppression duration, highlighting the vigorous nature of their tasks.

Moreover, the study observed a return to normal breathing rates (eupnea) by the end of the simulation in the 'Stop3' phase for most subjects, with respiratory rates settling within the 12 to 20 bpm range. However, an exception was noted in 'S2' from Team 2, who exhibited respiratory rates starting from 21 bpm at the onset, suggesting mild tachypnea. This condition could indicate pre-existing stress or initial heightened physiological arousal, which might affect the FF’s performance and recovery dynamics significantly. This nuanced understanding of both cardiac and respiratory responses underpins the complexity of physical and environmental stressors affecting FFs and underscores the importance of tailored training and operational strategies to enhance safety and efficiency in wildfire suppression. This study's in-depth analysis reveals the complex interplay between task-specific physical demands, environmental conditions, and physiological responses in wildland firefighting. It establishes a critical foundation for the in-field monitoring of environmental conditions alongside the physiological states and activity levels of FFs during live operations. This shift toward real-world applications aims to test the robustness of these technologies under challenging conditions, discover their limitations and understand how to enhance continuous monitoring in order to adapt to the dynamic needs of FFs during operations. This evaluation is crucial not only for validating the but also for identifying potential improvements and additions that could support FFs more effectively on the ground. Moreover, recovery strategies need to be emphasized, with a focus on active recovery sessions and optimized work-rest cycles to mitigate cardiac fatigue and enhance overall health out-comes for FFs. One of the key contributions of this study is the introduction of comprehensive respiratory monitoring in the field—a parameter often overlooked in other studies but crucial for assessing the physiological burden

on FFs. By integrating RR analysis, this research provides deeper insights into how FFs cope with stress and exertion over the duration of a wildfire suppression task. However, this study is not without limitations. The sample size and scope of monitored parameters were confined, pointing to the need for broader studies that incorporate a wider range of physiological and environmental variables.
In conclusion, this study pioneers the use of wearable technologies in real wildfire scenarios, significantly advancing operational monitoring of FFs. It sets the foundation for further research and protocols, aiming to enhance FFs' safety, efficiency, and effectiveness in wildfire management.

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Thermal physical modelling for eye injury prevention in high environmental temperature workplaces

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Abstract

Background: High temperatures are encountered in many workplaces as iron and steel foundries, nonferrous foundries, brick-firing and ceramic plants, glass products facilities, rubber products factories, electrical utilities, bakeries, laundries, chemical plants, mining sites, smelters, and steam tunnels. Workers in these industries can suffer from various diseases and injuries, including eye problems, due to exposure to high temperatures and handling of heavy materials.
Methods: This study aims to analyse the pressure inside the eye's anterior chamber, known as Intraocular Pressure (IOP), and its relation to the biomechanical properties of the cornea, specifically concerning the cornea's temperature. The approach used is based on the first law of thermodynamics. The results demonstrate the relationship between the ocular anterior chamber's temperature and the cornea's biomechanical properties.
Results: The IOP measures the cornea's elasticity and its refractive properties concerning its temperature. We develop a study to investigate how the cornea's elastic work, or potential energy, changes with temperature. Our findings indicate that as the temperature rises, the work done by the cornea decreases. The cornea's temperature is affected by both the surrounding environment and the temperature of the fluid in the front part of the eye. This suggests a link between the work done by the cornea against the pressure of the fluid in the front of the eye and the fluid. Accordingly, there is also a correlation between the thickness of the cornea and the IOP, and our modelling method enables us to establish this relationship.
Conclusions: The first law of thermodynamics is used to determine the work done by the anterior chamber against the internal cornea wall. Temperature regulates the aqueous humour's secretion, excretion, and flow dynamics, impacting IOP and related diseases. This has implications for developing preventive systems to protect workers' eyes from injury.

1 Introduction

The workplace can be a bustling environment with various tasks and machinery that pose potential risks to our eyes. Common types of eye hazards include chemical, mechanical, biological, and radiation risks, all of which can lead to thermal stress or injury.

Eye injuries can result in severe and long-lasting consequences, such as vision loss, blindness, pain, discomfort, corneal abrasions, chemical burns, conjunctivitis, detached retina, cataracts, glaucoma, and secondary infections. It's crucial to recognize the potential consequences of eye injuries and take proactive steps to prevent them. Proper eye protection, safe work practices, and immediate medical attention in case of an injury can significantly reduce the risk of these adverse outcomes.

Certain workplaces, like iron and steel foundries, nonferrous foundries, brick-firing and ceramic plants, glass product facilities, rubber product factories, electrical utilities, bakeries, laundries, chemical plants, mining sites, smelters, and steam tunnels, often expose workers to high temperatures. Workers in these industries may experience various diseases and injuries, including eye problems, due to extreme heat and the handling of heavy materials.

Such injuries affect not only the individuals but also workplace productivity and safety. We often take our vision for granted amidst our daily routines, making the importance of eye safety tips in the workplace more evident.

This study aims to analyse the pressure inside the eye's anterior chamber, known as intraocular pressure (IOP), and its relationship to the biomechanical properties of the cornea, specifically concerning the cornea's temperature. The approach is grounded in the first law of thermodynamics [1,2]. The aim is to show a relationship between the ocular anterior chamber temperature and the biomechanical properties of the cornea. IOP measures the cornea's elasticity and refractive properties concerning its temperature. Our study investigates how the elastic work or cornea potential energy changes with temperature. Findings indicate that as the temperature rises, the work done by the cornea decreases. The cornea's temperature is influenced by the surrounding environment, and the fluid in the front part of the eye. This suggests a connection between the work done by the cornea against the pressure of the fluid in the anterior chamber. Additionally, there is a correlation between corneal thickness and IOP, and our modelling method allows us to establish this relationship. To achieve this, we apply the first law of thermodynamics to determine the work done by the anterior chamber against the internal corneal wall. Temperature regulates the secretion, excretion, and flow dynamics of the aqueous humour, which in turn impacts IOP and related diseases [3]. This has implications for developing preventive systems to protect workers' eyes from injury, with particular regard to glaucoma and keratoconus induced by mechanical injuries. Glaucoma is a disease

that leads to progressive vision loss due to IOP disorders and is a major cause of blindness. Accurate IOP measurement is crucial after surgeries for corneal, lenticular, and vitreoretinal conditions. Central corneal thickness (CCT) plays a significant role in tonometry, and measuring CCT through pachymetry has become standard practice for accurate IOP evaluation. However, various algorithms for correcting IOP yield differing results, highlighting the need for a unified analysis method. The biomechanical properties of the cornea are complex, characterized by [4,9-16]:

- Heterogeneity, in dimensional properties;
- Near incompressibility, due to water and collagen fibres (Poisson's ratio ~0.5);
- Non-linear behaviour, in response to IOP changes.;
- Viscoelastic and creep behaviour, observed in tests;
- Structural anisotropy, from collagen fibril orientation.

Biomechanical issues [5-8] are crucial in conditions like keratoconus, which involves loss of corneal rigidity, and corneal ectasia after refractive surgery, resulting in deformation. Recent studies suggest that corneal temperature measurement is important for diagnosing ocular diseases. Despite various models for studying corneal properties and heat exchange, no comprehensive model currently links these properties with the thermal behaviour of the anterior chamber. This connection is vital for understanding aqueous humour flow, which maintains IOP and supports visual stability. Temperature regulates tissue metabolism, yet theoretical models supporting clinical evaluation are lacking. Given these complexities, we propose a new approach using irreversible bioengineering thermodynamics to study IOP and its relationship with corneal properties, particularly the risk of glaucoma in hypertensive patients.

2 Materials and methods

To introduce a thermodynamic approach to the analysis of the eyes injury risk in workplaces, we considered that the flows related to IOP are water inflows and outflows between the ocular anterior chamber and blood vessels. So, considering the eye as an open system concerning the body, we apply the first law of thermodynamics [1,2]:

$$\dot{Q} - \dot{W} = \frac{d}{dt}\left[U + p_0 V + \int_V \rho\left(e_k + e_p\right) dV \right]_{CV} + \dot{m}_{out}\left(h + e_k + e_p\right)_{out} - \dot{m}_{in}\left(h + e_k + e_p\right)_{in} \quad (1)$$

where $\dot{Q}$ is the heat power exchanged between the cornea and the external environment, $\dot{W}$ is the mechanical power carried out by the tissue concerning the pressure and elastic properties of the cornea, U is the internal energy, p_0 is the external environmental pressure, V is the volume of the anterior chamber, ρ is

the water density, e is the specific energy, *k* stands for kinetic, *p* as a subscript means potential, h is the specific enthalpy of the water, *in* means inflow, *out* means outflow, and CV means control volume.
The kinetic energy and the potential energy are so small that they can be considered null, and we analysed the behaviour of the eye during the time of observation, so that we integrate in time, obtaining:

$$Q - W = (m_{out} - m_{in})c_v T_w + p_0 \Delta V + m_{out} c_p T_w - m_{in} c_p T_{in} \quad (2)$$

where c_v is the specific heat at a constant volume of the water inside the anterior chamber, c_p is the specific heat at a constant pressure of the water, T_w is the temperature inside the anterior chamber, T_{in} = 37°C is the temperature of the inflow water, mw is the mass, T_0 is the external environmental temperature, considered in the range [-30°C, 40°C], and ΔV is the volume variation due to water stagnation in the ocular anterior chamber. Then, considering that the anterior chamber exchanges heat with the environment by the cornea surface, we can introduce the first law for this system:

$$Q = -m_w c_v \left(T_w - T_0\right) \quad (3)$$

obtaining:

$$-W = (m_{out} - m_{in})c_v T_w + p_0 \Delta V + m_{out} c_p T_w - m_{in} c_p T_{in} + m_w c_v \left(T_w - T_0\right) \quad (4)$$

Then, we can evaluate the work carried out by the water against the external surface of the anterior chamber as [2]:

$$W = -V \cdot \Delta \mathrm{IOP} \quad (5)$$

and the ocular anterior chamber temperature results can be obtained:

$$T_w = \frac{V}{c_w\left(2m_{out} - m_{in} + m_w\right)} \Delta \mathrm{IOP} - \frac{\mathrm{IOP}}{c_w\left(2m_{out} - m_{in} + m_w\right)} \Delta V + \frac{m_{in} T_{in} + m_w T_0}{2m_{out} - m_{in} + m_w} \quad (6)$$

where c_w = c_p = c_v is the specific heat of the liquid water. In an eye without any pressure diseases $m_{out} \approx min$, $p_0 \approx \mathrm{IOP}$ as it represents the pressure of the interior chamber against the elasticity of the cornea back wall.

Starting from this result, we can consider that the anterior chamber exchanges heat through the cornea surface. The heat transfer mechanisms are the conduction across the cornea length and the convection with the environmental air on the cornea's external surface. So, the value of the cornea temperature T_c can be obtained by the usual heat transfer approach [18], as follows:

$$T_c = T_w - \frac{T_w - T_0}{\frac{s}{\lambda} + \frac{1}{\alpha}} \cdot \frac{s}{\lambda} \tag{7}$$

where [18-21] s is the mean cornea thickness (0.5 mm), l is the cornea conductivity (0.6 W $m^{-1}K^{-1}$) and a is the convective heat transfer coefficient (50 W m^{-2} K^{-1}). The results obtained are represented in Figure 1. It should be noted that the cornea temperature is more affected by the environmental temperature and that the cornea temperature is crucial concerning the variation of the anterior chamber temperature. The data obtained agrees with the data in the literature [17-30], as discussed in the previous section, with an error of less than 1% (see Refs. [19,21]). The time of observation considered is greater than the thermal transient, evaluated [19] in 5000 s.
Now, considering the extended Bernoulli's equation:

$$W = \int pdV - p_0 \Delta V - W_\lambda - \Delta E_k - \Delta E_p \tag{8}$$

where W_λ is the work lost for irreversibility, E_k is the kinetic energy and E_p is the cornea elastic potential energy, and introducing this into the relation (4) it follows that the elastic potential variation of the cornea results as:

$$\Delta E_p = (m_{out} - m_{in}) c_w T_w + m_{out} c_w T_w - m_{in} c_w T_{in} + m_w c_w \left(T_w - T_0\right) \tag{9}$$

This result is represented in Figure 2. The shape has been obtained considering the kinetic energy and the work lost for irreversibility as being null. It should be emphasized that the cornea elastic work (variation of the elastic potential energy) depends on the temperature of the cornea.
Finally, considering the relation (9) and the relation (6) it follows that

$$\Delta E_p = Y \cdot s = (2m_{out} - m_{in})c_w \left(\frac{\Delta(V \cdot \mathrm{IOP})}{c_w(2m_{out} - m_{in} + m_w)} + \frac{m_{in}T_{in} + m_w T_0}{2m_{out} - m_{in} + m_w} \right) - m_{in}c_w T_{in} + \\ + m_w c_w \left[\left(\frac{\Delta(V \cdot \mathrm{IOP})}{c_w(2m_{out} - m_{in} + m_w)} + \frac{m_{in}T_{in} + m_w T_0}{2m_{out} - m_{in} + m_w} \right) - T_0 \right] \quad (10)$$

where Y is the Young modulus and s is the cornea thickness.

3 Results

The thermodynamic approach allows us effectively to analyse the effects of liquid flow in the ocular anterior chamber. Our results establish a clear relationship between the temperature of the anterior chamber and the environmental temperature.

As depicted in Figure 1, the temperature of water inside the anterior chamber (a) and the corneal temperature (b) consistently increases with rising environmental temperatures. This trend underscores the significance of environmental factors in influencing ocular temperatures. Figure 2 demonstrates the cornea's elastic potential energy relative to corneal temperature, revealing a definitive decrease in elastic potential energy as corneal temperature rises. Our findings align with previous studies referenced in [19] and [21], as well as recent research on humans [28-30]. These studies confirm that eyes with ischemic central venous retinal occlusion - resulting from high pressure - exhibit lower ocular surface temperatures compared to their non-ischemic counterparts. This relationship underscores our results, where corneal potential energy is directly tied to intraocular pressure.

Consequently, lower temperatures lead to higher corneal potential energy and increased intraocular pressure, resulting in significant ischemic effects on the optic nerve.

Our conclusions are consistent with experimental data summarized in the literature (Refs. [18-22]). It is crucial to assert that corneal temperature is influenced predominantly by environmental temperature rather than anterior chamber temperature.

In our evaluation of the elastic work (variation in potential energy) of the cornea concerning corneal temperature, we found a distinct decrease in work as temperature rises. Notably, corneal temperature is determined by both environmental and anterior chamber temperatures. Thus, an analytical relationship exists between the elastic work performed by the cornea against anterior chamber pressure and anterior chamber temperature, as well as between corneal thickness and intraocular pressure (IOP).

Our approach analytically describes this relationship. From equation (10), we can highlight that the difference in inflow and outflow of liquids serves as the primary determinant of variations in corneal elastic properties and the associated IOP.

Figure 1. Temperature of the ocular anterior chamber and the cornea.
Temperature of the ocular anterior chamber (a) and the cornea (b) were evaluated by using the equations (6) and (7) in relation to the variation of external environmental temperature.

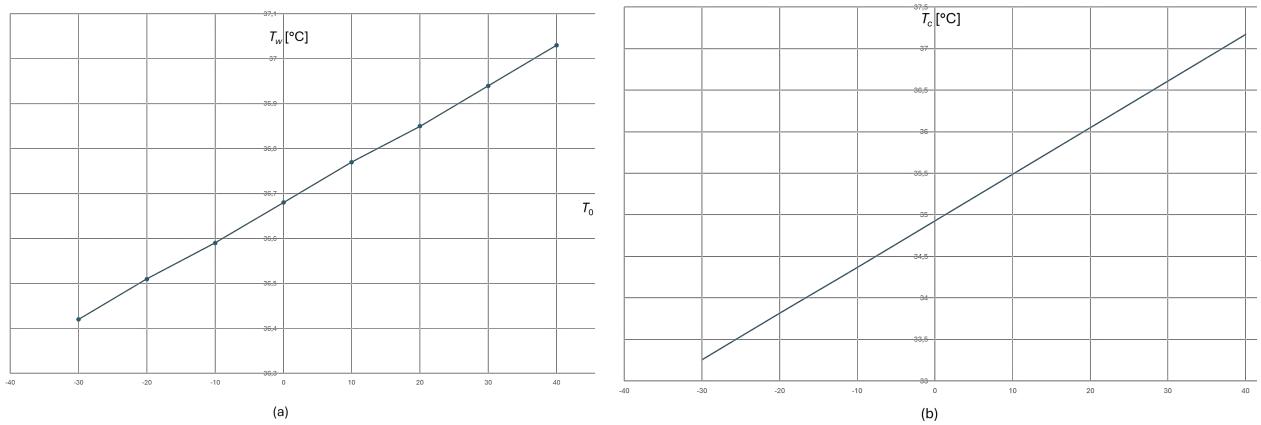


Figure 2. Elastic properties of the cornea as a function of cornea temperature.

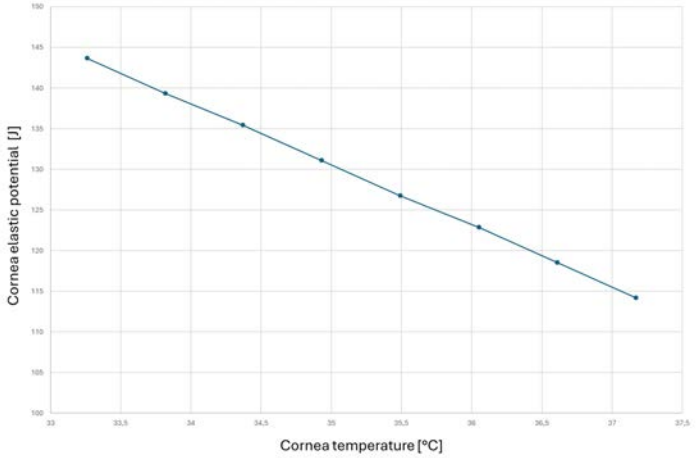
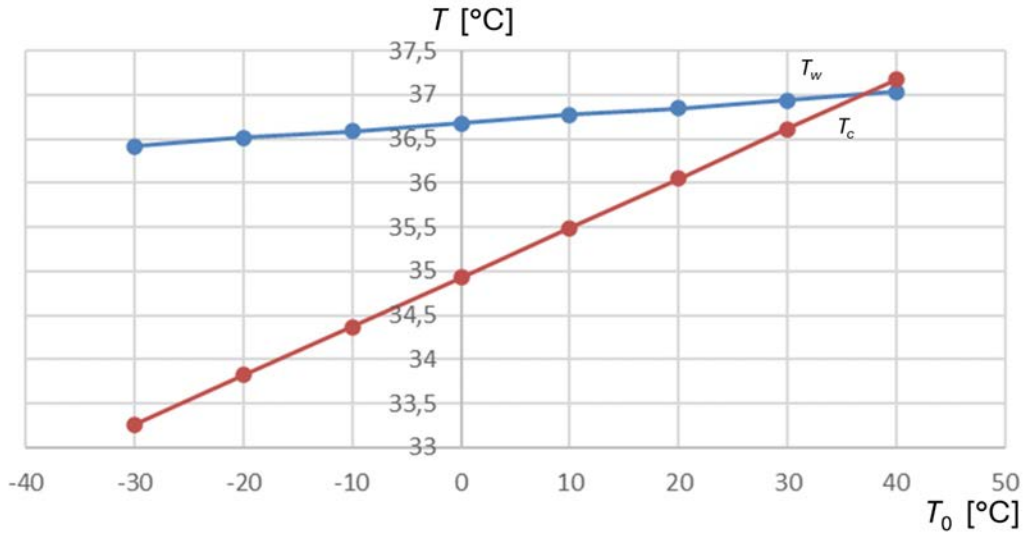


Figure 3. Risk condition.



In Figure 3 the risk condition is determined: it happens when the cornea temperature is higher than the interior chamber temperature, i.e., eye cannot outflow heat so it increases in its temperature with a related increase of pressure and possible damages to the optical nerve.
These results point out that:

- Any mechanical stress induces a temperature variation with a related IOP variation
- Any temperature variation causes an IOP increase

with the consequence of increasing the risk of inducing glaucoma. Consequently, it is possible to consider the use of glasses with an electronic thermometer in order to monitoring the temperature exposure of workers' eyes.

4 Discussion and conclusions

Glaucoma is a serious optic neuropathy that leads to the destruction of ganglion cells and fibers, resulting in an irreversible loss of visual field and potential blindness. Controlling intraocular pressure (IOP) is essential for preventing damage from glaucoma and safeguarding vision. Increased IOP is unequivocally a primary risk factor for the onset of this condition. Thermography has proven valuable in studying the vascular factors involved in the pathology of glaucoma. It demonstrates that ocular surface temperature can be an effective indicator of impaired retrobulbar hemodynamics in glaucoma research [21,28].
The cornea serves as the primary refractive structure of the eye, consisting of five distinct layers: the epithelium, Bowman's layer, stroma, Descemet's membrane, and endothelium. Its measures include a radius of 10-11 mm and a thickness of 0.5 mm [17].

The cornea actively exchanges heat with its environment and the anterior chamber, making its surface temperature critical for maintaining a consistent temperature in the anterior chamber. The corneal temperature can be accurately obtained by analysing conductive heat transfer across it, establishing a direct relationship between corneal temperature and the anterior chamber. Furthermore, the elastic properties of the cornea have a significant impact on IOP values. Goldmann and Schmidt's hypothesis from 1957 asserts that IOP is underestimated in patients with thin corneas and overestimated in those with thick corneas [23]. This hypothesis has been experimentally validated [29], confirming a reliable correlation between corneal thickness and IOP, which is driven by two main factors:

- Swelling Pressure (SP): The repulsion generated by negatively charged stromal glycosaminoglycans;
- Imbibition Pressure (IP): The negative pressure that facilitates fluid inflow into the cornea. Thus, IOP can be definitively expressed as the sum of these effects: IOP = SP + IP.

From our results, we can conclude that:

- There is a relationship between the temperature of the ocular anterior chamber and intraocular pressure (IOP);
- There is a relationship between corneal temperature and the temperature of the ocular anterior chamber;
- There is a relationship between corneal temperature and its elastic behaviour;
- There is a relationship between IOP and corneal thickness, which can be evaluated by measuring the temperature of the ocular anterior chamber.

The first principle of thermodynamics can be applied to evaluate the work done by the anterior chamber against the internal corneal wall. The temperature of the aqueous humour is linked to the difference between the heat dissipated across the cornea and the heat generated by metabolic activities and the vascular supply to the anterior chamber.

Therefore, temperature plays an essential role in regulating the secretion, excretion, and flow dynamics of aqueous humour, which in turn affects IOP regulation and related conditions, such as glaucoma.

Additionally, the correlation between the temperatures of the anterior chamber and cornea can be utilized to analyse tear film evaporation and its relation to environmental conditions. It is plausible that transient receptor potential channel isotopes may play a crucial role in controlling aqueous humour dynamics, as suggested by Fabiani [21].

Consequently, temperature could be viewed as a new target for managing glaucoma progression in patients with ocular hypertension. Notably, there is a

trend for ocular temperature to decrease with age, making it important to evaluate individual patients concerning their personal evolution.

Furthermore, a significant relationship between corneal elastic properties, refractive errors, and anterior chamber characteristics has been experimentally demonstrated, confirming our theoretical findings. A recent study highlighted that eyes with ischemic central venous retinal occlusion (CRVO) exhibit lower ocular surface temperatures than non-ischemic eyes [30]. Additionally, Galassi et al. defined ocular surface temperature as a marker of impaired retrobulbar hemodynamics in patients with glaucoma [28].

Applying the thermodynamic approach allows us to analyse liquid fluxes in the ocular anterior chamber. Variations in mass flows within the anterior chamber can lead to changes in IOP and, consequently, in the elastic properties of the cornea.

These corneal properties, in turn, affect the refractive properties of the eye; thus, changes in IOP could also be assessed through vision changes. Indeed, IOP depends solely on the flows of aqueous humour, which are maintained in the balance between secretion and excretion. Three mechanisms contribute to aqueous humour formation: diffusion, ultrafiltration, and active secretion.

In conclusion, there is a correlation between IOP and temperature, which can be measured using non-contact measurement systems. This characteristic is significant for designing non-contact tonometers for future home patient monitoring and related personalized therapies.

Lastly, the results obtained highlight the risk in some workplaces and also the critical temperature risk factor, suggesting the need to design new devices for the proximal eye temperature measurements.

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“Safety By Design” In vibrating machines: a dedicated multicriteria approach including the human factor

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Abstract
Vibration exposure, on the hand-arm system as well as on the whole body, has been scientifically proved to be correlated to several professional diseases, especially on workers who use machines in constructions, industry and agriculture. Vibrations can derive from machinery motion or from its interactions with the surrounding environment.
A previous work by some of the authors defined a first structured framework, based on a scientific multicriteria decisional approach, for the design of hand-held machines with reduced vibration emission through an adequate choice between several alternatives of technical solutions, while balancing reduced vibrations with other typical business constraints. In the present study, such methodology is taken up and its potential in contributing to obtain “safety by design” is deepened through the analysis of the introduction of uncertainties related to some possible human behaviors into such decision-making methodology.

1 Introduction

A significant number of machines in the European market emit vibrations, mainly in construction, industry, forestry and agriculture fields, producing a potentially dangerous exposure of workers, with consequent possible onset of occupational diseases. In the case of Hand-Arm Vibrations (HAV, vibrations transmitted to the human hand-arm system), such diseases can include vascular, bone, joint, neurological and/or muscular disorders. Directive 2006/42/EC (Machinery Directive) requires in fact machinery manufacturers to minimize such risk, by adopting optimal technical solutions during the design phase in order to reduce vibration emission. Such preliminary phase can be supported by experimental measurements, computational and lumped-mass models and test benches [1].

The interventions “at source” should be the first-choice solution, with respect to the use of Personal Protective Equipment and the reporting of residual risks.
At the same time, employers are also required by Directive 2002/44/EC (currently implemented in Italy by Legislative Decree n. 81 of 9 April 2008, also known as “Consolidated Act on health and safety at work” and subsequent further decrees) to minimize vibration exposure of workers, for example through an adequate organization of work shifts. When the so-called “exposure action values” (2.5 m/s^2 standardised to an eight-hour reference period for HAV) are exceeded, the employer must implement a programme of technical and/or organisational measures to minimise the exposure to mechanical vibrations. If even the so-called “exposure limit values” (5 m/s^2 standardised to an eight-hour reference period for HAV) are exceeded, immediate actions must be taken.
At the same time, many international standards and technical reports can help in correctly evaluating vibration emission and exposure [2].
In the wake of a growing interest of the international literature for decisional approaches for selecting safety devices, a previous work by some of the authors [3] – realized in collaboration with a brush-cutters manufacturer - already proposed a first structured framework for the design of hand-held machines with reduced vibration emission through an adequate choice between several alternatives of technical solutions. The objectives of guaranteeing reduced vibrations and safety were balanced by other business constraints (e.g. costs, machine efficiency, ergonomics, productivity). The applied analysis method was the Analytic Hierarchy Process (AHP), which has been proved to be useful when trying to make a good final choice while satisfying multiple constraints. It has been applied in many fields [4], also including safety domain, as in the case of optimal selection of safeguards [5].
Even the most recent scientific literature shows that safety criteria for vibrating tools still represent a dominant research topic, covering several fields: constructions [6,7], agriculture [8,9], generic tools for engineering industry [10,11] and even emergency management, as in the case of vibrations transmitted by portable wind extinguishers [12].
The present work aims to recover the proposed methodology and to deepen it through the introduction of some additional aspects related to the role of the human factor (human error, in particular). In this perspective, the problem of the reasonably foreseeable misuse (according to EN ISO 12100:2010) will be taken into account, together with the risks potentially connected to maintenance.

2 Hand-arm vibrations on portable machines

Vibrations transmitted to the hand-arm system of workers are generally emitted mainly by (i) portable machine tools held by employees in metalworking and carpentry plants, mining industry, construction sector, stone processing, forestry, etc. and (ii) agricultural and garden machines which are hand-driven by the

workers who follow the equipment on foot, as outlined by EN ISO 5349-1:2001. Both groups are listed and detailed in Table 1, where percussive and rotary tools are also marked.

Field of use	Machine details	Percussive tools	Rotary tools
Construction	Percussive hammers and breakers	✓	
	Concrete compactors (needle vibrators or vibrator plates)		
Engineering industry	Impact drills	✓	
	Impact wrenches	✓	
	Chipping hammers and scalers	✓	
	Hammers for corner breaking, shaping, riveting, flanging	✓	
	Shears and nibblers for metal	✓	
	Rotary tools for deburring		✓
Foundry	Sandblasters	✓	
	Rammers for moulding	✓	
	Circular saw, miter saw for degating		✓
	Portable grinding wheel for deburring		✓
Stone processing	Cubing machines		
	Rotating shaping machines with flexible shaft		✓
	Orbital and random orbital sanders		✓
	Circular saws and jig saws		✓
	Angle and axial grinders		✓
	Light duty straight grinders		
Wood	Nailing machines		
Agricultural, forestry and gardening works	Motor-cultivators		
	Brush-cutters		
	Shakers for hanging fruit (e.g. olives)		
	Lawnmowers		
	Chain saws, debarker		✓
Shoe factories	Riveting machines		
Health care	Dentist's drills, orthopaedic saw		

Table 1 – Most common vibrating hand-held and hand-guided machines.

2.1 Anti-vibration technical solutions

In the case of hand-held machines, several technical practical solutions are available in industrial practice in order to reduce HAV exposure. In particular, UNI/TR 11232-1:2007 distinguishes: (i) reduction of vibration magnitude at the

source from which the vibration is generated; (ii) reduction of vibration transmission from the source to handles and other surfaces in contact with the hands; (iii) reduction of vibration transmission from the grips or handles of the machine to the operator's hand-arm system through ergonomic design measures; (iv) thermal design to optimise hand temperature.
In this study, according to previous analyses [3], the following six groups of possible technical solutions have been considered, namely:

(a) *Insertion of anti-vibration systems.*
It can consist in interrupting vibration transmission along the path between vibration sources and handles or hand-held point, through the introduction of metal or elastomeric springs, friction, liquid or gas dampers, combinations of springs and dampers and rubber components in general. In some cases, a Tuned Vibration Absorber (TVA) can be used [13], that is a secondary mass-spring-damper system added to the machine and that allows vibration reduction - in a narrow frequency range - through a suitable selection of its physical parameters. However, recent studies [14] have shown that – e.g. in the case of a grass trimmer - an absorber can be effective for small speed ranges only, otherwise the absorber resonance frequency needs to be changed.

(b) *Changes to machine mechanics*
During the design phase, balancing of rotating or reciprocating parts can be obtained by introducing counter-rotating masses, lightening some moving parts or – e.g. for internal combustion engines – by switching from single-cylinder to multi-cylinders engines. Changes in the mechanisms of transmission of forces can be applied, for example by using belt drives instead of gear or chain drives.

(c) *Changes to geometry and/or materials of handles*
Wrapping rubber or other resilient materials (e.g. viscoelastic polymers) can be put around vibrating handles, obtaining an improvement in comfort. Their geometry can also be modified. Texture and material of the grip surface can be modified in order to significantly reduce the gripping or pushing forces exerted through the hand, with a reduction in vibration transmission.

(d) *Changes to geometry and/or materials of other components*
It is important to move away the resonances from the excitation frequencies, by acting on materials, dimensions and boundary conditions of components.

(e) *Implementation of strategies for producing/buying components with perfect feature repeatability*
The quality control system along the company production line (for internally produced components) or in the component choice criteria (for externally bought components) is fundamental, to guarantee the repeatability of components (related to emitted vibrations) and to avoid eccentric masses.

(f) Changes to expected conditions of use for workers

The manufacturer helps in reducing the final exposure of workers to vibrations by specifying, for example, the optimal positions for hands (working angle, etc.). Back-pack type machines can contribute to reducing the negative effects of HAV vibrations on the human body, as well as anti-vibration gloves. In order to design machines against the effects of cold, warmed handles or poorly dissipative materials can be adopted, just in order to reduce the negative effects of actual vibrations on the human body.

3 AHP methodology for vibrating hand-held machines

The Analytic Hierarchy Process is a multi-criteria analysis method that allows to select one alternative from a given set, where multiple decision criteria are involved, and to rank the alternatives available in a desirability order based on a rational framework of quantitative comparisons [15].

The method requires that a hierarchical structure is built, with a certain number of levels ranging from the objective to the alternatives and passing through the intermediate levels constituted by criteria and sub-criteria. The methodology then forces the implementation of pair-wise comparisons matrices of all the elements belonging to a certain level with the element of the upper level, based on evaluations produced by a group of experts.

The alternatives are compared in relation to the criteria of the last level and the evaluation continues up to the criteria of the first level, which are compared to the goal. Starting from comparison matrices and local priority vectors, a global priority vector - that measures the relative degree of importance of all possible alternatives, while identifying the best ones in relation to the target - is finally calculated [16].

3.1 The hierarchical structure including human factor

In the specific case of designing a generic hand-held machine with reduced vibrational emissions, the method proposed in this study analyses the six alternatives which have been already detailed in Par. 2.1 (see technical solutions from (a) to (f)).

In parallel, first level and second level criteria have to be defined. Their selection is generally based on evaluations coming from expert operators of the sectors. In this sense, the following criteria were already set during the implementation of the first version of the proposed methodology [3]:

(1) costs (for components and materials, manpower work and training, design, storage);
(2) health and safety (vibrations hazard, noise hazard, ergonomic hazard, other risks);
(3) machine efficiency (drivability, product quality and good functionality over time, engine performance (power, adaptability));

(4) compliance with other regulations (emissions (environmental impact), electromagnetic compatibility).

However, in the present study additional criteria had to be added, due to the decision to include components related to the human factor. Two main aspects have been therefore selected and introduced:

- reasonably foreseeable misuse, according to EN ISO 12100:2010 point 5.4 (e.g. loss of control of the machine by the operator, reflex behavior in case of malfunction or incident, lack of concentration or carelessness, adoption of the "line of least resistance" in carrying out a task, pressure to keep the machine running in all circumstances);
- risks related to maintenance (e.g. too complex maintenance procedures required, with possible consequent errors done by maintenance operators or managers).

The hierarchical structure shown in Figure 1 is finally obtained, where the two just mentioned aspects are highlighted through a green box. They have been introduced as additional subcriteria into the first level criterium "Health and safety".

In relation to machine efficiency, it must be observed that its drivability can be limited by excessive weight or stiffness of its components, included anti-vibration components. Moreover, a high-quality manufacturing process, where production tolerance is kept within a predefined range, has been observed as a necessary condition to have a constant machine efficiency over an extended period.

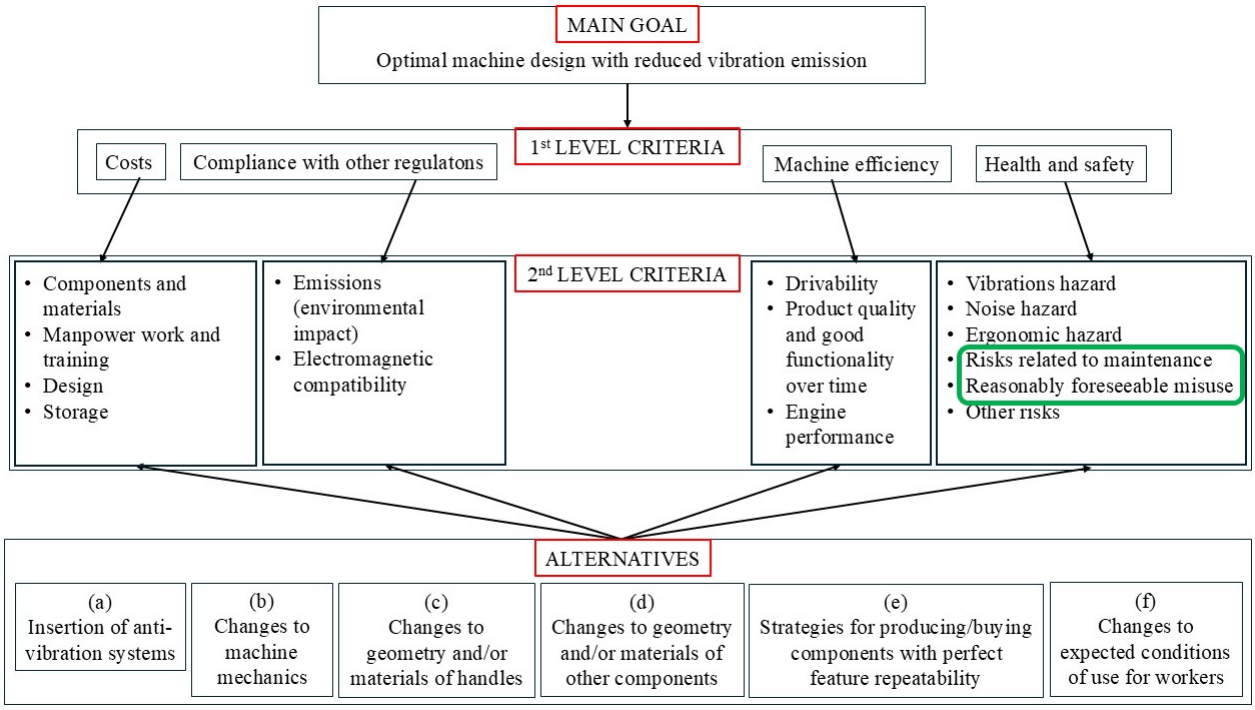

Fig. 1- Proposed AHP hierarchical structure.

The consequent general framework for AHP assessment is reported in Table 2 as for a real implementation. An example is shown here, with priority values taken (i) from the case of brush-cutters previously analyzed [3] (in black characters) and (ii) considering the case when 2nd level criteria priorities for risks related to maintenance and reasonably foreseeable misuse are added (green bold format) while the other components - also including "Other risks" (e.g. mechanical, electrical, thermal, radiation hazards) - are modified accordingly.
The table shows the calculated local priorities for the 1st level criteria in relation to the main goal (in black bold) as well as the calculated local priorities for the 2nd level criteria with respect to each main criterion (in italics). It is assumed here, for the sake of simplicity, that the priority value for the 1st level "Health and safety" criterion in relation to the main goal remains unchanged. Calculations have been carried out by using *SuperDecisions*, a free educational software that implements AHP.
It can be observed that, in this example, it was decided to give a particularly significant weight to "Risks related to maintenance" and it was supposed that such criterium could be positively influenced by a good quality and repeatability of components, but also negatively influenced by the addition of anti-vibration systems.

1st level criteria	**2nd level criteria**	**Criteria priorities (examples)**	**Alternatives**
1. Costs		**0.25**	a. Insertion of anti-vibration systems (springs, rubber components) b. Changes to machine mechanics c. Changes to geometry and/or materials of handles d. Changes to geometry and/or materials of other components
	for components and materials	*0.37*	
	for manpower work and training	*0.13*	
	for design	*0.42*	
	for storage	*0.08*	
2. Health and safety		**0.46**	
	vibrations hazard	*0.17* => ***0.15***	
	noise hazard	*0.10* => ***0.15***	
	ergonomic hazard	*0.24* => ***0.12***	
	RISKS RELATED TO MAINTENANCE	***0.21***	
	REASONABLY FORESEEABLE MISUSE	***0.18***	

	other risks	*0.49* => ***0.19***	e. Implementation of strategies for producing/buying components with perfect feature repeatability f. Changes in expected conditions of use for workers, including solutions for reducing weight impact
3. Machine efficiency		**0.20**	
	drivability	*0.29*	
	product quality and good functionality over time	*0.14*	
	engine performance (power, adaptability)	*0.57*	
4. Compliance with other regulations		**0.09**	
	emissions (environmental	*0.67*	
	electromagnetic	*0.33*	

Table 2 – Example of AHP framework and local priorities for the design of a low-vibrations hand-held machine.

The global priority vector (calculable starting from the priorities values) finally shows the relative degree of importance of all possible alternatives, attributing to each of them a value that is indicative of how much that solution is preferable to the others, as shown in Table 3.
In the original model (no addition of components related to human factor), results pointed out that the preferable solution consisted in the insertion of anti-vibration systems (29.2%), followed by changes to geometry and/or materials of handles (23.5%) and implementation of strategies for producing/buying components with perfect feature repeatability (20.2%). The introduction of the contribution of reasonably foreseeable misuse and maintenance risks has produced a new ranking, mainly resulting in a significant reduction of the gap between alternatives (e) and (c) and a decrease of the value corresponding to alternative (a).

Alternatives	**Ranking of alternatives WITHOUT additional human factors**	**Ranking of alternatives WITH additional human factors**
a) Insertion of anti-vibration systems	0.292	0.263
b) Changes to machine mechanics	0.057	0.082
) Changes to geometry and/or	0.235	0.217

materials of handles		
d) Changes to geometry and/or materials of other components	0.081	0.090
e) Implementation of strategies for producing/buying components with perfect feature repeatability	0.202	0.211
f) Changes to expected conditions of use for workers	0.133	0.137

Table 3 - Example of global priority vectors (ranking of alternatives) obtained for a model not including/including additional components related to human factor.

From a general point of view, it is reasonable to assume that different anti-vibrations alternatives can lead to different effects and risks in terms of both consequent maintenance and possible human errors, even if reasonably foreseeable. For example, the insertion of anti-vibration systems (alternative (a)) could lead to the need for frequent replacement of components, which should be appropriately installed but also appropriately purchased, in order to maintain a repeatable manufacturing quality. Similarly, eventual changes in expected conditions of use for workers (alternative (f)) could facilitate, in certain situations, loss of control of the machine by the operator.

The weights for criteria and sub-criteria can vary significantly across different case-studies, so they have to be assessed separately in each application. The possible extended use of the method on several portable machines necessarily forces to observe which aspects could vary significantly from one context to another. For example, specific production processes could require including (and paying) operators with higher levels of specialization. An additional cost is also represented by the design phase when preliminary research, study and prototyping are required due to a strong customization of the machine. Moreover, all the “other risks” can vary very significantly depending on the specific application sector.

The application of substantial changes to the machine’s mechanics is generally more expensive and sometimes it can have unexpected contraindications (e.g. occurrence of new resonances), so it has to be carefully evaluated in each situation.

The final application can be also different in terms of professional or personal use: in the second case, the machine is designed for being used only a few tens of hours a year, so higher levels of vibrations are accepted because their cumulative effect on user health is reduced.

4 Conclusions

A decisional framework based on an AHP approach, also taking into account some uncertainties related to human behavior, has been presented as a useful practical instrument for manufacturers of vibrating portable machines, for choosing and adopting optimal anti-vibration solutions while keeping a correct balance between safety constraints and other classical company objectives. With respect to previous implementations, two main additional aspects related to the human factor have been introduced, namely the reasonably foreseeable misuse and possible risks related to maintenance. The corresponding hierarchical structure has been described, together with possible categories of machines on which the method could be applied. It was observed that each specific application requires a dedicated assessment of criteria and sub-criteria, since they can vary significantly across different fields and case-studies. The introduction of uncertainty components which can arise in human decision-making ability can significantly influence the identification of the best alternatives, especially where company policy places special emphasis on the optimization of maintenance procedures and on the analysis (also on a historical basis) of accidents and near-misses caused by human error. The study aims to contribute to the dissemination of the culture of safety among machines manufacturers, by offering them a practical evaluation instrument for machinery design. The activity is expected to represent a preparatory work for a future on-field application of the methodology to a wide number of hand-held machines.

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The automated micronucleus test for occupational safety

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Abstract
In Italian law, Legislative Decree 81/08 provides – as part of the Risk Assessment – biological monitoring for the health and safety of workers exposed to carcinogens and mutagens, in terms of “internal dose indicators” and “biological effect indicators”. Regarding the latter ones, among the dozens of biomarkers used so far, those that highlight DNA damage could be particularly useful for occupational safety, as they are predictive of the development of carcinogenesis. The most popular, among these assays, is the micronucleus test. Unfortunately, the Decree 81/08 does not provide any procedural or quantitative specifications on this matter; for this reason, their application have been developed exclusively within the scope of scientific research.
The paper aims to present an innovative procedure for attempting to implement ‘biological effect indicators’ in Health Surveillance, through the development of a method that allows the micronucleus test to be performed in a non-invasive, fast and inexpensive manner. The test is carried out on immature erythrocytes (reticulocytes) in human blood smears.
The method will be implemented with a dedicated automated software that thanks to the setting of morphometric parameters (shape and size of the reticulocyte) and colorimetric parameters (presence of the orange color), will recognize and count only immature erythrocytes. Also, on the basis of morphometric and colorimetric parameters, any micronuclei will be detected. The software will be employed for analyzing blood smears and will provide the automated acquisition of images from the samples. The entire process will be validated using positive controls.
The application of this system may enhance worker health and safety by enabling the detection of "early damage," allowing for the application of corrective or protective measures before occupational diseases develop.
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1 Introduction

In the workplace, traditional industrial hygiene methodologies can only measure and control the chemicals present in the air, while skin absorption, ingestion and extra-work exposure to any harmful agents remain unobserved – and therefore uncontrolled. Biological monitoring (or biomonitoring) allows this gap to be filled, that is, to add to the monitoring of exposure the additional and fundamental monitoring of the absorbed dose and biological effects. In Italian legislation, Legislative Decree 81/08 provides – as part of the Risk Assessment activity – not only the assessment of exposure to chemical and physical agents, but also biological monitoring, mandatory for workers exposed to agents for which a biological limit value has been set. In addition to "exposure monitoring", therefore, Legislative Decree 81/08 also provides for "monitoring of the absorbed dose", for which procedures and values are specified (Annex XXXIX). As already mentioned, however, biomonitoring can include both the use of "internal dose indicators" and that of "biological effect indicators". The latter are mentioned in Title IX of Legislative Decree 81/08, but without further procedural or quantitative specifications. The implementation of "biological effect indicators" in the field of Health Surveillance would allow the detection of "early damage" and therefore the application of corrective/protective measures before the development of occupational pathologies.

Although, as already mentioned, "biological effect indicators" are not yet used by the subjects in charge of Health Surveillance, these have been widely developed in Scientific Research. Among the dozens of biomarkers used so far, those that highlight DNA damage could be particularly useful for Workplace Safety, as they are predictive of the development of carcinogenesis. Almost all scientific works published so far have evaluated biomarkers of genotoxic damage (DNA damage) using peripheral blood samples [1]: the reason is obviously the lower invasiveness of collecting this type of sample compared to biopsies of various kinds. The various tests applied so far include the detection of chromosomal aberrations, sister chromatid exchanges, DNA repair proteins, as well as the comet assay and the micronucleus test [2].

Most of these tests, however, require skills and resources that are difficult to find outside of specialized research laboratories. Among these, we can mention: a non-negligible quantity of blood for culturing the lymphocytes on which to perform the test; the preparation of metaphases (for chromosomal aberrations and sister chromatid exchanges); the use of immunofluorescence techniques (for DNA repair proteins); preparation of gel electrophoresis (for the comet assay).

For these reasons, the use of these tests has found widespread use in the field of scientific research, including the study of cohorts of professionally exposed workers and with significant associations between exposures and DNA damage detected, but has not managed to become commonly used outside of it. In other words, despite there being hundreds of articles on the subject in scientific journals, none of these tests are used by those responsible for Health Surveillance or Safety and Prevention.

2 The Micronucleus test on human samples

The cheapest and easiest to perform genotoxicity test is definitely the micronucleus test. If applied to erythrocytes (red blood cells), it does not require blood culture (which is instead necessary for its application to lymphocytes) and can be performed on simple blood smears. In this way, it is very minimally invasive and easy to perform. The test consists in detecting the frequency of erythrocytes containing a micronucleus. The latter is formed when a fragment or an entire chromosome is not included in one of the nuclei at the end of cell division (and is therefore the product of genotoxic damage). During the transition from erythroblast (precursor) to erythrocyte, the nucleus is expelled, but not the possible micronucleus. In this way, performing the test is made easier by the fact that erythrocytes normally do not contain DNA and therefore micronuclei (composed of DNA) are easily noticed. For these reasons, as well as for its proven sensitivity and specificity, the micronucleus test in animals (in vivo) is internationally standardized (OECD n°474 [3]) and recognized for the evaluation of induced DNA damage. In humans, however, the spleen removes micronuclei from erythrocytes during their maturation process [4]. For this reason, this test is considered inapplicable to human blood samples, unless only immature erythrocytes (reticulocytes) are counted.

In the present project, we are developing a method that allows the micronucleus test to be performed on immature erythrocytes (reticulocytes) in human blood smears (Figure 1). Its minimal invasiveness (one drop of blood per individual will be required), the ease of execution, the very low costs required and the integration with a dedicated automated software will make the test also executable by the personnel of the bodies responsible for the Health Surveillance of professionally exposed workers.

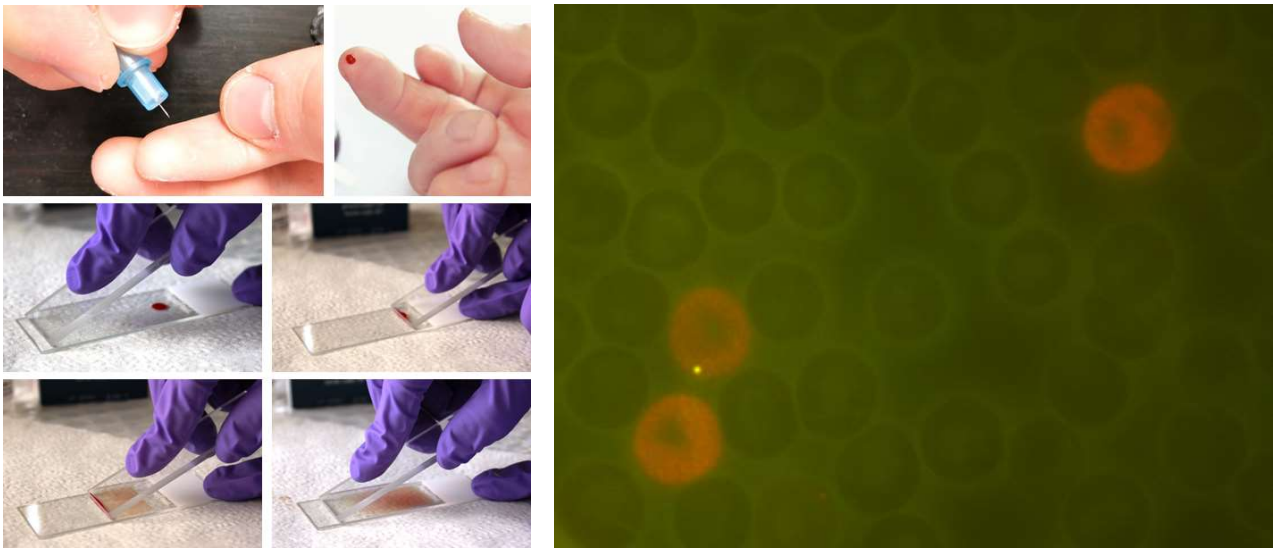

Fig.1. Left: blood sampling and smearing. Right: image of red blood cells, showing reticulocytes (in orange) and one micronucleus (in yellow).

3 Development of a Python-based algorithm

This study employed a comprehensive two-stage method to segment immature red blood cells and detect yellow micronuclei within them using Python and image processing libraries such as OpenCV, PIL, scikit-image, and numpy.

Original images, exported in TIFF format, were initially transformed from RGB to HSB (Hue, Saturation, Brightness) color space. This transformation is crucial for isolating specific hues, saturations, and brightness levels associated with target cellular components.

The HSB color space is a color model used to describe colors in terms of their shade (hue), vividness (saturation), and lightness (brightness). Hue represents the color type and is expressed as a degree on the color wheel from 0 to 360. Saturation indicates the intensity or purity of the color, ranging from pure color (100%) at full saturation to no color (0%) at zero saturation. Brightness describes the color's light or dark, with 100% brightness being the brightest possible and 0% completely dark (black). This model is beneficial in image processing for color filtering and modification because it separates color information (hue) from lighting information (brightness and saturation). In the current work, we adjusted the usual HSB scale to a 0-1 range, common in image processing libraries like OpenCV.

In the first stage, specific ranges for hue (0.02 to 0.167) and saturation (0.39 to 1.00) targeted the orange and red regions characteristic of immature red blood cells. The brightness range was dynamically adjusted based on histogram analysis to capture significant bright regions while avoiding anomalies in brightness peaks. These range-based masks were combined and only pixels that satisfy each condition were maintained in the final mask. Finally, the masks were refined through morphological operations, such as opening (to connect close objects) and closing, (to close small holes), to reduce noise and improve the continuity of detected regions. Figure 2 illustrates the segmentation process with examples of original images (A), corresponding HSB color space histograms and thresholds for immature red blood cell segmentation (B, C, and D), and final results showing detected immature red blood cells (E).

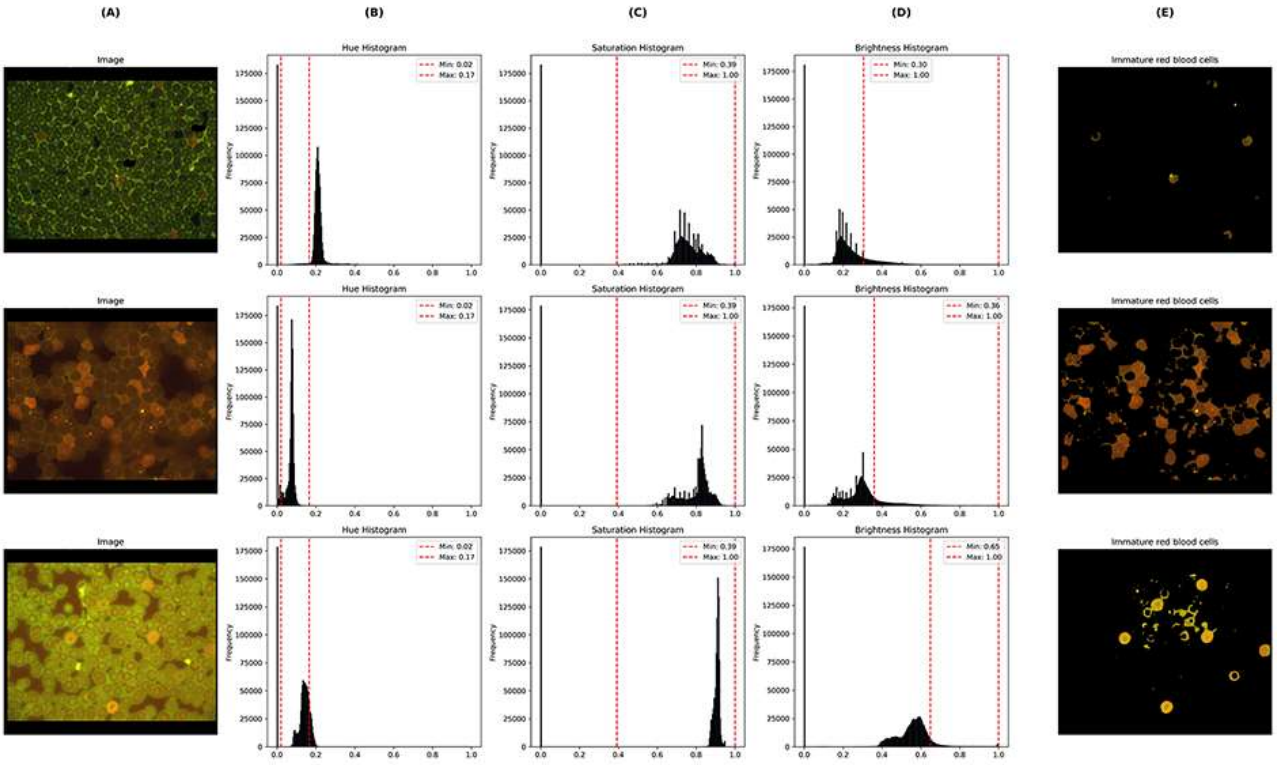

Fig. 2. Immature red blood cell segmentation examples. (A) original images; Hue (B), Saturation (C), and Brightness (D) histograms and ranges applied for immature red blood cell segmentation; final images (E) with the detected immature red blood cells.

The second stage focused on detecting yellow micronuclei within the previously segmented red blood cells. We employed a window/level adjustment function to enhance the contrast and brightness of the images, facilitating better visualization of interesting components. The level, the midpoint of the desired range of pixel intensities, was set to 200 and the window, which defines the width of this range centered on the level, was set to 20. Any values outside the range derived from the specified level and window were clipped to maintain visual integrity. Figure 3A shows examples of previously detected immature red blood cells while Figure 3B depicts the window/level adjustment results.

At this point, the images are converted into the HSB color space. Here, the hue range targets the orange-yellow-green hues (0.08 to 0.4), the full saturation range was set (0 to 1.0) and a mid-high brightness threshold (0.55 to 1.0) was applied to isolate the brightest yellow segments, likely representing micronuclei. Mask combinations and morphological refinements similar to those in the first stage were used to enhance the clarity and definition of the potential micronuclei as shown in Figure 3C.

Finally, we identified each remaining connected component in the images and extracted geometric and morphological properties from these regions. In particular, we considered the area, eccentricity, lengths of the major and minor axes, and the equivalent diameter (assuming the area of each region forms a perfect circle).

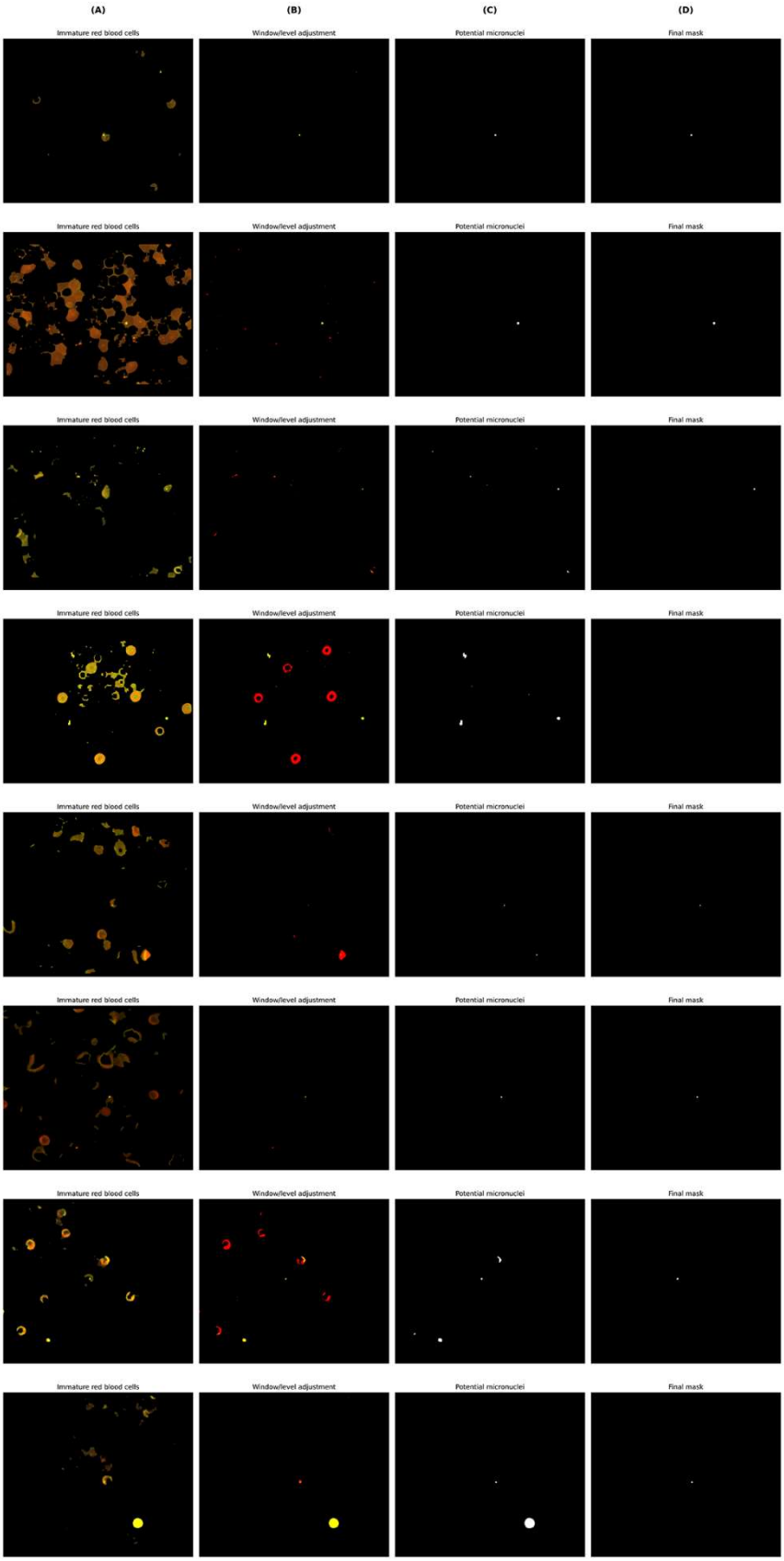

Fig. 3. Micronuclei segmentation examples. (A) previously detected immature red blood cell images; results of the window/level adjustment (B), potential micronuclei

after HSB thresholds and morphological operations (C), and final masks with the detected micronuclei (D).

Subsequent steps involve filtering the results to refine the selection of regions based on specific criteria. The aim was to keep only the regions that met specific dimensions and uniformity criteria and had low eccentricity, favoring small, compact, and symmetrical shapes. Initially, regions were filtered based on their area, retaining those between 20 and 170 pixels to exclude overly small or large objects. Additional filtering considers the shape and size consistency of these regions: differences between the major and minor axes lengths, and the equivalent diameter were calculated as percentages relative to the major and minor axes. Regions were retained if these differences fell within a specified tolerance (15% in this example), indicating that the regions are relatively uniform in shape. Finally, the eccentricity of each region was evaluated, with regions having an eccentricity of 0.65 or less being considered. This criterion ensures that the selected regions are not overly elongated, favoring more compact and symmetrical shapes. Regions satisfying these criteria likely represented yellow micronuclei and formed the final mask shown in Figure 3D. This method demonstrates a valid approach to segmenting specific cellular features using targeted color-based segmentation techniques, dynamic thresholding, and morphological operations to ensure precise and relevant detection of cellular components.
However, our method fails to detect the micronuclei that appear fainter, as shown in Figure 4. Further development will focus on improving these results to reduce false negative detections. Optimal values for window/level adjustments must be individuated for these cases.

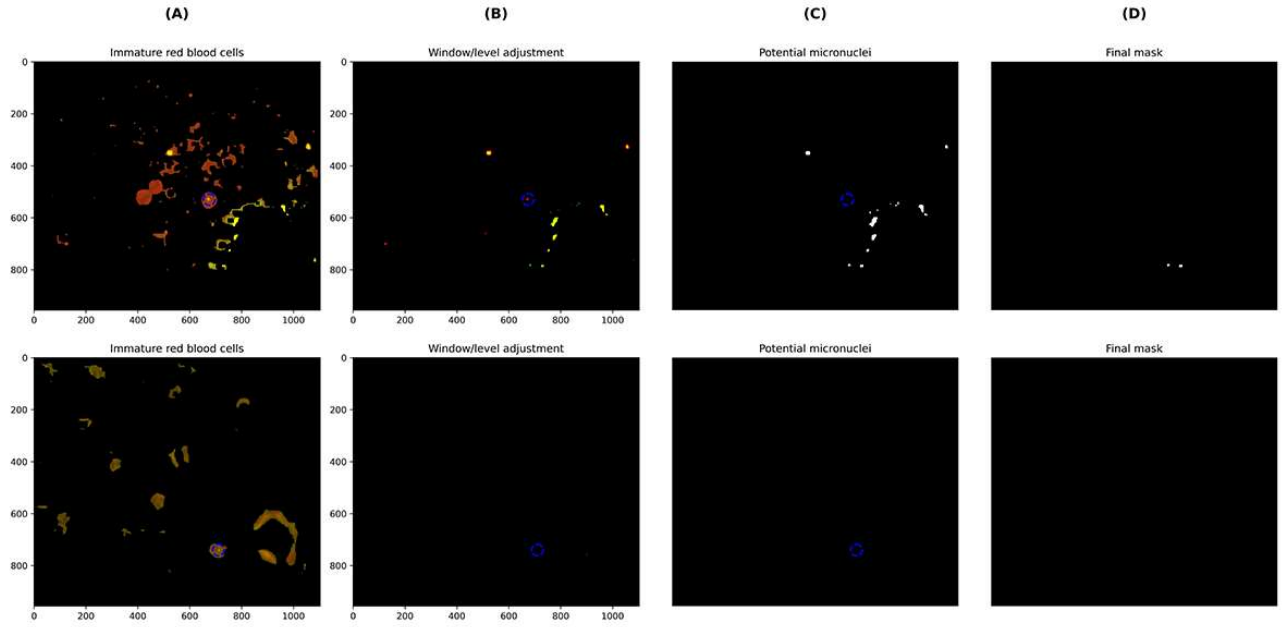

Fig. 4. Examples of micronuclei detection error. Micronuclei that should be segmented are highlighted with a blue dotted circle. In the first example, the micronucleus is missed because it appears red after the window/level adjustment (B) and does not satisfy the hue threshold. In the second example, the micronucleus is left out by the window/level adjustment function, which is suboptimal for this specific case.

4 Conclusions

The aim of this project is to develop a simple and economical method that allows the micronucleus test to be performed on immature erythrocytes in human blood smears. The consequence would be to make this genotoxicity test (the execution of which has so far been relegated to academic and scientific research environments) executable by a wide range of operators in the Safety and Prevention sector.
The development of this test will allow the implementation of Health Surveillance procedures regarding biological effect indicators, which are mentioned, but not explicitly stated, in Title IX of Legislative Decree 81/08. Furthermore, the use of this genotoxicity test, simple, non-invasive and economical, but predictive of carcinogenicity, will allow the detection of "early damage", or the presence of agents harmful to health before they lead to the development of pathologies. In this way, it will be possible to apply corrective/protective measures in a preventive manner, ensuring the health of workers and with significant savings for the National Health System. Furthermore, a further applicative fallout could be the use of the method, the object of this study, on a large scale for the conduction of studies oriented towards high-risk work environments.

5 References:

[1] Albertini RJ, Kaden DA. Mutagenicity monitoring in humans: global versus specific origin of mutations. Mut Res Rev. 2020; 786: 108341.
[2] Ladeira C, Smajdova L. The use of genotoxicity biomarkers in molecular epidemiology: applications in environmental, occupational and dietary studies. AIMS Genetics. 2017. 4: 166-191.
[3] OECD Guideline for the Testing of Chemicals: Mammalian Erythrocyte Micronucleus Test, Guideline 474. OECD. Paris, 1997.
[4] Udroiu I. (2006). Feasibility of conducting the micronucleus test in circulating erythrocytes from different mammalian species: an anatomical perspective. Environ Mol Mutag. 2006. 47: 643-646.

Tinting paste for auto paints: Center of excellence

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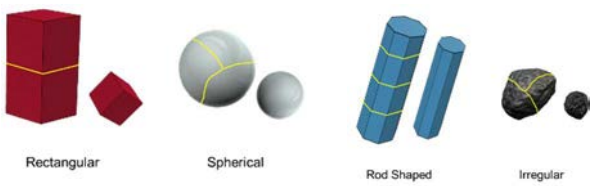
Abstract
The Paste Center of Production (PCoP) project at the industry of Quattordio site is a strategic initiative focused on tinting paste production. Its primary goal is to enhance efficiency by establishing a fully automated and monitored production process, significantly improving safety conditions.
Tinting paste production in this site currently relies heavily on manual operations, which include the handling of fine powders, manual dosing of powders into open mixing vessels, and exposure of chemical products in an open production cycle. Additionally, the manual handling of portable containers contributes to safety risks. Due to the department's design, production is limited to small batches of 1.500 liters, resulting in repetitive manual setups.
The production area is set to undergo substantial transformation, with a division into “Big Batch” and “Small Batch” production systems. This will optimize the batch sizes for high-demand products, thereby reducing the total number of batches produced annually. Both production segments will feature full automation, with a control system designed in collaboration with engineering and safety teams. A recipe management system will oversee the entire operation, minimizing potential manual errors. The new cycle will utilize a closed-loop system, automating the dosing of raw materials, managing cleaning cycles, and ensuring automated powder dosing in process tanks.
These improvements will decrease chemical exposure for operators and significantly reduce risks associated with manual processes, such as spills and the creation of flammable atmospheres.

1 Tinting Paste Current definition

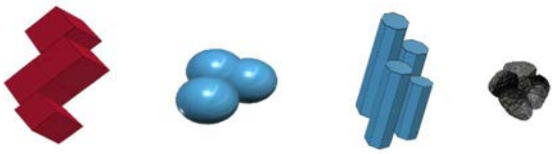
Tinting paste definition: fundamental colors used to adjust the exact color tone of a paint material. Color corrections are made using tinting pastes. To achieve the desired color tone, multiple color matching processes are often necessary.
The process of producing a basic paste consists mainly of reducing the particle size of solid pigments to a specific degree of required fineness to impart the desired colorimetric properties.

Pigments can be of four types:

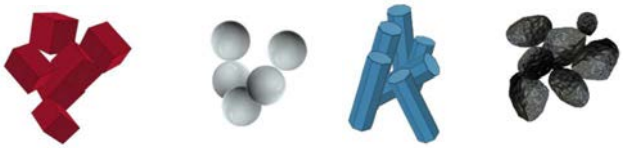
1. Primary Particles By means of appropriate physical procedures (e.g. by means of light microscope, electron microscope) recognizably as individual particle



2. Aggregates Unit grown together of facially contiguous primary particles which surface is smaller than the sum of the surfaces of the primary particles



3. Agglomerates: Unit not grown together of primary particles and/or aggregates contiguous e.g. on corners and edges, which total surface does not basically deviate from the sum of the single surfaces



4. Flocculates: In suspensions (e.g. in pigment binder systems) appearing to agglomerate, which can be divided by means of low shear forces

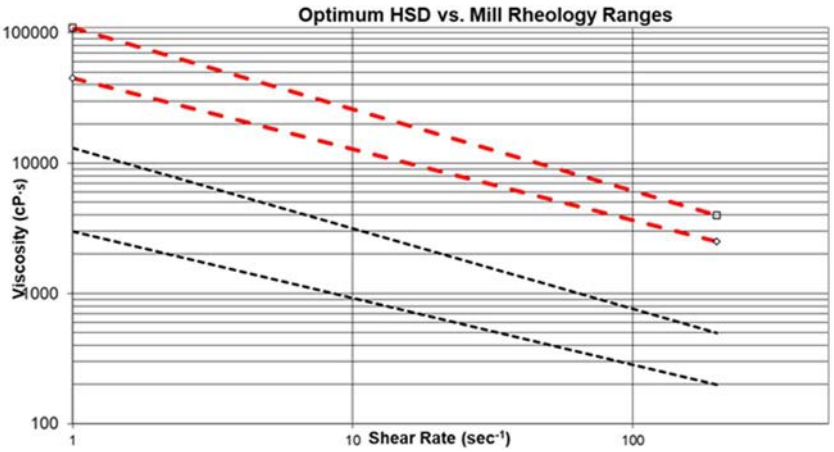
2 Tinting Paste Current industrial process

The current tinting paste manufacturing process is highly manual.
Reduction in pigment size to the required degree of fineness occurs through two main processes:

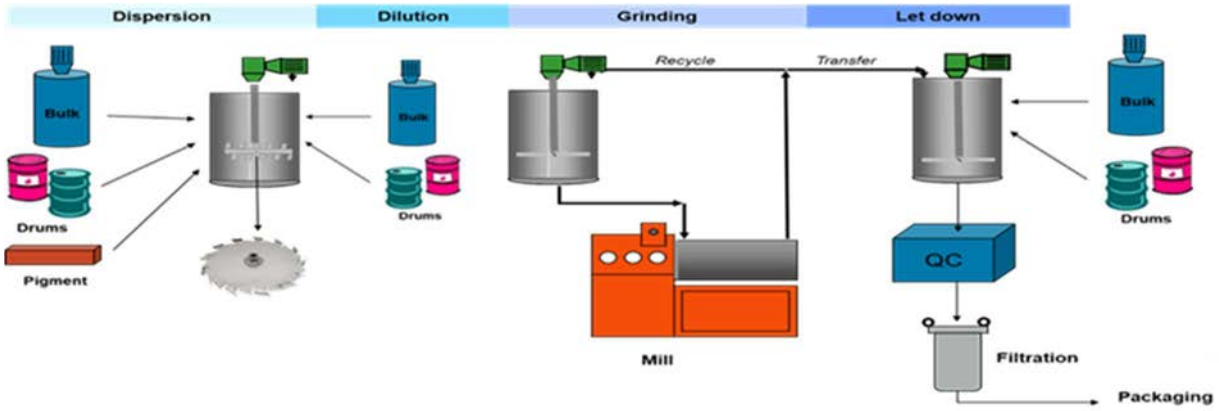
- Dispersion process
- Grinding process

The processes operate in series and aim to reduce pigment size to the required fineness required using specific equipment called high speed dispersers (HSD) and mills, respectively.
To enable the equipment to operate efficiently on pigment disintegration and at the same time to prevent that following disintegration the pigment tends to re-aggregate, these processes take place by keeping the pigment immersed in a specific liquid matrix that is intended both to stabilize the pigment following disintegration and to

facilitate the operation of dispersion and grinding through the adjustment of the viscosity of the liquid matrix that takes place through steps called “dilution” and “let-down”.
Optimum HSD rheology range in fact normally is significantly higher than optimum mill rheology range as showed in the graph below (HSD range in red vs Mill range in black) and the optimum mill rheology range is normally significantly higher of the final tinting paste rheology range required before to be used it in a basecoat production.



Below is a simplified production flow of base pastes where the main steps of pigment dispersion and grinding are shown along with dilution and let-down steps to reduce viscosity to the optimal ranges.



In Quattordio current process, these two processes are carried out on old machines (dispersers and mills) that require high manual activity and high exposure of the operator to the materials used since the loading and transfer activities are predominantly open loop, particularly during the dispersion and viscosity adjustment phases (dilution and let-down). Therefore, this process has several disadvantages for the company in terms of both safety and quality and productivity in one of the company's core processes since the production of tinting pastes is an indispensable process for the subsequent preparation of any type of basecoat.

The team project therefore focused on analyzing and evaluating process solutions to solve these problems trying to do so without simply upgrading the process solutions already known and in place at the site but interfacing externally to find and test on the market innovative and advanced machines.
The process choices made as well as the search for equipment were guided by the operating frequency (i.e., the frequency of use of the pigments involved and their quantities) by dividing the current process flow into two future flows of small batch production process with volumes below 1000 Liters bx and large batch production process with volumes above 1000 Liters up to 6000 Liters.
Choices made have all had as common denominators the objectives of:

- Implementation of a closed-loop process to reduce exposures.
- Use of innovative and less energy-consuming machines (sustainability)
- implementation of high level of automation to reduce handling and operator workloads (ergonomic and overall safety risk reduction).
- Implementations on process steps with higher safety and quality risk (from HAZOP safety risk analysis and PFMEA quality) of automatic control system from PLC to prevent human errors through introduction of error proofing systems.

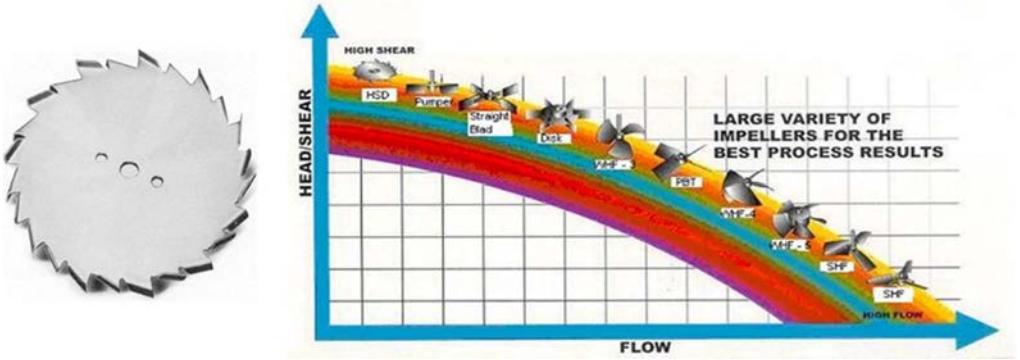
3 Current vs Future Process: description and benefit details by phase

The following are the main aspects of attention that have been considered in the current process and that have been subject to modifications in the future project.

3.1 Current process

3.1.1 Dispersion

In the current process to break down the pigment it is used a specialized mixing blade called High Speed Disperser (HSD). It is a specialized blade able to provide the highest shear rate compared to the other blade available in the market.



Due to the high shear rate during the process, overheating of the system also occurs and must be controlled as the products should not go over a certain temperature. Increased temperatures happen also during the subsequent grinding phase. To keep the temperatures in the desired parameters the two solutions that are adopted are as follows:

Used of cooling system during grinding.
Change of impeller from HSD to SHF at the end of dispersion phase.
Production currently takes place in an open-top mobile tank process using wall agitators so that the agitation system can be easily changed between dispersion and agitation during the recirculating grinding phase on mill.
The operator places the mobile tank under agitator equipped with HSD during dispersion and at the end of the activity positions the container under SHF agitator near mill to start recirculating grinding while meanwhile a new dispersion process can restart within another mobile tank.
Below some imagine of the main critical steps involved.

- Manual liquid raw material loading
- Manual loading of powder
- Manual cleaning of agitator after used
- Manual movement of mobile tanks to mill for the next phase

3.1.2 Grinding & let down

Grinding and Let Down

- Manual connection
- Manual cleaning of agitator after used
- Manual movement of mobile tanks to filling for the next phase

3.1.3 Filling

- Need to manually control the bottom with a spatula to ensure no sedimentation of powder has happened.
- Manual set up to connect the agitator for filling
- All activities in an open lid condition

The current situation shows as all the main activities are manual and involves:

- High manual intervention and low productivity;
- Operator exposure and extensive mask use;
- Ergonomic impacts (tank handling, fully manual agitator cleaning activities;
- Quality and contamination risks produced to external elements (rags, gloves etc.)

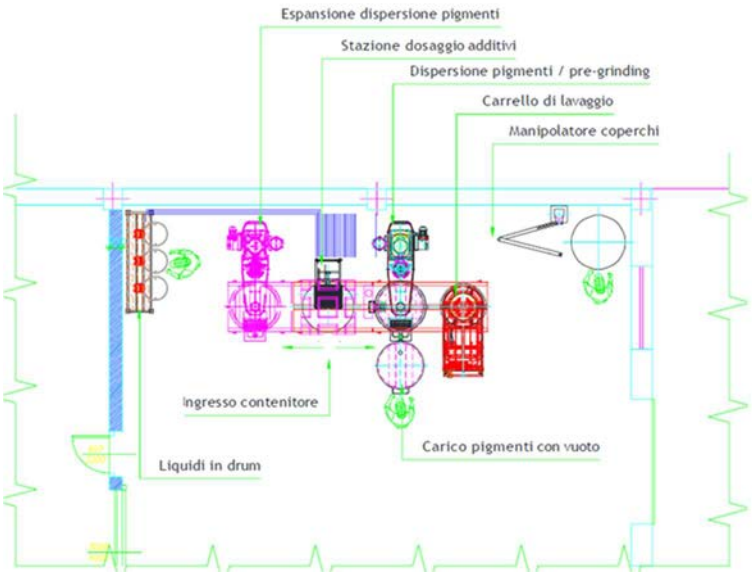
Limitations from a production point of view as it allows the production of a single batch size of 1000 liters linked to the maximum tank size. Production of larger batch sizes requires multiple daily breakdowns of the same activity. The future concept has been designed with the goal to minimize those activities. Future process small batches.

3.2 Future process

3.2.1 Future process: small batches

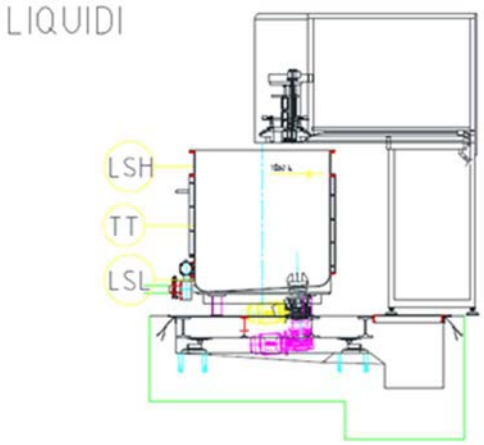
For small batches, the concept of production in 1000-liter mobile tanks will be maintained. Work was mainly done on mobile tank engineering by defining with suppliers Taylor-made tank concepts to allow closed-loop operations by defining mobile tanks with integrated agitator and automatic handling between liquid matrix preparation and dispersion execution stations.

Process flow plan for small batches:



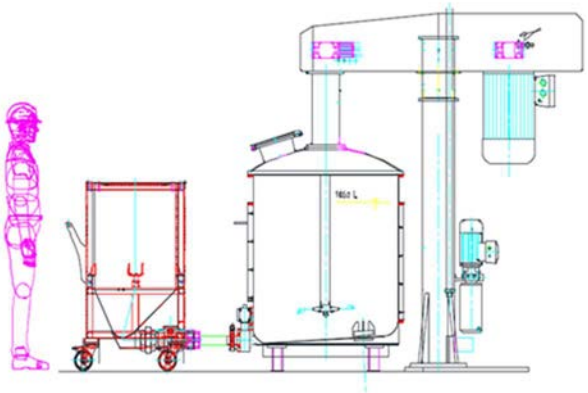
Phase 1: liquid raw material dosage

- Container insertion on scale station with centering and locking system.
- Automatic connection via docking station of gear motor on agitator.
- Agitators start (speed and cycles settable from SW).
- Start liquid dosing phase from SW recipe.
- Stop liquid dosing
- Stop agitator
- Disconnect docking station
- Container ready for transfer to pigment loading station.

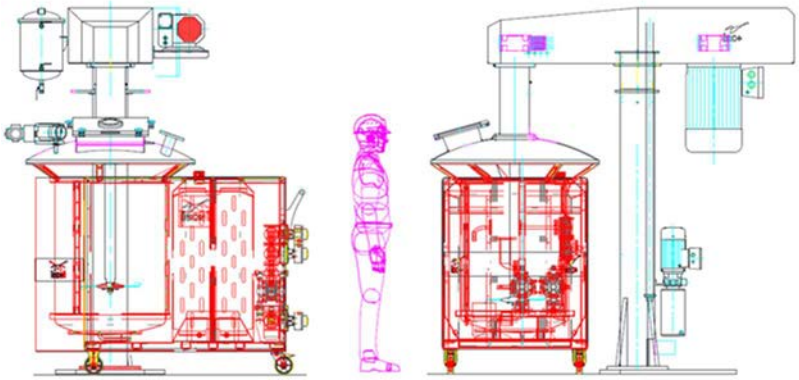


Phase 2: Pigment dosage and dispersion

- Automatic container positioning containing the first liquid phase. Manual connection of pigment loading hopper to disperser.
- Automatic suction on management
- SW of pigment into the disperser via static vacuum system in the hopper.
- Manual disconnection of the pigment loading hopper.
- Pigment dispersion.
- Tank sent to liquid loading station for formula completion.

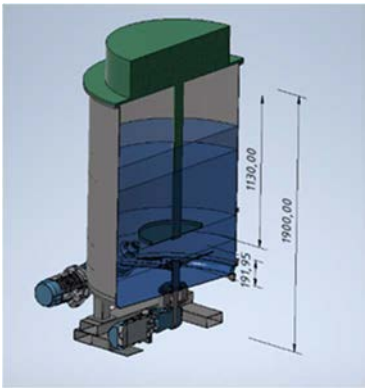


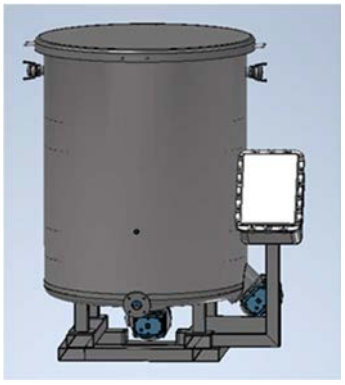
Phase 3: Automatic disperser washing



After the washing step is performed, a lid is placed with the aid of pantograph on top of the mobile tank to allow all subsequent steps (grinding and packaging) a closed-loop operation using the tank's built-in agitator as the tank required specific sizing for the needs, it was executed and defined through a 3-month prototyping and development process during which the correct position of the agitator and its dimensions were defined through specific tests performed at the Quattordio site that allowed the validation and definition of the relative constructs.

Phase 4: Grinding let down and filling

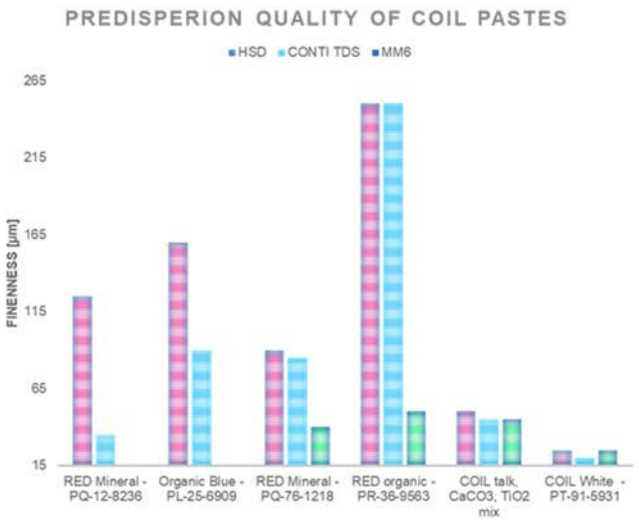


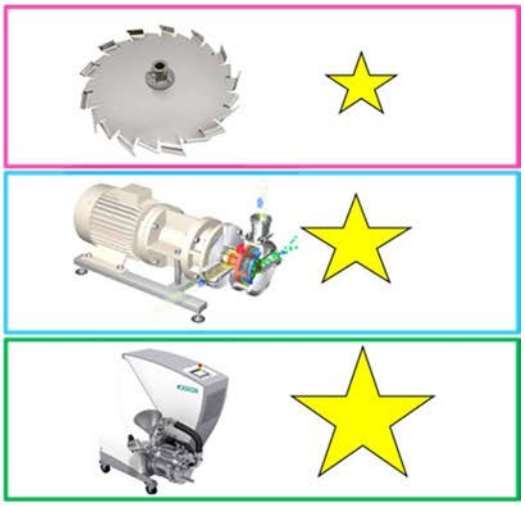


All following steps will operate on existing mills and equipment, but agitation of the container will always be provided by the integrated bottom agitator and the container will be closed with a lid.
Activities of checking the bottom, washing the mill agitator impellers, and anchoring the impellers for filling will no longer be provided.

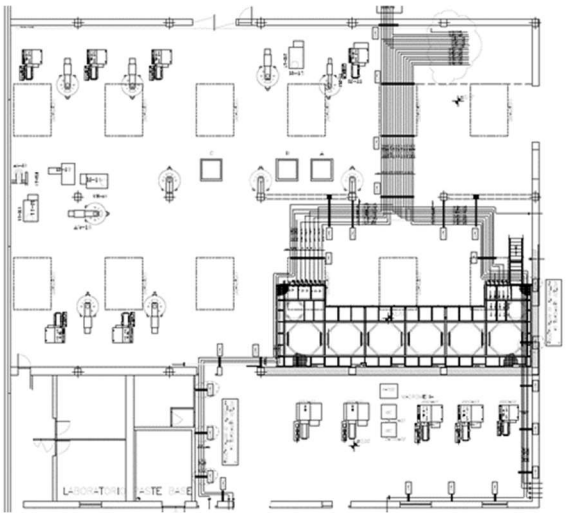
3.2.2 Future process: big batches

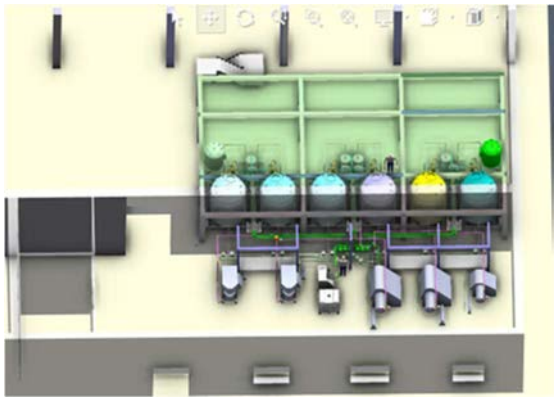
The big batches production process is the one that has required the largest change in equipment compared to the current process. Producing big batches facilitates the approach toward the use of closed tanks but at the same time required the search for more efficient machines at both the dispersion and milling levels to overcome the drawback of an excessive increase in milling and dispersion times if the current tools of HSD and conventional mills were used.
To the dispersion phase, the big batch process will use an innovative and recently introduced machine called Macromedia that was selected for its performance at the pigment disintegration level compared to other systems on the market.
Below you can see the comparison made on some pigments between dispersion following HSD (classical disperser), Rotostator and Macromedia.





In the big box concept has been in this way design a continue process in a closed loop system where all the steps from liquid raw material dosing to product ready to fill are in series and automated and fully controlled via PLC.
The liquid and pigment solution prepared in the process tanks will go in automatic mode before through macromedia to do the dispersion and after through the mills to do the grinding. Automatic valves will direct the flow to macromedia or grinding based on PLC input and the pigment will be reduced to the target level without manual intervention.
The viscosity adjustment activities of dilution and let down will be automatically done with the use of buffer tanks on the top of process tanks that will be preloaded the requested qty and then will move the fluid in the process tanks to adjust the viscosity in the target required
Below a 2D and 3D representation of the future process.





4 Conclusion

The "PCoP project" is fully aligned to the NIOSH concept **PtD** (Prevention Trough the Design) for:

- **Research:** To study effectiveness of current process, investigate additional solutions for existing design-related challenges, and identify future research needs.
- **Education:** Teach and motivate others to use priorities and processes in collaborative design and redesign of work processes, equipment, and tools.
- **Practice:** Increase use of "safety from design" by sharing case-studies and benchmarks in the Company.

The "PCoP project" is also fully aligned to the **Industry 4.0** approach:

- Proactive approach to risk assessment (occupational and process).
    - Development and deployment of automated processes to the inclusion of integrated risk identification and assessment processes. Risks can be analyzed during process development, allowing mitigation as part of the development process. Implementing changes so risks can be avoided, eliminated or reduced before deployment of an operation will be more cost-

effective than changing a process after deployment, and unacceptable risks will materialize.

The project combines high targets for productivity, quality, and efficiency including conditions and requirements for safety and ergonomics in the workplace. It is fundamental to define a system where operators and plant are integrated and in mutual interaction where manual operator activities and interventions are assisted by automation logics and machines and where the machines and logics are easily usable and intelligible to the operator.

Failure to work on both aspects leads to shortcuts that later turn out to be obstacles that both in the short but especially in the long run would prevent the achievement of the productivity and efficiency goals necessary to be competitive and assert one's competitiveness in the marketplace.

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Robotic systems in the preparation of antiblastic treatment and occupational health: a review

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Abstract

Due to their genotoxic, carcinogenic, teratogenic and reprotoxic properties, the manipulation of antineoplastic drugs (ADs), which involves the composition, administration and waste management, represents a considerable risk for healthcare workers (HCWs). The automation of work activities, with artificial intelligence (AI) and advanced robotics, is having significant implications on occupational safety and health. The aim of this paper was to evaluate the effects on occupational exposure to antiblastic drugs of robotic systems that replicate, in the preparation of chemotherapeutic drugs, what performed manually by human operator. The role of AI is to govern the flow of activities to control and track all data relating to prescriptions and therapies administered, minimizing the possibility of errors. We searched the computerized literature of MEDLINE, PubMed, Web of Science and Scopus Databases from 1/1/2018 through to 31/08/2024 to identify published data about the risk of occupational exposure for HCWs resulting from residual cytotoxic contamination for traditional handling procedures compared to the robotic system. Based on the abstract, articles have been either considered for further evaluation or discarded when the content was not considered pertinent to the purpose of the review. We also excluded articles in languages other than English or Italian. The comparison of the two preparation methods showed that, regarding the contamination of the compounding area, the robotic systems were associated with lower contamination; infusion bags and operators 'gloves resulted comparably contaminated for both manual and robotic compounding. The increase in cancer patients and the consequent increase of the number of chemotherapy preparations will lead to invest in robotic methods; further comparative studies would be useful and desirable to identify specific health risks of robotic methods and then educate pharmacists to adopt appropriate precautionary measures to mitigate those risks. The here presented study is part of the 2023-2025 European campaign EU OSHA, 'Safe and healthy work in the digital age', in which Inail is engaged in multidisciplinary programs aimed at identifying both the risks and the opportunities of digitization at work.

1 Introduction

In 2020, more than 19 million cases of cancer were diagnosed worldwide and, according to the Global Cancer Observatory (IARC, 2024), in the next two decades, 30 million new cases will be reached. Growing demands for anticancer treatments inevitably would necessitate an increase in the number of HCWs needed to care for those patients [1]. Among the antineoplastic chemotherapeutic agents, ADs exert cytotoxic and cytostatic effects by blocking or slowing down cell proliferation by different mechanisms. According to their mechanism of action, these treatments can be classified into alkylating agents, cytotoxic antibiotics, antimetabolites, antimitotic agents, topoisomerase inhibitors and drugs that act by other means. ADs do not distinguish the tumor cell from the normal one, so even non-cancerous cells, especially those with high turnover, can suffer the cytotoxic and genotoxic effect [2]. In recent years, traditional anticancer chemotherapy has been bordered by '*targeted therapies*' with molecularly targeted drugs that interfere in a much more targeted way with a specific molecule or process of cancer cells, without damaging normal cells or in any case with fewer side effects [3]. An example is monoclonal antibodies that recognize certain types of proteins found on the surface of some cancer cells by firmly joining them and stimulate the body's immune system to attack the cancer cells (Figure 1).

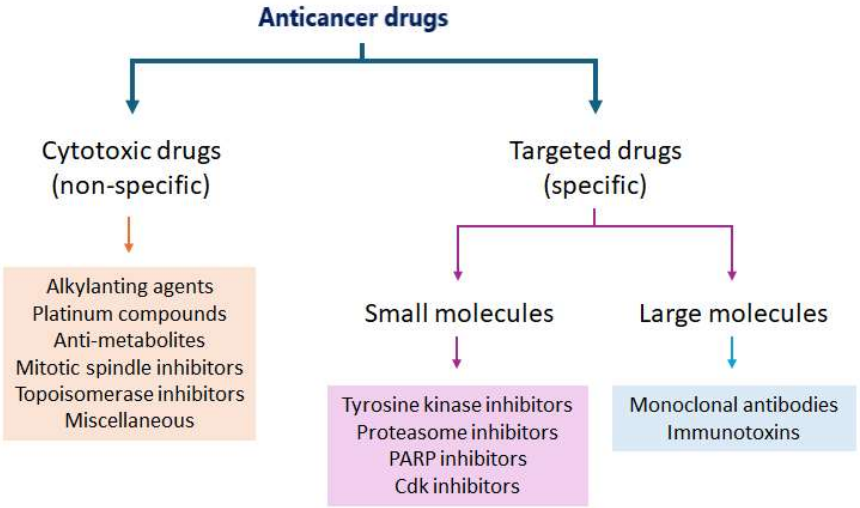

Fig. 1. Anticancer drugs categorization.

Several ADs are classified as carcinogenic, mutagenic, and/or toxic for reproduction. The IARC (International Agency for Research on Cancer) has evaluated numerous ADs and has classified them differently as certain (Group 1), probable (2A) or possible (2B) carcinogens for humans and not classifiable as to carcinogenicity to humans (Group 3). Relating to reprotoxic occupational exposures, the Parliament and the Council of the European Union has recently adopted the Directive 2022/431 (CMRD), transposed nationally by Legislative Decree No. 135 of 4 September 2024. The CMRD extended the scope previously set by Directive 2004/37/EC (CMD) by adding reprotoxic substances, i.e. substances toxic to reproduction, to the original classification on the

protection of workers exposed to the risks arising from carcinogens and mutagens [4]. The European Commission has specified that dangerous drugs, those containing substances classified as carcinogenic, mutagenic, reprotoxic, must also be included in the CMRD. Of extreme importance is the Commission's declaration establishing the inclusion, in the scope of the directive, of dangerous drugs (HMPs), i.e. those drugs containing substances that meet the criteria for classification as carcinogenic, mutagenic, toxic for reproduction category 1A and 1B, to the CLP (Classification, Labelling and Packaging), for each of the above classifications. Occupational exposure to ADs mainly affects workers in the health sector not only working in oncology, but also in the field of immunology, rheumatology, nephrology and dermatology as the use of these drugs is expanding in the treatment of non-oncological diseases. In the workplace, absorption can take place mainly by inhalation or percutaneously. The other routes of penetration into the body, such as the ocular route, due to spraying, and the digestive route, due to the ingestion of contaminated food, are occasional and due to accidents. The occupational exposure to ADs has been associated with skin conditions, fertility problems, and some types of cancer, although most of the available epidemiological data refer to periods in which the handling of these drugs took place in a different way from the current ones. In the handling of chemotherapy and antiblastic drugs, most dangerous operations are those that may involve the formation of vapors and/or aerosols and/or the diffusion of the preparation in the form of drops. Workers potentially more exposed to antineoplastic drugs include oncology pharmacy staff (laboratory technicians and nurses) during the preparation of mixtures, nursing during day hospital administration and waste disposal department. One of the most critical phases of the chemotherapy preparation process is preparation, in which the highest level of exposure for the operator is recorded [5]. The preparation of oncological therapies must be carried out in a dedicated environment called UFA (Antiblastic Drugs Unit). It is a controlled atmosphere clean room, i.e. a totally sterile and protected environment. Biological safety cabinets and protective devices are generally recognized to minimize the external exposure during the handling of antineoplastic drugs; more recently, robotic systems are available that can replicate what the operator performs manually. They are designed to improve both patient safety by automated procedures and complete traceability of the drug preparation process, and workers' health by limiting exposure to leakages and aerosols of ADs. However, contamination of the outer surfaces of the ready-to-administer preparations cannot be totally excluded. Thereby the hazardous residues may be transferred to the preparation and even administration areas. Until now, only few studies have been published regarding workplace contamination during automated compounding. The aim of the present article was to evaluate contamination risk and the quality of the working environment for HCWs of the robotic system, compared with the traditional manual system in preparing these hazardous drugs.

2 Methods

A systematic literature search was performed consulting the banks MEDLINE, PubMed, Web of Science and Scopus Databases, focusing on studies published from 1/1/2018 through to 31/08/2024. The goal was to evaluate any potential advantages, in terms of reduction of occupational exposure to ADs for HCWs, in the use of automated robotic systems compared to traditional manual ones for preparation of anti-cancer therapies. The search strings were obtained by combining the keywords (robotic antineoplastic preparation, compounding robot chemotherapy, co-robot adjuvant drug preparation) in combination with relevant key words, “residual cytotoxic contamination”, “occupational exposure”, “hazardous drugs”; additional searches included the terms “staff safety, “HCWs health”. We also utilized information from three current reviews (Elisabeth Farcy *et al*., 2019) on the impact of technology-assisted workflow (TAWF) systems for drug compounding in pharmacy practice and more generally on robotic system for cytotoxic preparations (Gennaro Laus, 2023; Sangyoon Shin *et al*., 2023), respectively [6-8]. For each search strategy, articles were selected based on of title, then abstract, then full text; based on the abstract, articles have been either considered for further evaluation or discarded when the content was not considered pertinent to the purpose of the review. Abstracts, thesis, descriptive articles without original data were also excluded. We, lastly, excluded articles in languages other than Italian or English.

3 Results and Discussion

Approximately 8 million HCWs are unnecessarily exposed to highly toxic drugs used to treat cancer; as a result, concerns regarding the long-term occupational exposure remain high and the implementation of mitigation measures is critical. An important step taken to protect workers from ADs contamination has been to centralize preparation in specialized pharmacies (UFA), ensuring a high technical standard, including safety measures such as isolators, biological safety cabinets (BSCs) and personal protective equipment (Figure 2). However, even if modern guidelines and good manufacturing practices are strictly applied, widespread contamination is still possible [9]. The introduction of robotic systems in hospital pharmacies has increased in recent years and has already been implemented in several international centers.

Fig. 2. ADs compounding by conventional manual procedure in a biological safety cabinet (BSC) in which vertical laminar flow, directed from top to bottom, establishes a barrier between the inside of the hood and the operator. Royalty-free Inail image (ID 446VWSDZDHTQ-225-4340).

The present three-year (2023-2025) EU OSHA Healthy Workplaces Campaign is dedicated to the 'Safe and healthy work in the digital age', with the aim to raise awareness around the occupational safety and health (OSH) challenges, risks and opportunities related to the digital technologies. Cobotics is a neologism derived from the words "robotics" and "collaboration". It corresponds to the collaboration between a man and a robot. Collaborative robotics is a technology that is a that uses robotics, mechanics, electronics and cognitive sciences to assist humans in their daily tasks. The solutions offered by cobotics are being considered when robots alone cannot replace humans in his expertise, his know-how, his sensitivity, his perception of things and its environment. Robotic preparation environments offer the potential for safer and more convenient preparation of antineoplastic and adjuvant drugs. However, technological interventions can also introduce unintended consequences, including potential or actual harmful ones. Therefore, we undertook a study analyzing the most recent data published in the literature – from the beginning of 2018 to the present day, about the impact of corobots that prepares antineoplastic and adjuvant drugs on staff safety. In hospitals, drug corobots are generally based on a software capable of supporting and documenting the different steps of antineoplastic preparation,

which verify the conformity of the preparation by gravimetric systems with high precision scales, barcode readers to verify the identity of the ingredients/supplies used, and cameras to document the process. The international scientific literature on robotic systems is still not very significant from a quantitative and qualitative point of view, even though it is a technology that has been on the market for years. A total of 38 studies were initially identified relevant to the review, later reduced to 34 because 4 of them were duplicates. The selection of relevant articles was conducted using eligibility criteria based on the study design, comparison and outcome. Outcomes related to the performance of the compounding robot were measured in terms of HCWs safety, including drug contamination of infusion bags or gloves worn by the robot operator. The articles screened were 29, nine of which afterwards excluded because they contained French/Portuguese/Spanish language or because published prior to January 2018. Of these, 5 articles were excluded since they did not provide any possible indication that could be considered usable in the present study. Studies related to robotic surgery, non-robotic combination, accuracy and drug preparation time, and anyway computerization of workflow data not related to the issue of occupational health protection improvement were also excluded. Therefore, 15 articles have been considered for the purposes of this revision. Although the robotic method offers significant and irrefutable advantages both for patients, reducing the risk of error on dosage, and for the company, reducing costs, however there are not as many certainties related to the advantages for operators, in terms of an unanswerable occupational exposure reduction. Four different types of workplace pollution from the preparation of antiblastic drugs can be distinguished:

1) Environmental contamination, when traces or residues are accidentally introduced into or around the compounding area, causing pollution of surfaces and therefore potential exposure of pharmacy staff.

2) External contamination, when traces or residues are left outside the final drug container (e.g., an infusion bag or syringe), causing potential exposure of healthcare workers in handling the final containers.

3) Cross-contamination, if traces or residues are transferred to the next or any other subsequent preparation, causing unintentional exposure of a patient to this drug.

4) External cross-contamination, in case traces or residues are transferred outside the final container of the subsequent preparation or any subsequent preparation. This phenomenon is also called carry-over and causes the potential exposure of health care workers who handle the final containers. Werumeus Buning et al. compared environmental and external contamination of traces of cytostatics using a robotic system (APOTECA-chemo) or the conventional manual compounding procedure [10]. The authors found external environmental contamination for both the manual and robotic technique, with better results for the robotic technique, especially after optimization of the cleaning protocol. The study conducted by Hao et al. reached similar results, indicating that the compounding antiblastic with the robotic system (WEINAS) can dramatically reduce environmental contamination over

manual compounding with the BSC [11]. Two studies investigating the robotic system CytoCare® and the RIVA robot (ARxIUM), respectively, were excluded due to accidental drug spillage [12-13]. Generally, the comparison between manual and automated preparation has shown that the environmental contamination is lower in robotic systems, although for some studies of them this decrease was not statistically significant [14-16]. Concerning the external contamination and cross-contamination, results of the present paper analysis show that antiblastic contamination was detected on infusion bags - this point is important for nurses who will be in contact with the preparations when administering them to patients - and on the gloves for both preparation methods, although it was not later detected inside gloves or on the hands or in the urine samples of the operators or in the ambient air samples. Despite this, the robotic system generally allows preparation with low levels of contamination [10,17-22]. Besides, most robots use ventilated needles (i.e., with air intakes) or not to collect anticancer drug vials, which can generate aerosols or microdroplets in the preparation chamber. Some robots manage the internal pressures of the vials by compensating them to limit this risk [23]. Other systems offer a self-cleaning procedure to reduce chemical contamination of the robot's working environment [24]. Automated systems using closed transfer systems instead of needles for collecting anticancer drug vials are also available on the market, demonstrating good control of this contamination.

4 Conclusion

For reasons of optimization, safety, precision, autonomy and control of human resources, several centers have equipped themselves with one or more automated or robotic systems. This technological change is accompanied by a paradigm shift, from manual preparation to robotic preparation. Automation and computerization of the entire drug process in hospital pharmacies will intensify in the coming years, integrating artificial intelligence with the creation of centralized units that allow extending production to parenteral nutrition but also to all injectable health products. There will also be more solutions on the market and the choice of solution first requires a good definition of the need. The results of this study highlight that the robotic organizational process, since the interaction with the ADs is minimal, the operator is protected from accidental exposure and the risk of contamination is mostly localized within the work area of the robot, although episodes of external contamination such as those of infusion bag or syringe and gloves are not completely excluded, as reported in some studies. To support decisions on the usefulness of switching to an automated system versus manual preparation of chemotherapy in protecting healthcare workers, as well as to obtain specific information on the performance of different automated systems placed on the market, further comparative studies would be appropriate, especially regarding possible best practice strategies for eliminating or at least reducing overall exposure.

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Industrial cyber shield: a comparison of two real-time data capture probes

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Abstract
In recent years, Industrial Cyber-Physical Systems (ICPS) have become increasingly vulnerable to cyber-attacks due to the exposure of traditional industrial protocols to the Internet. These protocols, which were initially designed without inherent security features, pose significant risks to Supervisory Control and Data Acquisition (SCADA) networks, as attackers can exploit them to manipulate industrial physical processes directly. To mitigate these risks, the Italian national project Industrial Cyber Shield (ICS) is focused on developing an intrusion response system designed to assist operators in implementing security countermeasures when critical anomalies are detected in SCADA networks. A key component of this system is the Anomaly Detection System (ADS), which utilizes real-time data probes to monitor and analyze both SCADA network traffic and physical process data. However, there is a notable gap in existing research regarding the real-time performance of data capture solutions. Addressing this gap, this paper presents two innovative data capture probes tailored for anomaly detection in ICPSs. Implemented in Python and C++, these probes enable a comparative evaluation of real-time performance metrics. Their effectiveness is validated through deployment in a laboratory SCADA network simulating a water distribution system, providing practical insights into their operational capabilities.

1 Introduction

Over the past few years, Industrial Cyber-Physical Systems (ICPS) have become increasingly susceptible to cyber-attacks. This is largely due to the widespread adoption of open and heterogeneous protocols that enable remote Internet connectivity [1]. While these advancements offer significant benefits such as resource optimization and customizable production lines, they have also introduced new vulnerabilities into Supervisory Control and Data Acquisition (SCADA) networks. Many cyber-attacks now exploit traditional industrial protocols, which were initially developed without a strong focus on security. During the early stages of the third industrial revolution, industrial networks operated under the outdated concept of "security by obscurity," relying on physical and logical isolation from external systems to maintain security [2]. In this context, it is essential to enhance SCADA network security by integrating detection and intrusion response systems that can

automatically transition industrial systems into a secure state. However, current research often neglects the development of automatic response mechanisms within SCADA networks due to the inherent risks of managing complex industrial processes. Incorrect handling of such processes can lead to severe consequences, including environmental damage, production downtime, and even loss of human life [3], [4].

To address this gap, the Italian national project Industrial Cyber Shield (ICS), funded by INAIL, focuses on creating an effective intrusion response system. This system is designed to assist security teams in determining suitable countermeasures and autonomously implement them during critical operational conditions [5]. A fundamental element of such a system is a robust Anomaly Detection System (ADS), capable of identifying potential cyber and physical anomalies within the SCADA network in real time. The ADS relies on a data capture probe to collect relevant cyber and physical data, ensuring the real-time detection of anomalies [6]. The probe must monitor SCADA traffic thoroughly and extract key statistical features, which are analyzed by the ADS to flag anomalies [7].

Ensuring the real-time performance of both the data capture probe and ADS algorithms is critical, necessitating the evaluation of metrics such as CPU usage, memory consumption, and detection latency. However, current literature provides limited exploration of real-time performance in data capture probes for anomaly detection. Manivannan et al. [8] propose an online data acquisition and control system for real-time applications, but it is not optimized for anomaly detection and lacks performance metrics. Similarly, Sarma et al. [9] describe a low-cost data acquisition system built in Python, but it does not involve SCADA networks or integrate anomaly detection algorithms. Atmoko et al. [10] analyze IoT data acquisition using MQTT and HTTP protocols, focusing on communication performance rather than real-time data capture for anomaly detection. Real et al. [11] present a data acquisition solution using an Arduino Due board, which is not tailored for SCADA networks or linked to detection mechanisms. Moreover, most anomaly detection research centers around offline data processing, neglecting real-time performance considerations for SCADA networks [12, 13, 14].

This paper addresses these gaps by comparing the real-time performance of two data capture probes for anomaly detection in ICPSs, one developed in Python and the other in C++. Both probes are designed to monitor SCADA network traffic and extract meaningful features for subsequent analysis by anomaly detection algorithms. The evaluation is conducted on a real SCADA infrastructure, specifically a water distribution testbed in a controlled laboratory environment [15].

The paper is structured as follows: Section 2 provides an overview of the SCADA architecture and the implementation of the two data capture probes. Section 3 presents the experimental results, while Section 4 concludes the paper.

2 Data capture probe implementation

2.1. SCADA architecture

For the implementation of the data capture probes, this study utilizes a laboratory-based water distribution infrastructure, referred to as the WDT, specifically designed for cyber-physical security testing [15]. The SCADA network setup and its connected devices are depicted in Figure 1, while Figure 2 provides a visual representation of the testbed. The SCADA network comprises four main components: a Programmable Logic Controller (PLC)

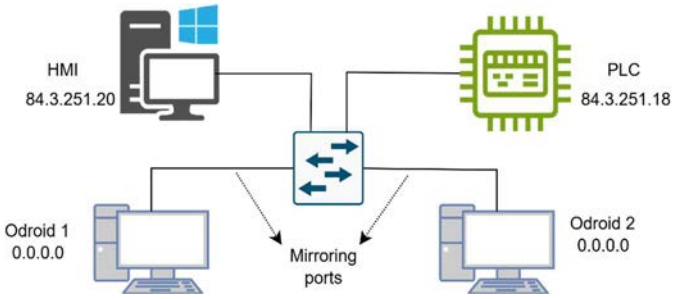

Fig. 1 SCADA network.

Fig. 2 Graphical view of the Water Distribuion Testbed.

that manages the control processes, a Human Machine Interface (HMI) that displays the status of the industrial process by retrieving physical control data from the PLC, and two data capture probes-one developed in Python and the other in C++.

The communication within the system is based on the Modbus TCP/IP protocol, with the HMI acting as the client and the PLC as the server. The data capture probes are hosted on two Odroid H3+ devices, each equipped with an Intel® Quad-Core Processor Jasper Lake N6005 running at 2 GHz and 16 GB of RAM. These devices are connected to mirrored ports on the network switch, enabling them to monitor all communication between the PLC and the HMI. Physical process data is extracted by capturing Modbus response packets sent by the PLC to the HMI, as these packets contain status information about the pumps, valves, and sensors in the testbed.

The physical testbed infrastructure includes five polyurethane tanks (T1 through T5), 20 solenoid valves (V1 through V20, Evian© Series 263), three small-scale pumps (P1, P2, P3, Pipe 151 410), one EK-DCP 2.2 pump (P4), five pressure sensors (S1 through S5, WIKA© S-11), and eight manual valves designed to simulate water leaks in tanks or pipes. The PLC used is a Modicon M340, while the HMI is implemented using Movicon 11.6 software installed on a Windows Server 2012 machine with an Intel® Xeon® CPU E5-2620 v2 @ 2.10 GHz and 16 GB of RAM.

The anomaly detection systems are deployed on the two Odroid devices and are composed of five separate Long Short-Term Memory (LSTM) deep neural networks, each responsible for monitoring the water levels in one of the five WDT tanks. These

networks' performance has been comprehensively analyzed in our earlier work [14]. In brief, each LSTM network processes a time series of 20 samples and predicts the water level for the 21st time step. If the discrepancy between the predicted and actual water level exceeds a predefined threshold, an anomaly is detected. The features required for each LSTM model depend on the specific tank being monitored.

2.2. C++ implementation

When developing an application that demands near real-time execution, using a language
like C++ is often the optimal approach. The primary reason is performance. In particular, C++ offers significant advantages due to several critical features:

- **Compiler Efficiency**: The compiler utilized in this case is g++ (Ubuntu 11.4.0-1ubuntu1 22.04) version 11.4.0. Compilers translate source code directly into machine code, eliminating the overhead associated with interpretation. Additionally, this specific compiler generates highly optimized code, ensuring smooth execution with minimal latency.
- **Memory Management**: C++ provides fine-grained control over memory allocation and deallocation, making it an ideal choice for applications running on Single-Board Computers (SBCs) with constrained memory and CPU capabilities.
- **Thread Support**: C++ supports the creation of true operating system threads through libraries such as thread or pthread. These threads enable genuine parallel processing, a key advantage in resource-limited environments where multithreading can substantially boost performance.
- **POSIX** (Portable Operating System Interface for Unix): C++ supports the use of standard POSIX commands and libraries, allowing close interaction with the OS.

2.2.1. Software Structure

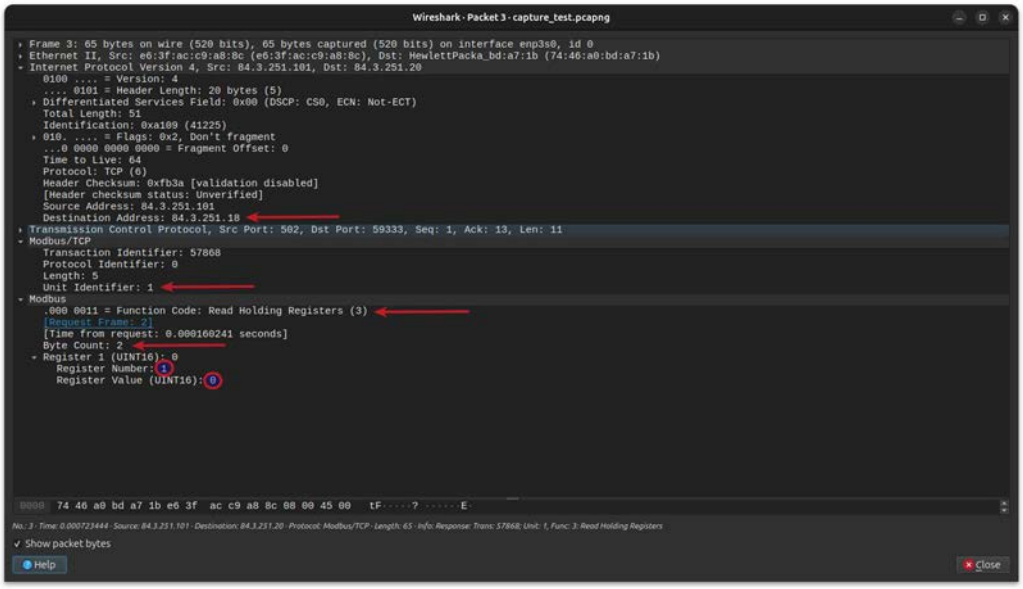

Fig. 3 Modbus packet captured by packetHandler(...).

The program employs a producer-consumer architecture. The producer adds rows of register values to a double-ended queue (deque). When the deque reaches its maximum capacity, it signals the consumer. The consumer applies the LSTM model to the first 20 rows for inference, then removes the oldest row from the front of the deque and notifies the producer that space is available.

The program begins by invoking two primary functions: capturePackets(...) and startInferenceThreads(). The capturePackets(...) function runs on its dedicated thread and receives a pointer to a pcap capture session as input. It dispatches the packetHandler(...) function to handle incoming network packets. The capturePackets(...) function processes only packets destined for the HMI, as these packets contain the requested status of the WDT pumps, valves, and tank water level sensors. Figure 3 illustrates a captured Modbus response packet sent to the HMI (IP address 84.3.251.20), with key packet details marked by red arrows. The Modbus/TCP header contains the Unit Identifier (Unit ID), which uniquely identifies the physical device whose data was requested by the HMI. The Unit ID serves as the key in a hashmap, structured as follows:

- 1st vector: Indicates the LSTM model to which the captured value should be sent.
- 2nd vector: Specifies the number of features required by the corresponding LSTM model.
- 3rd vector: Identifies the position index of the feature within each time series sample.

- 4th vector: Contains the min-max normalization values.

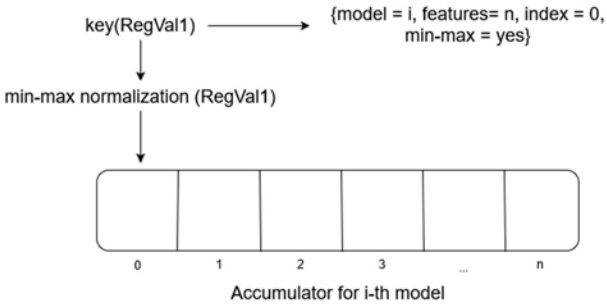

Fig. 4 Storing a captured Modbus value into the accumulator.

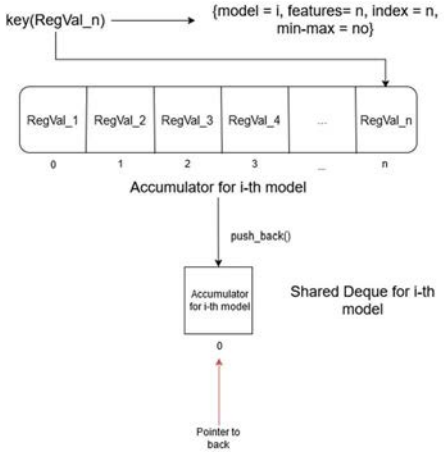

Fig. 5 Inserting the accumulator into the tensor structure.

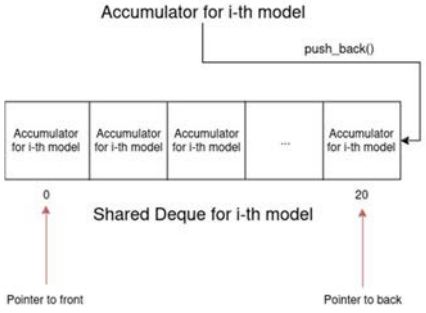

Fig. 6 Full deque.

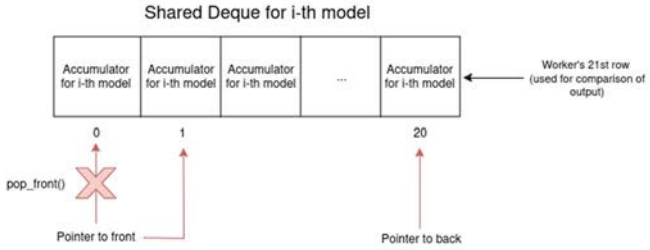

Fig. 7 Popping logic of worker inference threads.

For this SCADA network configuration, two Modbus functions are supported: *read coils* (function code 01) and *read holding registers* (function code 03). After identifying the function code, the system determines the number of registers or coils to be read. As shown in Figure 3, a byte count of 2 signifies a single register, as each register comprises 2 bytes. The extracted register or coil values are normalized (if necessary) and then stored in an accumulator (Figure 4). Once the accumulator is full, it forms a row in a tensor structure representing the time series input for the LSTM model (Figure 5). After each accumulator is filled and added to the deque, it is cleared for reuse.

Once 21 rows are added to the deque for the *i-th* model, the shared deque structure is ready for processing. Front and back pointers are maintained for efficient access (Figure 6). Worker inference threads, corresponding to the LSTM models, are notified when the deque is ready.

The startInferenceThreads() function initializes five inference threads, each dedicated to one LSTM model. This function defines the model paths, input/output names, and thresholds. A vector of threads is created, and the emplace_back(...) method is used to add modelInferenceWorker(...) threads. Each modelInferenceWorker(...) receives the appropriate model path, input/output names, and threshold, and operates on its own thread. Once a thread is active, it waits for a notification from the capturePackets(...) function. To prevent unnecessary wake-ups, a condition variable is paired with an additional check to ensure the deque is full before proceeding. Inference is performed on 20 out of the 21 rows in the tensor. The 21st row is preserved and compared with the LSTM's prediction. The inference worker then removes the front row from the deque (the oldest data) and signals the producer to append new data to the back.
Ultimately, the packetHandler(...) producer and the modelInferenceWorker(...) consumers collaboratively manage a shared structure, ensuring the deque always contains the latest data at the back and the oldest data at the front (see Figure 7).

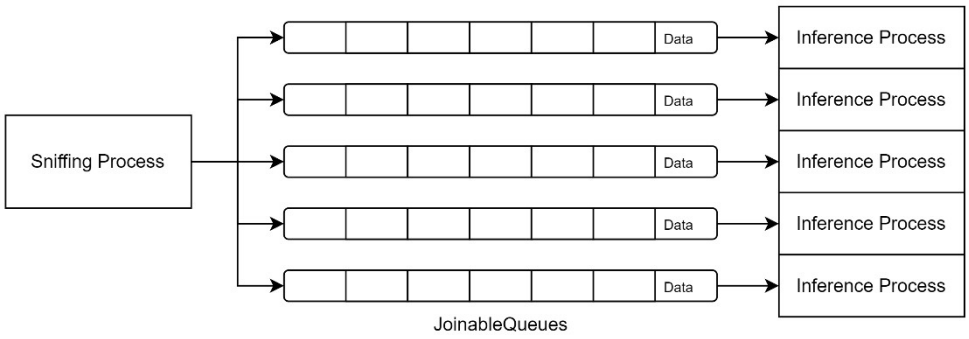

Fig. 8 Producer-Consumer Architecture with Sniffing Process and Inference Processes

2.3. Python implementation

The Python implementation follows a producer-consumer pattern, utilizing multiprocessing for parallel execution. The producer collects data from a network interface and organizes it into device-specific structures. Each monitored tank corresponds to an instance of the Device class, whose key attribute is a feature matrix that stores normalized data extracted from SCADA network packets. When a matrix is fully populated, its content is pushed into a dedicated multiprocessing queue (JoinableQueue), which acts as the communication bridge between the producer and the consumers.
For network packet sniffing, the scapy library is employed. The sniff() function accepts a *prn* parameter, specifying a callback function to process each captured packet. In this case, the callback function is *classify_packet*, which extracts relevant data from each packet, formats it appropriately, and assigns it to the correct Device object. This method ensures efficient packet categorization and routing to the corresponding queues.

Consumers are implemented as independent processes, with each one dedicated to a specific tank being monitored. These processes retrieve data from their respective queues, execute tasks such as inference with pretrained LSTM models, and update the corresponding outputs. This separation of roles enables parallel and scalable management of multiple tanks.
The main program is responsible for initializing the devices and coordinating the various processes, including packet sniffing and queue management.
Figure 8 depicts the producer-consumer structure. The sniffing process (producer) captures network data and distributes it to tank-specific JoinableQueues. Each queue serves as a buffer for its associated inference process (consumer), enabling scalable and efficient parallel processing across multiple devices.

2.4. Real-time performance metrics

This section outlines the methodology for collecting real-time performance metrics in both Python and C++ implementations. The primary objective is to evaluate the total time during which inference is stalled due to threads or processes being in a waiting state.

2.4.1 C++ performance metrics evaluation

High performance is characterized by minimal time wasted. In the C++ implementation, wasted time is tracked by measuring how long a thread spends waiting when attempting to add an accumulator to a full deque (tensor). Before entering a wait state, the thread records the current time. It then checks if the deque is full. If full, the thread waits for a signal indicating that space has become available. Once the wait ends and the thread can continue, the current time is recorded again. The difference between the recorded times is calculated and added to a cumulative total. A higher cumulative total indicates greater inefficiency or bottlenecks during execution.

2.4.2 Python performances metrics evaluation

To evaluate performance, the code incorporates specialized queue monitoring processes that continuously track the length of each device’s queue. If a queue's size exceeds one, it signifies that the system is temporarily unable to process incoming data fast enough, resulting in a backlog—or "overcrowding"—of unprocessed items.
When overcrowding occurs (queue length > 1), the monitoring process logs the start time of the event. It continues to monitor how long the queue remains above this threshold, effectively calculating the system's delay or "wait time". Once the queue size drops back to 1 or below, the end time of the overcrowding period is recorded. By aggregating these measurements over time, the monitoring processes provide valuable insights into performance bottlenecks. For example, if specific device queues consistently exceed the threshold for prolonged periods, it may indicate:
(1) Inference workers are taking too long to process the data.

(2) The network is delivering packets at a rate that surpasses the system's processing capacity.
(3) Other performance constraints, such as hardware limitations or inefficiencies, require attention.
This method enables precise identification and resolution of system inefficiencies.

3 Results and discussion

Polling time [ms]	# pkt/s	Avg CPU Usage [%]	Avg Memory Usage [%]	Max_RSS [KB]	Tank_1 [ms]	Tank_2 [ms]	Tank_3 [ms]	Tank_4 [ms]	Tank_5 [ms]
1000	63	2.67	0.13	178'232	0.37	0.62	0.44	0.26	0.55
900	70	2.73	0.14	179'312	0.44	0.55	0.21	0.43	0.55
800	75	2.9	0.14	178'300	0.59	0.58	0.43	0.59	0.68
700	86	3.09	0.15	177'484	0.65	0.69	0.74	0.53	0.64
600	97	3.24	0.16	178'496	0.91	0.71	0.58	0.72	0.29
500	115	3.78	0.16	178'396	0.61	0.58	0.96	1.13	0.63
400	140	4.21	0.17	178'436	33.97	8.48	16.28	18.9	47.96
300	178	5.11	0.18	178'556	154.26	64.61	63.14	78.05	151.33
200	200	5.44	0.18	178'484	109.72	113.22	176.71	108.17	120.74
100	202	5.24	0.18	179'436	222.06	96.8	74.73	83.35	239.18

Table 1 C++ real-time performance metrics.

Polling time [ms]	# pkt/s	Avg CPU Usage [%]	Avg Memory Usage [%]	Max_RSS [KB]	Tank_1 [ms]	Tank_2 [ms]	Tank_3 [ms]	Tank_4 [ms]	Tank_5 [ms]
1000	63	23.09	0.81	459'300	0.0	0.73	0.0	0.28	0.0
900	70	24.23	0.81	459'344	1.53	1.47	1.38	1.24	0.6
800	75	24.38	0.81	459'560	183.93	545.59	403.49	364.24	127.6
700	86	24.38	0.81	459'600	192.89	1420.96	408.67	2398.53	1953.0
600	97	23.5	0.81	459'724	1320.4	1077.99	1362.91	3173.58	1863.26
500	115	23.84	0.8	459'816	2302.34	2780.46	1516.47	2863.08	1467.99
400	140	23.21	0.8	460'236	5851.82	13356.34	4651.23	8123.1	2720.57
300	178	23.99	0.8	460'204	5736.3	9885.36	4948.94	3211.03	7709.45
200	200	23.35	0.81	460'116	5245.87	6677.99	3636.15	5735.96	7619.71
100	202	23.39	0.81	459'948	11525.84	4379.17	11644.93	8385.48	3681.65

Table 2 Python real-time performance metrics.

This section presents the real-time performance metrics for the data capture probes developed in C++ and Python. Alongside the metrics outlined in Section 2.4, additional measures are introduced: Average CPU Usage (%), Average Memory Usage (%), and Maximum Resident Set Size (RSS) in kilobytes. These metrics are evaluated over a 1-minute runtime under varying packet transmission rates within the SCADA network. The packet transmission rate is adjusted by modifying the polling time parameter in the Movicon HMI software, which specifies the interval in milliseconds for HMI-to-PLC communication to read or write data.

Tables 1 and 2 summarize the performance metrics for the C++ and Python probes, respectively. The first column lists the polling times (in milliseconds), while the second column corresponds to the associated packet transmission rate from the HMI. Both tables show a clear upward trend in all performance metrics as the packet transmission rate increases. Notably, the C++ implementation demonstrates superior efficiency compared to Python, exhibiting lower CPU usage, memory consumption, maximum RSS, and wasted time across all LSTM inference models.
Specifically:

- CPU Usage: The C++ probe consistently maintains an average CPU usage below 6%, while the Python version exceeds 20%.
- Memory Usage: C++ keeps average memory usage below 0.20%, whereas Python surpasses 0.8%.
- Maximum RSS: For C++, this metric remains under 180’000 KB, while Python exceeds 450’000 KB.

Regarding wasted time (in milliseconds), the C++ implementation proves better suited for real-time anomaly detection scenarios, as its wasted time consistently stays below 1 second, regardless of polling time. In contrast, the Python implementation exceeds 1 second at a polling time of 700 ms (fewer than 100 packets transmitted). The most significant delay occurs with the LSTM inference model for Tank 2, where the Python implementation reaches 13.4 seconds at a polling time of 400 ms.
These results highlight the C++ probe's ability to handle real-time processing demands more effectively, making it a preferable choice for high-performance anomaly detection in SCADA environments.

4 Conclusions

This paper tackles the challenge of real-time anomaly detection in Industrial Cyber-Physical Systems (ICPS) by comparing the performance of two data capture probes developed in Python and C++. These probes are designed to gather and process physical process data from a SCADA network, facilitating Anomaly Detection Systems (ADS) in identifying anomalies in physical processes. The study evaluates critical real-time performance metrics, including Average CPU usage, Average Memory usage, Maximum Resident Set Size (RSS), and total inference wasted time.
The evaluation is conducted on a SCADA network configured with a water distribution testbed in a controlled laboratory setting. The results indicate that the performance of both Python and C++ capture probes is heavily influenced by the Movicon polling time parameter, which governs the packet transmission rate. However, the C++ probe proves to be the only viable option for real-time anomaly detection, as it consistently maintains inference wasted time below one second for all LSTM models. On the other hand, the Python probe is only effective at higher polling time values, corresponding to lower packet transmission rates.
Future research will explore the extraction of network statistics from SCADA traffic using both data capture probes. These statistics will be utilized as input for network

anomaly detection models, aiming to detect anomalies within SCADA network flows effectively.

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Use of Safety Instrumented Systems for safety at workplaces such as process plants

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Abstract

Process plants (i.e. chemical plants) are dangerous places due to explosion, overfilling and chemical release. Companies operating chemical plants, which represent potential hazards for people and environment, must minimize the risk raised by the process in emergency.

Chemical plants are designed to keep operations under control and are equipped with control and alarm systems. According to the method LOPA (Layers Of Protection Analysis), Basic Process Control Systems (BPCS) and Alarm Systems are the first two layers of protection:

- BPCS are designed to run the process within safe ranges of pressure, temperature and level;
- alarm systems are set to let operators take corrective actions before an event becomes an accident.

At times, control and alarm systems do not reduce the process risk to a tolerable value:

- BPCS are too slow to intervene;
- alarm systems might be ignored without taking correcting actions.

Chemical companies have recently decided to implement the “functional safety”, which aims at reducing the risks by using Safety Instrumented Systems (SIS) that represent an additional layer of the LOPA. They are made of sensors, logic solvers and final elements that work together for the single purpose of bringing the process to a safe state when determined conditions are violated. The logic solver takes the input and determines the output to satisfy a safety function, called Safety Instrumented Functions, or SIF.

Even SIS can fail since they might not respond when their action is required by the process. The probability that SIS fail is the Probability of Failure on Demand, or PFD.

Main purpose of this work is the calculation of the PFD of SIS with different “system architectures” to minimize risk in those workplaces, using the IEC 61508, basic standard for functional safety, well known as "Functional safety of electrical/electronic/programmable electronic safety related systems”.

1 Probability of Failure on Demand (PFD)

IEC 61508 provides, among other features, equations for determining the Probability of Failure on Demand (PFD). This is the probability that a system fails and is not able

to perform its safety function when required. PFD is unitless since it represents a probability of failure.
PFD is usually determined as an average probability over a time period. The average Probability of Failure on Demand (PFD_{AVG}) is the likelihood that a safety-related system does not perform the required safety function under defined conditions, within a stated time period.
The standard was issued to achieve this target: defining quantitative methods to determine, for Safety Instrumented Systems (SIS), the PFD_{AVG} in case of low and high demand mode of operation. Low demand mode refers to the frequency at which SIS are called to operate.
Low demand mode of operation is typically found in the process industry. A typical example is an emergency shutdown system which only becomes active when the process gets out of control. This normally occurs less than once a year.
For this reason, the definition of "low demand mode" is "no greater than one demand per year". "High demand mode of operation" usually has no meaning for process instrumentation design.
In order to get a scale of performance of a SIS, the concept of Safety Integrity Level (SIL) is introduced by the standard. IEC 61508 uses PFD as the metric range upon which the SIL is evaluated.
The standard defines four SIL levels, from SIL1 to SIL4, expressed in terms of PFD as shown in the following table:

SIL	PFD
1	0,1 ≥ PFD > 0,01
2	0,01 ≥ PFD > 0,001
3	0,001 ≥ PFD > 0,0001
4	0,0001 ≥ PFD > 0,00001

Table 1

2 Failure rates λ according to IEC 61508

When dealing with components used in safety-related systems, it is crucial to know the value of the failure rate λ. It has units of inverse time and it is common practice to use units of "failures per billion (10^9) hours". This unit is known as Failures In Time, or FIT. For example, if a pressure sensor experiences seven thousand failures per billion operating hours, at 20°C, it has a failure rate of 7000 FIT.
The failures of a safety-related system can be "safe" or "dangerous". According to IEC 61508, there are four types of failures:

- Safe Detected (SD) failures;
- Safe Undetected (SU) failures;
- Dangerous Detected (DD) failures;
- Dangerous Undetected (DU) failures.

By definition, a safe failure is the failure of a component, inside a system that plays a role in implementing a safety function, that has no effect on the safety function.
A dangerous failure is the failure of a component, inside a system that plays a part in implementing a safety function, that prevents the system from operating when required by the process that is about to reach a potentially hazardous state.
Beside being safe or dangerous, failures are also classified as detected or undetected by IEC 61508.
It is quite easy to understand what a dangerous failure is. Instead, it is not intuitive to realize what a dangerous detected failure is.
A dangerous detected failure is a failure that can prevent the SIS from performing the safety function but, since it is detected soon after its occurrence by internal diagnostics, it is considered to be “safe”.
IEC 61508 defines safe a failure that is either safe by design or it is a dangerous failure that is detected and immediately corrected.
A critical state is caused by undetectable dangerous failures. After their occurrence, there is no way to detect them in safety-related systems. They exist until the system is shut down in order to carry out proof tests. The tests require that all components are put offline. Proof tests are carried out every Tp hours. While proof tests are carried out, the safety function is unavailable.
The total failure rate λ is the sum of four components:

$$\lambda = \lambda_{SD} + \lambda_{SU} + \lambda_{DD} + \lambda_{DU} \quad (1)$$

where:

- λ_{SD} is the Safe Detected failure rate;
- λ_{SU} is the Safe Undetected failure rate;
- λ_{DD} is the Dangerous Detected failure rate;
- λ_{DU} is the Dangerous Undetected failure rate.

3 Risk analysis

Risk analysis normally consists of two steps:

- hazard identification;
- risk assessment.

The main purpose of the hazard identification is to identify the potential source of harm. The hazard identification is carried out using a HazOp (Hazard and Operability) analysis. The analysis is developed by different experts, such as process technicians, safety experts and operating personnel.
The attention is focused on the main separator used in a batch process that has a daily cycle.

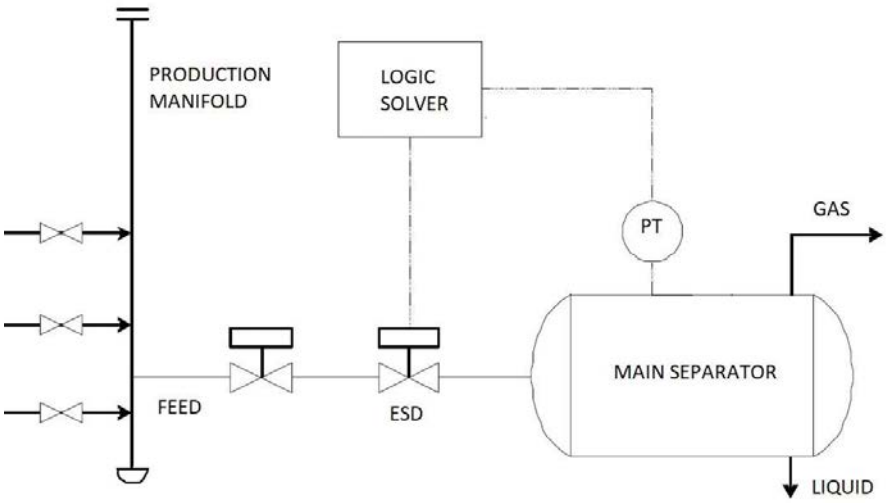


Fig. 1

The HazOp analysis points out that an overpressure might be the initiating cause of a sequence leading to a major accident.
Once the HazOp analysis has been carried out, a quantitative analysis is needed to determine the frequence of occurrence of the initiating event. The Fault Tree Analysis (FTA) is used for the quantitative analysis. FTA leads to the frequency of occurrence of the initiating cause f_0, assumed to be equal to 1×10^{-2} occ/yr. The frequency of occurrence of the initiating cause has units of inverse time, usually expressed in years.
A key principle of the standard IEC 61508 is that the measures taken to ensure safety should always be commensurate with the risk posed by the process. In order to reduce the risk posed by the overpressure, we need to determine the countermeasures that play a role on the development of the mitigating safety functions. These measures are defined as layers of technical and organisational nature, which are intended to ensure that the evaluated risk is reduced at least to a tolerable level. The ALARP principle provides the tolerable level of risk.
The ALARP principle defines a risk introducing three regions.

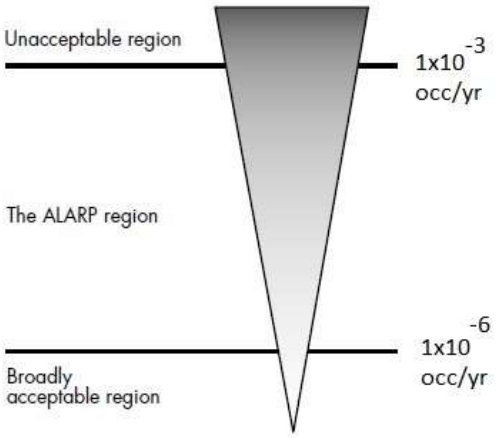


Fig. 2 – The ALARP principle

If risk lies in the "unacceptable region", the process poses a risk that cannot be accepted. The risk has to be first reduced at least as far as the ALARP region. In the "broadly acceptable region", the risk is considered to be negligible and it is accepted without any further reduction. According to the ALARP principle, a frequency of occurrence not greater than to 1 x 10^{-6} occ/yr introduces a risk that can be accepted.
The main purpose of the risk assessment is to identify the countermeasures that are needed to reduce the risk posed by the initiating cause. For this purpose, a Layers Of Protection Analysis (LOPA) is carried out. LOPA is a method of analyzing the frequency of a harmful event, based on an initiating event likelihood, by taking in account the probability of failure of a series of Independent Protection Layers (IPL), capable of preventing the harmful outcome.
The considered chemical plant is designed to keep the pressure vessel under control. The column is equipped with control and alarm systems since it is:

- maintained within a prescribed pressure range using a control loop;
- operated by trained operators, able to manage the alarm signals in the control room.

Neverthless, the perceived hazard is that the basic process control system and the alarm system might fail, exposing the vessel to overpressure. Mitigative measures, such as control and alarm systems, are layers used to reduce the frequency of the accident, but they have a probability of failure (PFD).
The PFD of the control and alarm systems is provided by IEC 61511, that has been developed after IEC 61508 to be a specific application for the process industry:

$PFD_{BPCS} = 1 \times 10^{-1}$

- probability that the BPCS fails: one upon ten demands;

$PFD_{ALARM_SYSTEM} = 1 \times 10^{-1}$

- probability that the "alarm system" fails: one upon ten demands.

The frequency of occurrence of the harmful scenario can be now determined:

$$f_0 \times PFD_{BPCS} \times PFD_{ALARM_SYSTEM} = f_{SCENARIO} \quad (2)$$

where:

$f_0 = 1 \times 10^{-2} \frac{occ}{yr}$

Therefore, we have:

$$1 \times 10^{-2} \left[\frac{occ}{yr} \right] \times 1 \times 10^{-1} \times 1 \times 10^{-1} = f_{SCENARIO} \left[\frac{occ}{yr} \right] \quad (3)$$

Hence:

$f_{SCENARIO} = 1 \times 10^{-4} \frac{occ}{yr}$

The frequency of occurrence of the harmful scenario has to be compared with the tolerability criteria to determine if it is acceptable as it is or, if it is not tolerable, by how much much it needs to be reduced.

Unfortunately, control and alarm systems do not reduce the frequency of occurrence of the harmful scenario to the tolerable level, assumed not greater than 1 x 10^{-6} occ/yr by the ALARP principle.

Since these two layers are inadequate in reducing the frequency of occurrence of the harmful scenario below a tolerable level, a third independent layer has to be introduced in the safety chain. A Safety Instrumented System (SIS) is proposed by IEC 61508. The required average probability of failure on demand (PFD_{AVG}) of the Safety Instrumented System (SIS) is given by the ratio difference between:

- tolerable frequency of occurrence of the harmful scenario (not greater than 1 x 10^{-6} occ/yr according to the ALARP principle);
- evaluated frequency of occurrence of the harmful outcome (1 x 10^{-4} occ/yr).

$\frac{1 \times 10^{-6}}{1 \times 10^{-4}} \geq PFD_{AVG,SIS}$

$1 \times 10^{-2} \geq PFD_{AVG,SIS}$

From table 1, a required SIL equal to SIL2 is needed for the Safety Instrumented System.

The real problem of estimating the PFD_{AVG} of a Safety Instrumented System is that it is also necessary to consider the “voting architecture” of the safety-related system. In the next chapter, the attention is focused on this calculation.

4 Calculating the average probability of failure of a SIS

To evaluate the probability that a safety-related system correctly performs the intended function is essential in the Reliability Engineering. Part 6 of the IEC 61508 provides an overview of suitable mathematical methods that can be used to obtain the PFD_{AVG} for low demand of operation. However, since most of the approaches come from complex methods, a set of simplified formulas is also provided. To avoid complication, only the simplified calculations are introduced in the following.

A question arises: considering a safety-related system, is it correct to say that the greater its redundancy degree, the lower its PFD_{AVG}?
Failure rate λ is assumed to be constant with time. This means that we consider the component during its "useful life" when the failure rate keeps constant over time. Supposing as initial condition that Reliability is equal to 1 at time t = 0, the R(t) function reduces with time. The component is completely reliable at t = 0 and its probability of failure increases over time.
Analytically, this means that the probability of the component performing the safety function at time t is given by:

$$R(t) = e^{-\lambda_{DU} \cdot t} \tag{4}$$

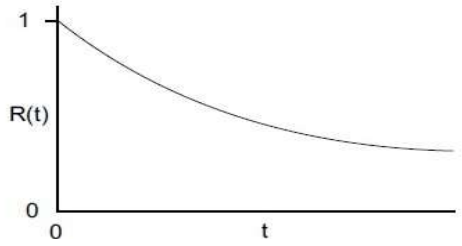


Fig. 3 – Reliability vs time

Conversely, the probability of the component failing at time t is given by:

$$F(t) = 1 - R(t) = 1 - e^{-\lambda_{DU} \cdot t} \tag{5}$$

The standard only deals with λ_{DU} to calculate the PFD_{AVG}, so that we do not need to be concerned with the total failure rate λ. Figure 4 shows that the probability of failure F(t) increases with time.

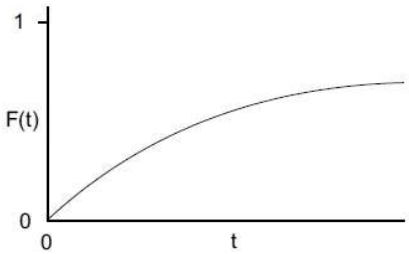


Fig. 4 – Probability of failure vs time

Whenever a proof test is carried out, the safety function is proved to work since every dangerous failure is detected and immediately corrected. This means that the proof test is designed to bring the system to a safe state on the detection of a dangerous failure. The probability of failure on demand is reset to zero at once (see Figure 5).

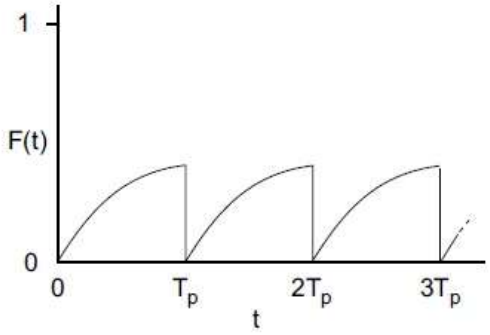


Fig. 5

5 Voting architecture 1oo1

Let's consider a 1oo1 (1 out of 1) subsystem with Dangerous Undetected (DU) failure rate λ_{DU}. This architecture consists of a single channel where any failure leads to the failure of the safety function when a demand arises.

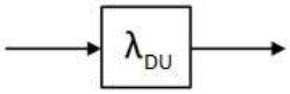


Fig. 6

Let's start from the Unreliability function F(t) of the subsystem, written using the complementary expression (5).
If we assume that:
$\lambda_{DU}*t << 1$
the following approximation is acceptable:

$$e^{-\lambda_{DU}\cdot t} \cong 1-\lambda_{DU}\cdot t \tag{6}$$

As a consequence, the Unreliability function F(t) of the subsystem can be approximated as follows:

$$F(t) = 1-e^{-\lambda_{DU}\cdot t} \cong 1-(1-\lambda_{DU}\cdot t) = \lambda_{DU}\cdot t \tag{7}$$

In low demand mode of operation, the average PFD can be calculated by integrating the PFD(t) function over the test interval T_p.

The average probability of failure on demand is given by:

$$PFD_{AVG_1OO1} = \frac{1}{T_p}\cdot\int_0^{T_p} PFD(t)\cdot dt = \frac{1}{T_p}\cdot\int_0^{T_p} F(t)\cdot dt \tag{8}$$

$$PFD_{AVG_1OO1} = \frac{1}{T_p} \cdot \int_0^{T_p} (\lambda_{DU} \cdot t) \cdot dt = \frac{1}{T_p} \cdot \lambda_{DU} \cdot \int_0^{T_p} t \cdot dt \quad (9)$$

$$PFD_{AVG_1OO1} = \frac{1}{2} \cdot \frac{1}{T_p} \cdot \lambda_{DU} \cdot \left[t^2\right]_0^{T_p} = \frac{1}{2} \cdot \frac{1}{T_p} \cdot \lambda_{DU} \cdot \left[T_p^2 - 0\right] \quad (10)$$

$$PFD_{AVG_1OO1} = \frac{1}{2} \cdot \lambda_{DU} \cdot T_p \quad (11)$$

which is the formula normally used for 1oo1 safety systems.

6 Voting architecture 1oo2

Considering a 1oo2 (1 out of 2) subsystem, where each component has the same dangerous undetected failure rate λ_{DU}, the safety function is still guaranteed if at least one of them is correctly functioning.

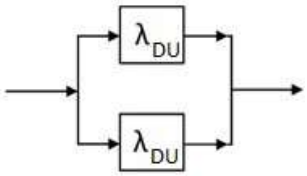


Fig. 7

This voting architecture consists of two channels connected in parallel, such that each channel can process the safety function. A failure has to be in both channels before the safety-related system fails on demand.

Supposing that each component of the subsystem is, for example, a pressure transmitter, if one of them detects a dangerous situation, the logic solver triggers a shutdown.

For two components connected in parallel, knowing their F(t), the total failure probability function Ftot(t) of the system is obtained through this formula:

$$F_{tot}(t) = \prod_{i=1}^{2} F_i(t) = F_1(t) \times F_2(t) \quad (12)$$

where:

$F_1(t) \cong \lambda_{DU,1} \cdot t$

$F_2(t) \cong \lambda_{DU,2} \cdot t$

Since the two components connected in parallel have the same Dangerous Undetected (DU) failure rate λ_{DU}:

$\lambda_{DU,1} = \lambda_{DU,2} = \lambda_{DU}$

Therefore, we have:

$$F_{tot}(t) \cong \lambda_{DU}^2 \cdot t^2 \quad (13)$$

Hence:

$$PFD_{AVG_1OO2} = \frac{1}{T_p} \cdot \int_0^{T_p} \left(\lambda_{DU}^2 \cdot t^2\right) \cdot dt = \frac{1}{T_p} \cdot \lambda_{DU}^2 \cdot \int_0^{T_p} t^2 \cdot dt \tag{14}$$

$$PFD_{AVG_1OO2} = \frac{1}{3} \cdot \frac{1}{T_p} \cdot \lambda_{DU}^2 \cdot \left[t^3\right]_0^{T_p} = \frac{1}{3} \cdot \frac{1}{T_p} \cdot \lambda_{du}^2 \cdot \left[T_p^3 - 0\right] \tag{15}$$

$$PFD_{AVG_1OO2} = \frac{1}{3} \cdot \lambda_{DU}^2 \cdot T_p^2 \tag{16}$$

7 Voting architecture 1oo3

Considering a 1oo3 (1 out of 3) subsystem, where each component has the same dangerous undetected failure rate λ_{DU}, the safety function is guaranteed if at least one of them is correctly functioning. In case of two faults, the safety function is still guaranteed.

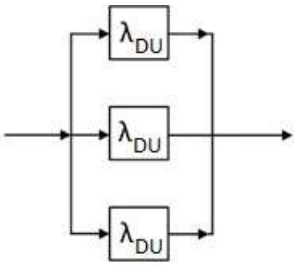


Fig. 8

Similarly, we have:

$$PFD_{AVG_1OO3} = \frac{1}{4} \cdot \lambda_{DU}^3 \cdot T_p^3 \tag{17}$$

The formulas for the average PFD are summarised in the following table where only the dangerous undetected part of the failure rate is significant.

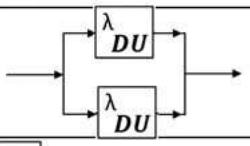
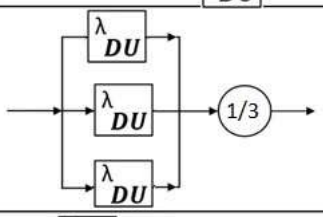
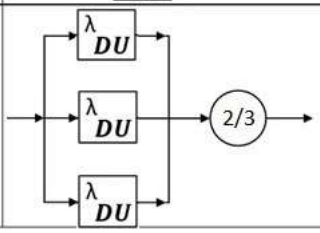
voting architecture	configuration	PFD_{avg}
1-out-of-1 **(1oo1)**		$\frac{\lambda_{DU} \cdot T_p}{2}$
1-out-of-2 **(1oo2)**		$\frac{\lambda_{DU}^2 \cdot T_p^2}{3}$
1-out-of-3 **(1oo3)**		$\frac{\lambda_{DU}^3 \cdot T_p^3}{4}$
2-out-of-3 **(2oo3)**		$\lambda_{DU}^2 \cdot T_p^2$

Table 2

The 2oo3 (2 out of 3) voting architecture needs some explanations:

- "2" is the number of components of the subsystem that are required to run to be sure that the safety-related system functions on demand;
- "3" is the total number of components of the subsystem.

Supposing that each component of the subsystem is, for instance, a pressure sensor, if one of them detects high pressure, the logic solver does not trigger the shutdown of the process. This voting architecture requires that two sensors detect a high pressure at the same time in order to let the logic solver trigger the process shutdown.

In this case, another formula is used to evaluate the PFD_{AVG}:

$$PFD_{AVG_2OO3} = \lambda_{DU}^2 \cdot T_p^2 \tag{18}$$

The only disadvantage of these simplified equations is their lack of consideration of imperfect proof tests that lead the PFD_{AVG} increasing over time.

Let's now consider pressure sensors coming from the same production batch and, therefore, having the same Dangerous Undetected (DU) failure rate: λ_{DU} = 700 FIT (Failure In Time: 10^{-9} failures/hours).

Let 'assume that the proof test interval T_p is equal to 1 year: Tp = 8760 operating hours.

With these data, we can calculate the average PFD of subsystems having different voting architectures. The results are shown in the following table.

$PFD_{AVG,\ 1OO1}$	$3{,}07 \times 10^{-3}$
$PFD_{AVG,\ 1OO2}$	$1{,}25 \times 10^{-5}$
$PFD_{AVG,\ 1OO3}$	$5{,}76 \times 10^{-8}$
$PFD_{AVG,\ 2OO3}$	$3{,}76 \times 10^{-5}$

Table 3

7 Conclusions

The paper presents a method that uses the IEC 61508 equations to determine the average PFD of safety-related systems. The PFD_{AVG} is calculated by considering the average value of the PFD(t) function over the proof test interval, assumed to equal to T_p hours.

Eventually, different voting architectures of safety-related systems are taken in account to prove that the greater the redundancy degree of the safety systems, the smaller their PFD_{AVG} over time. In this way, the paper demonstrates that functional safety is an innovative technology for safety in the process plants.

8 References

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[3] Dimitri B. Kececioglou: "Reliability Engineering Handbook" – DEStech Publications.

Ergonomics, workplace safety and pallet stability: the dea project and the new dispenser hi.dea

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Abstract
International regulations ask companies to take care of their workers, paying attention to the social dimension of sustainability. In this contest, an Italian packaging films producer conceptualized the need of a new film packaging dispenser to facilitate the operations of workers, promoting correct posture and avoiding trauma during the work routine. The so-called Dispenser Eumos Application (DEA) project was therefore set up to study all aspects of manual packaging and develop a method to improve and streamline this type of application, which is too often left to the subjectivity of the human operator. The work was carried out in-house, with the support of highly specialized product designers, and resulted in the development from scratch of a next-generation dispenser (patent pending) that could be a natural extension of the operator's manual dexterity, improving performance and benefits in the short, medium and long term. The final element of the project was the development of a durable, cost-effective and ergonomic dispenser to assist the operator in manual packaging operations and contribute to high standards of health and safety at work. This latter aspect was certified by sliding acceleration tests according to European Safe Logistics Association (Eumos) 40509-20, which is a non-profit association dedicated to improving safety throughout the logistics chain exchanging the best practices when working towards higher transport safety standards for logistics. Finally, the positive impact on the health and safety of manual packing workers, including a reduction in injuries and musculoskeletal disorders, was monitored through the LEA posture analysis system and the Rapid Upper Limb Assessment (RULA) ergonomic standard.

1 Introduction

International regulations ask companies to take care of their workers, paying attention to the social dimension of sustainability. Workplace safety, Corporate Social Responsibility (CSR) and sustainability are deeply interconnected. Ensuring safe working conditions is a fundamental aspect of a company's social responsibility. By prioritizing employee well-being, businesses not only comply with legal standards but also foster trust and loyalty. This contributes to long-term sustainability, as a safe and healthy workforce is more productive and engaged. Moreover, companies that

emphasize safety and CSR are often seen as more ethical and attractive to stakeholders [1]. Sustainability also includes environmental practices, and a safe workplace reduces the likelihood of accidents that could harm both people and the planet. In essence, integrating safety, CSR, and sustainability leads to a more resilient, responsible, and sustainable business model. Ergonomic risks are yet another important consideration in blue collar jobs.

Ergonomics, the science of designing and arranging workspaces, equipment, and tasks to fit the capabilities and limitations of workers, is fundamental to ensuring health and safety in the logistics industry. Logistics is a physically demanding sector, where workers frequently perform repetitive motions, lift heavy objects, and operate in fast-paced environments. Poor ergonomic practices can lead to a range of health issues, including Musculoskeletal Disorders (MSDs), fatigue, and long-term injuries that affect productivity and overall worker well-being. As the global demand for logistics services grows—driven by e-commerce, just-in-time delivery, and global supply chains—the focus on ergonomics in this sector has become more critical than ever. One of the key ergonomic challenges in logistics is the physical strain workers endure from manual handling tasks. Many logistics jobs involve repetitive movements, awkward postures, and heavy lifting, all of which can lead to cumulative trauma injuries. Over time, these strains can result in conditions like back pain, joint degeneration, and other MSDs, which are among the leading causes of lost workdays in the industry [2]. Without proper ergonomic interventions, the long-term effects on worker health can be severe, leading to reduced productivity and even permanent disability in extreme cases. Warehouse workers often need to manually wrap pallets instead of using robots due to several factors: the flexibility required for handling irregularly shaped or fragile goods that robots may struggle to wrap correctly; the high cost of automation makes it impractical for smaller warehouses. In some cases, the variability of load sizes and materials also demands human judgment. Lastly, manual wrapping allows for real-time adjustments and inspection, which automated systems cannot always replicate efficiently. An additional factor compounding the need for ergonomic improvements in logistics is the aging workforce [3]. In many industrialized countries, the average age of workers in sectors like logistics is steadily increasing [4]. Older workers may be more susceptible to injury and may recover more slowly from physical strain compared to their younger counterparts. Age-related declines in strength, flexibility, and balance can make physically demanding tasks more hazardous for older employees. As a result, aging workers are at a higher risk of developing chronic injuries related to poor ergonomic conditions [5]. Therefore, the logistics industry must adapt to this demographic shift by implementing ergonomic solutions that accommodate an aging workforce. For example, reducing the need for manual lifting and bending through mechanized tools and automated systems can mitigate the risk of injury [6]. Additionally, ergonomic training tailored to older workers—focusing on safe body mechanics, stretching exercises, and regular rest breaks—can help reduce the impact of aging on worker

health. By addressing the specific needs of older employees, companies can maintain productivity while ensuring that workers remain healthy and engaged as they age [7]. Recent technological advancements have introduced innovative solutions to many of the ergonomic challenges faced by logistics workers [8]. Automation and robotics are revolutionizing the way tasks are performed in warehouses and distribution centers. For instance, automated conveyor systems and robotic picking machines can reduce the need for workers to handle heavy loads or perform repetitive motions [9]. Exoskeletons are another emerging technology with potential ergonomic benefits [10]. These wearable devices are designed to support and enhance human movement, providing workers with additional strength and reducing the load on their muscles and joints. In logistics, exoskeletons can assist workers in lifting heavy objects, reducing the risk of back injuries and other MSDs [11]. Wearable sensors are also gaining traction in the logistics sector. These devices monitor workers' movements in real time, providing feedback on posture, lifting techniques, and body mechanics. By alerting workers when they are at risk of injury, wearable sensors can help prevent accidents before they occur [12]. Moreover, the data collected from these sensors can be used to identify patterns of risky behavior, allowing companies to make informed decisions about ergonomic interventions. While technological advancements offer significant potential for improving ergonomics in logistics, they are not a cure-all. Many warehouses and distribution centers still rely heavily on manual labor, and even with the best technology, ergonomic risks cannot be entirely eliminated. High work demands, tight delivery schedules, and the constant pressure to increase efficiency can sometimes lead to the neglect of proper ergonomic practices. Workers may skip safety procedures or adopt poor body mechanics to keep up with the pace of work, increasing their risk of injury [13]. To address these challenges, a holistic approach to ergonomics is needed. This includes not only the adoption of ergonomic technologies but also a strong focus on education, training, and organizational culture. Workers should receive regular training on proper lifting techniques, posture, and body mechanics, and management should prioritize ergonomics as part of the company's overall safety strategy. Additionally, regular risk assessments should be conducted to identify and address potential ergonomic hazards before they lead to injury. Moreover, the involvement of workers in the development and implementation of ergonomic solutions is essential. Employees are often the best source of information about the physical demands of their tasks and involving them in the process can lead to more practical and effective solutions. Encouraging worker feedback and participation in ergonomic initiatives can also improve compliance and increase the likelihood of success. A comprehensive approach that combines technology with training, risk assessment, and worker involvement is essential for creating a safer and healthier work environment in logistics. By addressing these challenges head-on, companies can not only improve the well-being of their employees but also enhance productivity and efficiency, ensuring a sustainable future for the logistics industry.

In this contest, the present work aims at contributing to scientific literature with an example of new technology easily implementable for enhancing the social sustainability of logistic operation. The paper presents a case study developed by an Italian packaging films producer who conceptualized the need of a new film packaging dispenser to facilitate the operations of workers, promoting correct posture and avoiding trauma during the work routine. Section 2 illustrates the materials and methods used in the case study. Then, the results of the application are presented highlighting its advantages and disadvantages. Finally, in the last section, the conclusions of the work are discussed.

2 Materials and methods

The aim of the research was to identify a more sustainable scenario for manual pallet wrapping operators. For this purpose, a traditional scenario was identified and compared with the proposal of an innovative scenario. This section not only describes the two selected scenarios (sub-sections 2.1 and 2.2), but also the methods used to compare them (sub-section 2.3).

Since the logistics sector is characterized by great variability in the weight and dimensions of the palletized goods, which inevitably translates into the overall shape of the load, the load chosen for the case study has an extremely irregular profile; specifically, the load has the characteristics summarized in Table 1, which are commonly seen in real-life sector practice.

Characteristics	Quantity
Load average perimeter (top)	3.6 m
Load average perimeter (middle)	3.56 m
Load average perimeter (bottom)	3.6 m
Load heigh	1.37 m
Load weight	384 kg

Table 1 - description of the load used for the case study

2.1 Description of the current scenario

Most operators in the logistics sector are still wrapping loads manually: this activity represents a risk in the workplace, because they are forced to walk backwards without seeing exactly what is happening behind them. Moreover, manual wrapping has critical issues related to the posture that the operators are forced to adopt, especially when bending to wrap the lower part of the load or when twisting their trunks to wrap around the goods. In addition, the manual activity, related to the strength and subjectivity of the operator, does not guarantee that the goods are wrapped in a consistent and replicable manner, with the risk of shipping loads that are unstable during transportation, thus endangering road safety firstly, as well as the integrity of the wrapped goods. A stretch film reel was chosen to represent the

current scenario: LLDPE stretch film for general use with standard mechanical properties (elongation, puncture, tearing), referred to in this article as standard film. Its characteristics are summarized in Table 2. The market offers the possibility of using special dispensers that help the operator to dispense the film evenly, reducing the strain on muscles and joints. These dispensers, as well as being still not very widespread, have some criticalities that make them inefficient from an ergonomic point of view. The initial analysis of the dispensers available in the European market has in fact revealed, in experts' opinion, that some of them are too heavy (their weight being more than 2 kg) and that others do not allow for an actual reduction in the workload of the operator, who (for example) has to keep bending to wrap the lower part of the load. In some cases, the dispensers show both criticalities.

2.2 Description of the new scenario with the DEA Project

In order to reduce and/or eliminate the state-of-the-art criticalities of the hand wrapping, especially but not exclusively for the logistics sector, a new scenario was considered by an Italian packaging film producer. In the so-called Dispenser Eumos Application (DEA) project, the company developed both a specific hand wrapping method and a next-generation (HI.DEA) dispenser. The manual packaging method defines a new type of film reel: 555 Rigid NetRoll film, thinner stretch film available in virgin raw materials or post-consumer recycled LLDPE with high mechanical properties (elongation, puncture, tearing), reel without paper core, referred to in this article as innovative film (Table 2).

Film Type	Film width	Film thickness	Reel length	Film support	Reel gross weight
Traditional standard film	500 mm	23 µm	180 m	Cardboard tube (600 g)	2.5 kg
Innovative film	450 mm	12 µm	180 m	No paper core: the film is wounded on itself	0.895 kg

Table 2 - current scenario and innovative scenarios, stretch film reel features

The new load wrapping scheme for the optimization of the operator movements, illustrated in Figure 1, can be described as follows: the operator must avoid bending to fix the stretch film at the wooden pallet and start wrapping at the bottom of the load. On the contrary, the wrapping cycle must begin at the top of the pallet. The wrapping cycle is made of 10 wraps, 2 at the top of the load, 4 downwards and 4 at the bottom of the load. The operator must ensure that he also wraps the top of the wooden pallet to secure the goods to the pallet. Moreover, he must wrap the goods to have at least 50% film overlap. The stretch applied by the operator on the stretch film should be consistent over time.

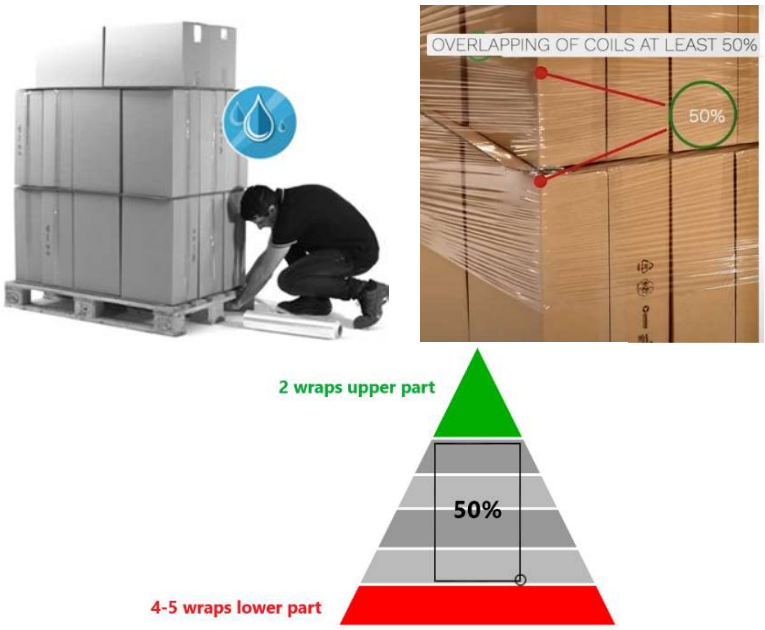

Fig. 1. New wrapping scheme: start wrapping at the top of the load instead of at the bottom. Film overlapping should be around 50% and pyramidal wrapping pattern with 4 wraps at the bottom and 2 wraps at the top of the load.

The HI.DEA dispenser (Figure 2) brings together a series of innovations that optimize manual packaging operations. Firstly, it is extremely light (1.3 kg). Therefore, the total weight of the dispenser and the innovative film is 2.195 kg, namely 12% lower than the weight of the standard reference reel (2.5 kg). Secondly, it is extremely ergonomic thanks to its peculiar 'harp' shape, the knobs which are placed to facilitate the wrapping of the upper and central part of the load, and above all thanks to the presence of a wheel that allows the lower part of the load to be wrapped without bending, providing support for the operator who relieves effort during the packing phase. Moreover, it allows a constant and regular stretch to be applied to the stretch film, thanks to its special knob for adjusting the brake applied to the reel-holder.

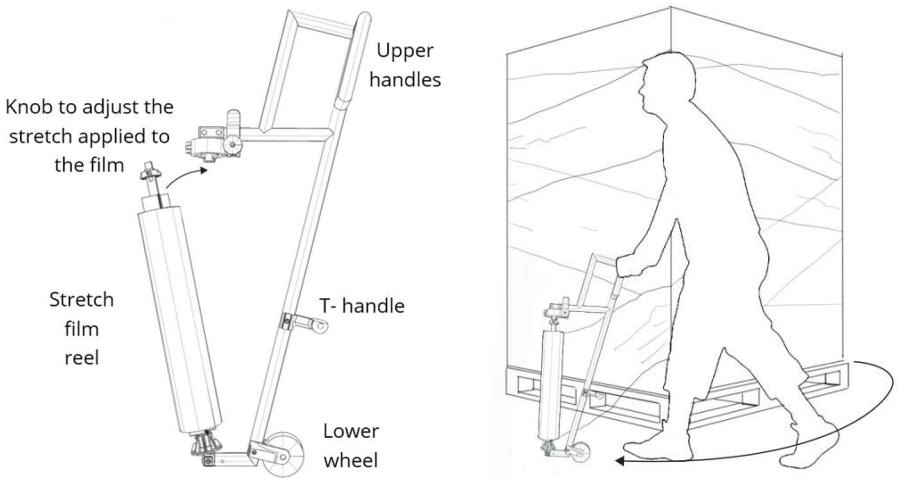

Fig. 2. The HI.DEA Dispenser

2.3 Methods to compare the traditional and innovative scenarios

LEA SOFTWARE

The traditional standard film and the innovative film, described in Table 2, have been compared in real life tests of hand wrapping. Clearly, the innovative film has been used with the HI.DEA dispenser; for ease of comparison, in both cases the hand wrapping cycle has been kept fixed as described in Section 2.2. The hand wrapping operations have been registered and evaluated with LEA, a postural analysis software capable of detecting the position of the main joints of the human body and measuring their angles with respect to a reference position. Specifically, this tool is based on the Rapid Upper Limb Assessment (RULA) approach [14]: it returns to the user a series of biomechanical scores that classify the impact of the movement on the human body. Score 1 or 2 means that the movement or posture is overall correct, and it can be maintained or repeated for long periods; score 3 or 4 indicates that changes in the posture may be required; scores 5 or 6 are the worst scenario which requires immediate modification to the movements. For a better understanding, Figure 3 shows the angle of the trunk with respect to the vertical (neutral) position:

- If the back is straight (0° angle), the score is 1.
- If the back is tilted between 0° and 20° forward, the score is 2.
- If the back is tilted between 20° and 60° forward, the score is 3.
- If the back is tilted beyond 60° forward, the score is 4.

Additionally, if the back is inside bending (lateral flexion) or twisted (rotating), you need to add 1 point for each movement.

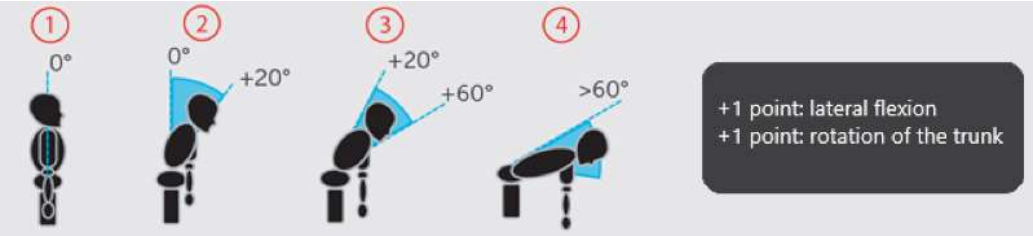

Fig. 3. Example (trunk) of RULA scores.

HAND WRAPPER TESTER

The stretch films used for the study have been tested on the Hand Wrapper Tester (HWT) system to measure the holding force they are able to exert, in compliance with the international standard ASTM 8314-20. In addition, the film consumption per pallet has been registered.

EUMOS ACCELARATION TESTS

After the wrapping cycle, the unit load has been tested in compliance with the international standard Eumos 40509-2020, especially designed to measure the rigidity of a unit load, i.e. the stability of the wrapped goods during transportation.

This test prescribes subjecting the load to a certain acceleration, achieved and maintained for a certain time interval, measuring the maximum elastic deformation (i.e. during the test) and permanent deformation (i.e. after the test) of the goods. The test is considered successfully passed if the elastic and plastic deformation remain within 10% and 5% of the height of the load respectively. The load unit is considered completely stable if it passes the test at a set acceleration of 0.5 g. The acceleration tests have been run at "TechLab" accredited by ACCREDIA (Lab n° 1772L).

3. Results and discussion

3.1 ERGONOMICS ANALYSIS

The comparative LEA analysis between the HI.DEA dispenser coupled with the innovative film and the traditional film itself used without any dispenser show a significant reduction of the RULA score, especially for the trunk, the right shoulder and the right elbow of the operator:

- Trunk: the HI.DEA dispenser allows the operator to spend 53% of the time in a correct position; moreover, a score above 4 has never been registered. On the other hand, the traditional wrapping method leads to 45% of the time with a negative (5-6) score, that calls for posture correction.
- Right shoulder: the use of the dispenser leads to a fully correct position.
- Right Elbow: the use of the dispenser has overall positive effect on the posture of the operator; specifically, the time with bad posture (5-6) decreases from 23% to 8%.

The left shoulder and elbow, which are not heavily involved in the wrapping process, remain unaltered. Results are summarized in Table 3 and illustrated in Figure 4.

	TRUNK			RIGHT SHOULDER			RIGHT ELBOW		
Score RULA		Time Percentage			Time Percentage			Time Percentage	
		Innovative scenario	Traditional scenario		Innovative scenario	Traditional scenario		Innovative scenario	Traditional scenario
Score 1-2		53%	20%		98%	48%		45%	20%
Score 3-4		47%	35%		2%	52%		47%	57%
Score 5-6		0%	45%		0%	0%		8%	23%

Table 3 - LEA postural analysis

Fig. 4. LEA comparison between traditional film application and innovative scenario

3.1 HWT ANALYSIS

The results indicate a comparable holding force between the traditional standard film and the innovative film, both at the top and bottom of the load. The film consumption drops from 332 to 150 g per pallet, thus leading to 55% material saving (Table 4).

Product	Holding Force [kg]		Film Consumption [g]	Saving [%]
	Top Position	Bottom Position		
Traditional scenario	4.96	10.34	332	-
Innovative scenario	5.93	9.36	150	55%

Table 4 - HWT tests

3.2 EUMOS ANALYSIS

The unit load passed the acceleration tests at 0.5 g, both with the traditional film and the innovative film. The results are shown in Table 5 and Figure 5.

Measured quantity	Film type	Measured value [mm]	Acceptability criterion in the teste method		Extended uncertainly value [mm]	Maximum admissible value [mm]	Outcome
			Maximum percentage value [%]	Maximum numerical value [mm]			
Maximum permanent deformation on the horizontal axis	Standard	4.04	5%	68.44	0.56	67.88	OK
	Innovative	7.7				67.88	
Maximum permanent deformation on the horizontal axis within h=20 cm	Standard	1.49	/	40	0.56	39.44	OK
	Innovative	2.49				39.44	
Maximum temporary deformation on the horizontal axis	Standard	31.35	10%	136.88	2.83	134.05	OK
	Innovative	87.07				134.05	

Table 5 - Acceleration test results (EUMOS 40509-20)

The actual benefit related to the use of innovative film and the HI.DEA dispenser is the possibility to reduce the amount of the film per pallet, without compromising on the security of the unit load. The stretch film reel contains the same number of meters as the traditional standard film described in Table 2, but its weight is 64.2% lower, as a consequence of the lower thickness and of the absence of the paper core. Moreover, the film used contains 60% PCR plastic and that means a reduced environmental impact [15].

Fig. 5. EUMOS 40509-20 Test pallet stability

4 Conclusions

In a national and international context that asks companies to increase social sustainability in operations involving their workers, this article aimed to analyze a case study in the logistics sector. In particular, the traditional scenario in which an operator manually wraps a load with plastic film was compared with an innovative scenario given by the combination of an advanced film and a patented technology consisting of a dispenser that allows the operator not to bend during wrapping operations. The two scenarios were compared using different methodologies, namely the LEA software based on the RULA approach, the Hand Wrapper Tester (HWT) system, and the Eumos acceleration test. All tests recorded results in favor of the new scenario, confirming it to be more sustainable from a social (allowing operators to reduce physical effort), economic and environmental (reducing the amount of material used) point of view. Overall, this case study has shown how shrewdness in technology and materials can bring great benefits not only to the operators but also to the environment. It can therefore positively influence companies that want to introduce more comfortable and suitable practices for operators of all ages into their operations. The results can be extended to all realities in which similar works are carried out, becoming an inspiration and/or starting point for the introduction of innovative practices to enhance the sustainability of many sectors.

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BVHSE Batch Vacuum-Heated Solvent Extraction with an innovative intensified evaporator/extractor SKID

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Abstract
Innovative technologies for the safety of living environments and anthropic settlements with the circular economy are becoming increasingly important in many industrial sectors. This work illustrates how a breakthrough technological solution obtained from experimental and plant research could be crucial for promoting reducing waste, dependence on raw materials through their reuse, and lowering the atmospheric emissions from hazardous waste incineration in line with the UN 2030 sustainable development agenda and the EU green deal 2050. The benefits achieved by IsAgro Spa through collaboration with public institutions such as the University of L'Aquila and Inail in reducing and qualifying the solid and liquid wastes in its chemical plant in Bussi sul Tirino (PE) are illustrated. The first economic feasibility analyses highlight that the BVHSE technology can reduce waste disposal and incineration costs, resulting in a payback time on investment return of about a year.

1 Introduction

The chemical plant of IsAgro spa in Bussi sul Tirino (PE) has been wholly dedicated and specialized to Tetraconazole TCZ ($C_{13}H_{11}Cl_2F_4N_3O$ - CAS 112281-77-3) production since 2006. Tetraconazole is an active liquid ingredient used broadly as a fungicide in the agro-pharmaceutical sector and belongs to the triazole class. It is classified as H302 and H332, harmful if swallowed or inhaled, and H400 and H411 as Very toxic to aquatic life with long-lasting effects. TCZ, due to its high toxicity, controls various fungal infections, such as Septoria and Rhynchosporium, on cereals, sugarbeet, and other crops [1]. Its mode of action is systemic with protectant, eradicant, and curative properties. It is a sterol biosynthesis inhibitor that acts mainly on the vegetative stages of fungi by blocking the mycelial growth either inside or on the surface of the host plant [2]. It is an isomeric mixture of the R (+) and S(-) to form a chiral molecule with a chemical structure reported in Figure 1:

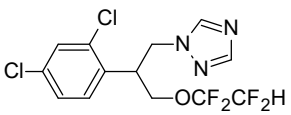

Fig. 1 - Tetraconazole (TCZ) structure

2 Tetraconazole synthesis process plant

The highly complex TCZ synthesis reaction based on the conversion of M-Alcohol with TFE must be conducted with dissolved powder catalyst KOH in a mixed aqueous solvent of Toluene/DMSO at lower than zero centigrade temperatures. While toluene hazards are well known, DMSO is reported to be an irritant substance that causes skin, eye, and respiratory irritation [4], but there is no unanimity consensus on it. TCZ is a valuable product, but the DMSO is also a pricey essential solvent, so post-product separation and waste treatment make the most significant plant sections dedicated to high economic and environmental incidence in its operation. Figure 2 shows the process flow diagram with the batch reactors and the continuous post-treatment sections that make the chemical synthesis process of TCZ.

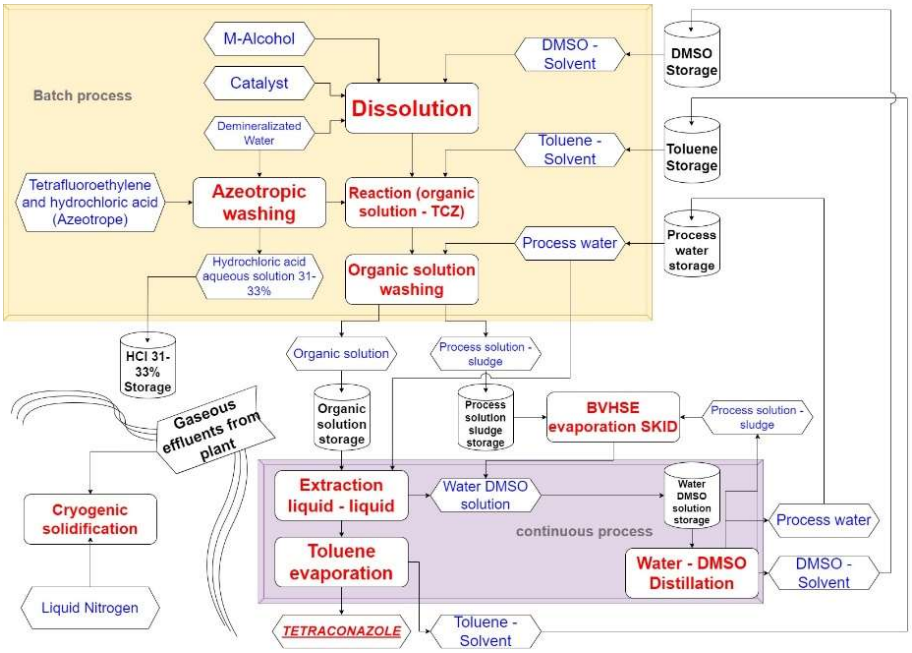

Fig. 2 - TCZ Process flow diagram

The technicality of the batch reactors and the complex reaction mechanisms are not of main concern here and are reported elsewhere [5]. The product stream flowing out from the reactors mainly contains TCZ with unreacted reactants, solvents DMSO, and toluene with suspended solids formed of KOH powders, secondary byproducts, and impurities.

Therefore, a downstream section separates and purifies the product stream by washing with a specific volume of recycled process water, resulting in two distinct liquid organic and aqueous phases (Figure 4). The main product TCZ is the lighter organic phase, which is streamed to a buffer tank and fed continuously into the subsequent separation units consisting of the primary liquid-liquid extraction of dissolved DMSO from the organic solution by water, the evaporation of toluene

and, finally, the vacuum distillation of the water-DMSO solution. The first column recovers the process water from the top, while the second recovers the DMSO. Additionally, residue wastewater with a high DMSO concentration is recovered from the bottom of the second column.
The distillation section is the subject of an ongoing research study on twin digitalization.

2.1 Wastewater characterization

This report aims to describe the breakthrough BVHSE: Batch Vacuum Heated Solvent Extraction process for treatment of the heavier phase or the principal wastewater stream with high solid suspensions and traces of aromatic substances (1.5% w toluene) that contain a high percentage in weight of valuable and hazardous DMSO (>75% w). Figure 3 shows a typical composition determined by gas chromatography.

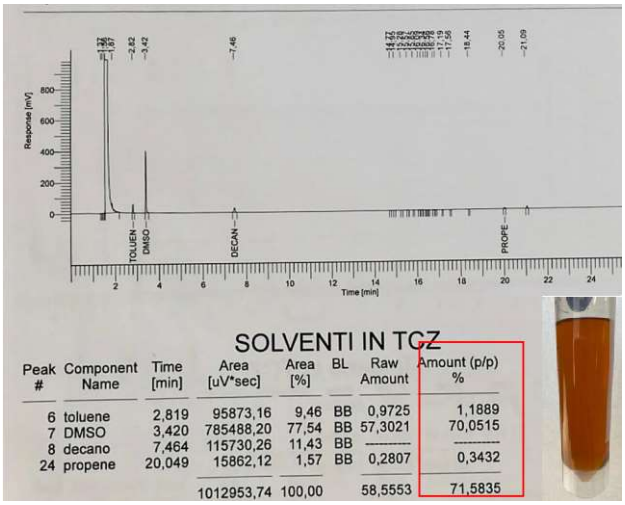

Fig. 3 Wastewater sample composition by gas chromatography

This effluent is classified as HP3 inflammable, HP4 irritant, and HP10, HP14 eco-toxic within the CER 07 04 01 category. It has been sent to disposal with very high costs for transport and storage (Figure 4) and safety hazards for plant operators, but also in terms of losing the unproductively substantive amount of DMSO and makeup with new procurement before the start-up of BVHSE process with the steam-jacketed evaporator SKID at its core (Figure 7).

Fig.4 Stockpile of the wastewater containers (L), Reactor inspection blub (R)

3 Research objectives and the plant development

Due to its high sulphur concentration, wastewater disposal generated increasing difficulties in management and incineration costs that significantly impact the economy of the process as the local regulatory standards advance. Hence, valorising waste in this plant would bring significant environmental, safety, and economic advantages.

The volatility of water compared to DMSO (Tb=198 °C) is excellent and sufficient compared to toluene (Tb=110 °C), which indicates the effectiveness of evaporative separation. However, the principal idea behind the new BVHSE process is multi-layered, trying to separate a 'dry' solid waste (% moisture) with low sulphur content, which is to be disposed of in total agreement with environment rules, recovering selectively by vacuum-controlled evaporation the primary solvents DMSO and toluene to be recycled and finally reusing the process water. All operations are conducted efficiently and subsequently in a confined single batch apparatus made of a steam-jacketed evaporator, called SKID, operating up to 160°C under a controlled mid-vacuum and directly coupled to its shell and tube condenser cooled by the process water. The evaporator has an internal rotating double helix screw, which could help discharge solid wastes.

3.1 preliminary Bench scale studies

Given DMSO's low vapor pressure and thermal stability, a preliminary study was conducted on a bench scale using the same available auxiliary plant services of the steam line and the vacuum line. The geometry and thermal efficiency of the steam-jacket evaporator have been investigated. The three different experimental runs have been conducted respectively with pure water to assess mainly the rate of vaporization, condensation, and the heat transfer coefficients with a binary solution of DMSO (70% w) in water to assess mainly the possibility of multistep operation with relatively high negative gauge pressures and finally with a sample of the wastewater, to assess mainly the yields of products particularly the drying

of solid as a function of controlled depression by the vacuum plant aspiration and the analysing the whole process safety and the strategies of the plant control.
In Figure 5, a sketch of the bench scale plant and its layout shows the steam-jacket evaporator E1 and the water-cooled condenser C1 with online measuring points for temperature, pressure, and the level of liquid condensate during each experimental run.

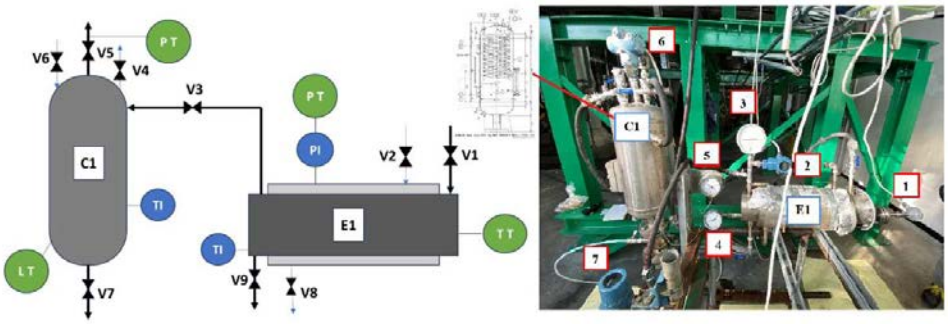

Fig. 5 – Bench scale plant scheme and layout

Because the wastewater evaporation experiments are of significant interest here, we report concisely only a typical multistage experimental run with its operative procedure and the relevant temperature and pressure.
About 500 g of the wastewater is introduced into the evaporator E1 and heated using steam. The solution reaches a temperature sufficient to generate vapours that move towards the condenser C1, where they condense with industrial water, and the condensate accumulates at the bottom of C1. The system is brought to various vacuum pressure levels as needed by aspiration. As shown in Figure 6, the experimental tests were conducted on the wastewater at decreasing selected pressure values. From the first stage at atmospheric pressure, a distillate mainly composed of water, amounting to 17% of the total, is recovered.

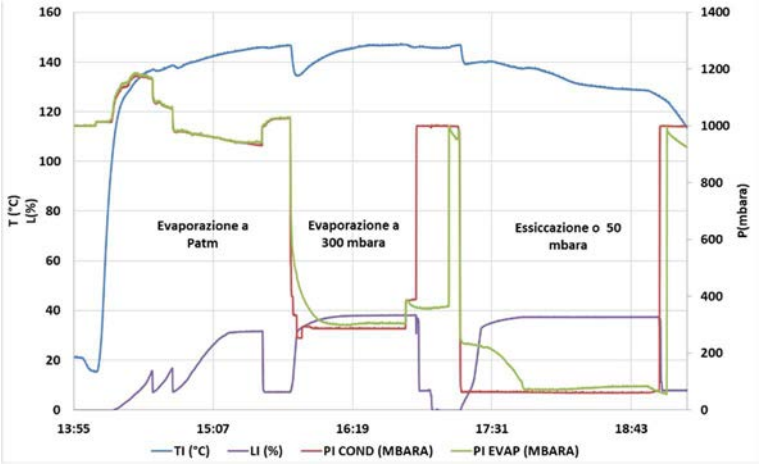

Fig. 6 – Process variables profiles on the bench scale plant

From the second stage, at 300 mbar, a highly concentrated DMSO distillate, constituting 37.6% of the total, is recovered, and all the remaining water is removed from the evaporator. The concentrated DMSO is separated from the solid in the final stage at 50 mbar and collected as distillate in the evaporator. The DMSO collected in this final stage has less than 1% moisture content, perfectly meeting the process requirements. This final distillate constitutes about 35% of the initial solution. In this phase, approximately 43% of the total initial DMSO in the wastewater is recovered, which can be directly stored without further treatment. The dry solid residue in the evaporator is about 7.5% of the initial wastewater, contains less than 5% sulfur, and is significantly less hazardous.

4 Start-up of the Batch Vacuum Heated Solvent Extraction Pilot plant

The finding of the experimental runs on the bench scale has led to the design, construction commissioning, and, finally, the start-up of the BVHSE process with the steam-jacketed evaporator SKID at its core in the pilot scale. The following CDS screen shoot (Figure 7) reports the BVHSE process's actual operation and its main components: the wastewater storage tank 02-S-34, steam-jacked Evaporator SKID 02-EV-03, Shell and tube condenser 02-E-32, vacuum unit 02-G-01 and the condensate storage tank 02-s-36.

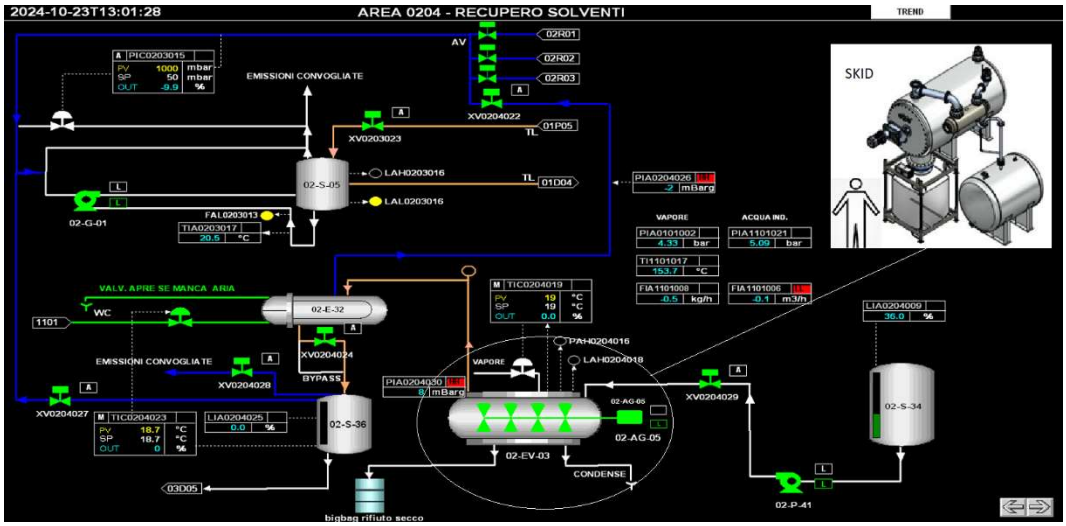

Fig. 7 – Screen shoot of DCS panel for BVHSE pilot plant

The batch process operation starts with loading 2500 Liters of sludge into the skid, opening steam to the jacket, and starting the evaporation of the wastewater, maintaining the lowest vacuum level of -950 mbarg. Observe the level increase in the condensate storage tank 02-S-36 and the temperature of the evaporator 02-EV-032 up to 120°C. Once temperature and level remain constant, the batch evaporation operation terminates, and after cooling, the solid is extracted and discharged into a big bag.

Figure 8 shows the temperature pressure level of condensate and steam consumption history with different colours. The red curve shows the temperature history inside the skid evaporator with distinguishable patterns attributable to initial heating up, primary evaporation of toluene followed by water, and finally, the high boiling temperature DMSO at approximately 120°C. The green curve identifies the condensate level in the tank, which rises until it reaches a plateau value as the wastewater holdup inside the skid decreases simultaneously. The purple curve identifies the pressure inside the evaporator, which remains controlled to -950 mbarg as soon as the evaporation initiates and finally backs to the atmospheric pressure when the dry solid discharges.

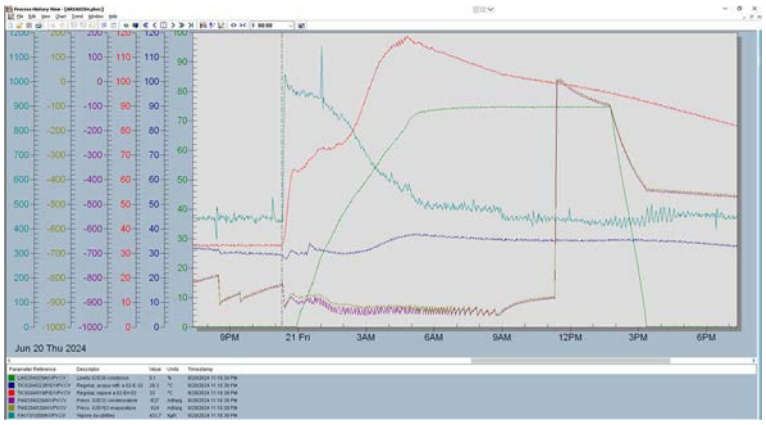

Fig. 8 – Process variables profiles on the BVHSE pilot plant

5 Primary plant sheet economic balance

The table reports a comparison between the actual economic balance against the historical data.

Cost of solvent before the evaporator skid		
Annual production	284000	kg TCZ/year
Quant. of DMSO/quant. of TCZ	*0,11*	kg DMSO/kg TCZ
Total DMSO cost	≈166000	€/year
Disposal of wastewater before the evaporator skid		
Quant. of waste/quant. of TCZ	0,18	kg wastewater/kg TCZ
Annual production of wastewater	51120	kg wastewater/year
Total disposal cost	≈100000	€/year
Total cost of DMSO and disposal before the evaporator skid ≈ 266000 €/year		

It is easy to quantify the potential economic impact of the breakthrough BHVS process with the SKID evaporator, analysing the savings from solvent recovery and the reported reduced waste disposal data.

Gain from solvent recovery after the evaporator skid		
Quant. of DMSO recovery	18318	Kg DMSO/year
Annual DMSO saving	≈97000	€/year
Disposal of dry waste after the evaporator skid		
Annual production of dry waste	14200	Kg waste/year
Total disposal cost	≈11000	€/year
Quant. of waste saved	36920	Kg waste/year
Total cost of DMSO and disposal after the evaporator = 108000 €/year		

The comparison in the table shows that the studied and designed process has brought improvements in environmental sustainability and is highly cost-effective for the company with minimal energy consumption.

6 Conclusion

This work illustrates how a breakthrough technological solution such as BVHSE Batch Vacuum-Heated Solvent Extraction with its innovative evaporator/extractor SKID obtained from experimental and plant research in collaboration with public institutes could be crucial for promoting reducing waste dependence on raw materials through their reuse and reducing atmospheric emissions from hazard waste incineration in line with UN 2030 Sustainable Development Agenda and the EU Green Deal 2050. The innovative wastewater treatment process significantly decreases the overall volume of fluid waste by at least 80%, reduces the quantity and the sulphur contents of solid wastes, which suggests lower pollutant emissions into the atmosphere due to incineration, decreases the flammability hazard of waste stored on-site and enhancing the safety for plant operators; reducing the dependency on the virgin raw hazardous materials, promoting process water reuse and substantially supporting a more sustainable and circular model of chemical production beside economic benefits. The pilot plant experiments have shown more potential to be explored by multi-stage evaporation and pilot plant optimization, which make part of the efforts in active ongoing research.ù

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[6] Convenzione di collaborazione Univaq - Isagro spa, prot. 14 6 2022, 2274 del 2022, 25 maggio 2022, 77 del 2022.

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Development of a mortar prototype for immobilizing ILW radioactive waste

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Abstract
One of the key aspects of radioactive waste storage is developing confinement methods and systems that can ensure the physical separation of radionuclides from the workers handling such materials, the population and the environment. The National Repository, a multi-barrier engineering structure, allows the confinement of radioactive waste (mainly ILW, intermediate level waste) for approximately 300 years. To guarantee these timeframes, each barrier must be thoroughly characterized, with particular attention given to the first barrier, consisting of a cementitious mortar immobilizing the ILW, which is poured into a steel container. The development of this mortar involves a detailed study of the aggregate, binder, and additives. A multifactorial approach is used, primarily investigating the achievement of specific workability and mechanical strength characteristics of the mortar. To obtain the desired properties, the first characterization is done on the aggregate's granulometry, comparing the natural composition with theoretical curves that make the grout more compact. The aggregate was then mixed with three different types of cement, water, and superplasticizer. By adjusting the water/cement ratio, sand/cement ratio, and the amount of superplasticizer, the workability was evaluated through slump tests to determine the best cement to use in the mix. Once the cement was selected, different w/c (water-to-cement) and s/c (sand-to-cement) ratios were studied, maintaining equal workability, to maximize the mechanical strength achieved at 28 days. This approach led to the development of an initial mortar prototype that meets the basic requirements for the immobilization of ILW

1 Introduction

INAIL, the National Institute for Insurance against Accidents at Work in Italy, is actively involved in the field of nuclear decommissioning, contributing to the development of innovative solutions for the safe management of radioactive waste [1], [2], [3]. The safe storage of radioactive waste is a great challenge for ensuring the protection of workers, the public, and the environment from the harmful effects of radionuclides. Among the various strategies adopted, the use of multi-barrier engineering systems, such as the National Repository[4], plays a key role. This repository is designed to confine radioactive waste, primarily intermediate-level waste (ILW), for a period of approximately 300 years. Central to the effectiveness of this system is the first barrier,

a cementitious matrix specifically developed to immobilize ILW within steel containers, that forms the waste package.
The simplest matrix that can be developed are a cement paste and a mortar, but the multifactorial process is complex and demands rigorous attention to material selection and formulation. The mortar must meet stringent requirements according to National Laws as the Technical Guide 33 [5], which can be achieved by working on the workability of the fresh mortar and mechanical strength to ensure both immediate handling and long-term durability under operational conditions. These key parameters may influence the performance of the mortar, including the retention capacity of the radionuclides (proven by leaching tests) and the resistance to freeze-thaw cycles. Type of cement, type of aggregate and its granulometric composition, water/cement and aggregate/cement ratios, and the use of additives (as the superplasticizer) are fundamental parameters to be tested for obtaining a good matrix for the immobilization.
This study presents a systematic approach to formulating a simple immobilizing mortar for ILW.
By characterizing aggregate granulometry, evaluating various cement types, and optimizing mix proportions, the study aims to achieve a mortar prototype capable of meeting the functional and safety requirements for long-term waste confinement.

2 Materials

2.1 Cement

Cement is the most common used binder for waste immobilization, and it is the main component of a matrix. When properly mixed with other materials, it provides to mechanical strength and chemical stability of the paste or the mortar.
Cement clinker [6] comes from limestone ($CaCO_3$), clay (composed by many oxides as SiO_2, Al_2O_3 and Fe_2O_3) and gypsum ($CaSO_4 \cdot 2H_2O$). All these materials are mixed, then heated in a rotary kiln at temperatures between 1400°C and 1500°C to form new oxides [7], that are the main clinker compounds:

- Tricalcium silicate ($3Cao \cdot SiO_2$). This is the responsible for early strength of the cement
- Dicalcium silicate ($2CaO \cdot SiO_2$). It contributes to the long-term strength
- Tricalcium aluminate ($3CaO \cdot Al_2O_3$). It reacts rapidly with water and contributes to heat generation during hydration
- Tetracalcium aluminoferrite ($4CaO \cdot Al_2O_3 \cdot Fe_2O_3$). It influences mainly the color of cement, playing a minor role in mechanical properties

After cooling, the clinker is finely ground together with gypsum, obtaining the OPC (Ordinary Portland Cement), classified as CEM I according to EN 197-1 Standard [8].
When the clinker encounters water, hydration reactions begin to occur, obtaining many compounds such as $C-S-H$, which is the main responsible of mechanical strength (it

forms a reticule that give hardness to the matrix and can trap contaminants), ettringite, portlandite etc. [9].
CEM I is the "standard" cement used for many applications, but to improve performances, it is possible to evaluate another type of cement which release low hydration heat and can be durable over the year. An example may be the CEM IV type, which is similar to OPC but there is a partial replacement of clinker with pozzolana, that forms more $C-S-H$ and can reduce heat released during hydration.
If mixed with water, it can be obtained a "cement paste", otherwise, adding aggregates with a certain granulometry, it can be obtained a mortar.

2.2 Aggregates

Aggregates are inert material formed by any stone of siliceous or silico-aluminous nature that can be used to improve performance of a cement mortar [10].
They can derive from many types of rocks (igneous, sedimentary etc.) and are divided mainly in two categories: fine aggregates (as sand, $d \leq 4\ mm$), to obtain mortars, and coarse aggregates (as gravel, $> 4mm$), to obtain concrete. Other two possible categorizations follow UNI 8520 Standard [11] (according to bulk density and according to nature). For the scope of the work, is possible to use only fine aggregates, to avoid taking up too much space for radioactive waste. Aggregates can enhance the compressive strength, durability to chemical attacks, resistance to freeze-thaw cycles and can reduce the effect of shrinkage and bleeding.
Aggregates must be characterized properly using sieves to know the granulometric distribution of particle size that can be modified (if necessary) to get closer to theoretical granulometric distribution curves (as Fuller, the most used).

2.3 Water

Mixing water is a key component for producing cement paste and mortars, as it directly influences mechanical properties and long-term durability.
Specification for the mixing water comes from the EN 1008 Standard [12] and this to avoid that chemical species in water could compromise matrix characteristics (ex. Sulfates, organic substances, chlorides etc.). In most cases, potable water already meets all the requirements of this Standard, making it suitable as mixing water, but to avoid all the possible undesirable effects, it is suggested to use demineralised water.

2.4 Additives

The achievement of a cementitious matrix with the desired characteristics is often obtained using admixtures [13] that, if added in small quantities to the mix, can significantly modify the properties.
There are a lot of additives, as accelerators, retarders, air-entraining agents, plasticizers, and shrinkage-reducing admixtures.
Among plasticizers, superplasticizers [14], [15] are of particular interest, especially for applications requiring high performance, such as the production of cementitious materials with a low water-to-cement ratio (to maximize compressive strength). They

work by adsorbing onto cement particles particles, reducing flocculation and enhancing particle dispersion, and significantly impacting on the rheology of the fresh mortar.

2.5 Waste

There are many options to simulate a radioactive waste, and it depends mainly on the physical-chemical characteristics and level of radioactivity, for which is decided also the route of disposal.

A possibility is to dissolve metallic ions into an aqueous solution, used to replace mixing water partially. In this way, waste is homogeneously dispersed into the matrix.

Obviously, testing with actual radionuclides is dangerous, and for this reason, an approach involves the use of "surrogate radionuclides", that are chemical tracers which simulate the physical-chemical behaviour of radionuclides. An example is to use stable isotopes of Co and Cs to simulate $60Co$ and $137Cs$, or Pb to simulate radionuclides with high atomic number.

According to limits imposed by national laws for radionuclides, in this case Italian laws [16], [17], [18] , quantities of surrogate radionuclides can be too small to be detected with instrumentation for chemical tracers, and for this, quantities used are higher than the real ones, but they are below levels that could compromise matrix properties.

3 Methodologies for the development

3.1 Methodological approach

Experimental tests for matrix development will aim to achieve performance aligned with the criteria outlined in Technical Guide N°33 [5], particularly regarding the mechanical stability and durability, that are essential for the confinement of ILW and LLW (low level waste). Although the performances will be evaluated against specified safety requirements, only a subset of the listed criteria will be prioritized for final qualification. The focus will be on key parameters that directly impact the mortar effectiveness in immobilizing and containing radionuclides.

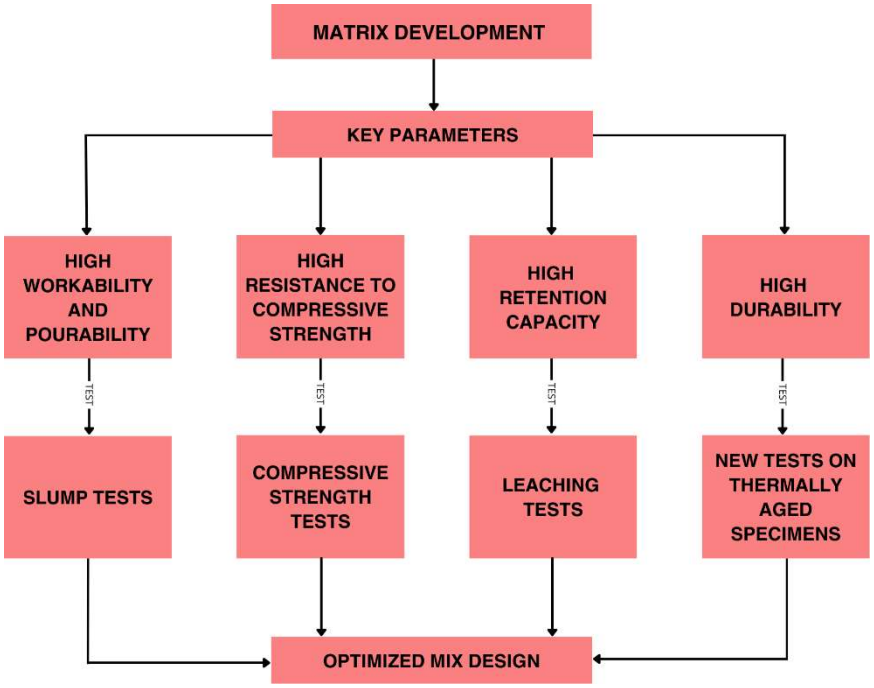

Fig. 1. Schematic matrix development approach

3.2 Aggregate granulometric characterization

Before starting, if the matrix is a mortar, it is essential to characterize the aggregate.

In general, it is used a fine aggregate ($d < 4mm$), whose that natural granulometric distribution is characterized using many sieves with mesh openings according to standards (for example, ASTM [19]). Aggregate passes though sieves (stacked in descending order of mesh size) and after, quantities between two contiguous sieves are collected creating the distribution. After that, this natural distribution is compared with theoretical granulometric distributions such as Fuller's curve (most used) [20], [21]. If natural distribution is far from the theoretical one, is possible to modify the granulometry, for example, eliminating part of the aggregate with a certain particle size.

3.3 Workability

This is the real first step for the activity. Fresh mix must be poured, but high pourability means also high water-to-cement ratio, and that decrease the compressive strength of the hardened matrix. Otherwise, with a low water-to-cement ratio, high compressive strength can be obtained, but there is the risk that if too low, there is the possibility that materials cannot mix properly, or the cement cannot reacts completely with water. For this reason, is important to reach a compromise between the pourability (high as possible) and the water-to-cement ratio (low as possible) of the mix, and this compromise can be evaluated with slump tests.

According to standards [22], slump tests can give a measurement of consistency for a fresh cement paste or mortar using a steel cone (Abrams cone) in which the mix is poured, then the cone is removed and the mix collapses on its own weight. After that,

the lowering is measured, and this responds to a consistency class (rigid, wet, plastic, semi-fluid, superfluid). Another possibility is to perform a mini-slump test with a reduced Abrams cone, investigating the spreading diameter of the collapsed mix [23], [24], for which is chosen a range for a good workability.
This test is performed varying water-to-cement ratio, aggregate-to-cement ratio, granulometry of aggregate (if this is used) and quantities of superplasticizer.

3.4 Specimen preparation

After obtaining many mix combinations with slump tests, specimens must be prepared for being ready to compression tests.
According to standards [25], specimens can be cubic with dimensions as 10 cm x 10 cm x 10 cm. Firstly, cement and aggregate are placed into a bowl secured to a laboratory mixer, then water and superplasticizer are introduced gradually and, after that, all the materials are mixed. This procedure is performed to obtain "blank" specimens, but for "contaminated" specimens is possible to replace part of mixing water with surrogate radionuclide solution by maintaining water-to-cement ratio unchanged.
Once the fresh mix is homogenized, it is poured into cubic moulds, which are placed into a curing chamber with controlled conditions (temperature at 25°C and 100% of relative humidity) for 28 days. After that, specimens are ready for compression tests.

3.5 Compression tests

Compression tests give one of the main key parameters to understand whether the mix is suitable for the purpose or not.
After 28 days of curing, specimens are de-moulded, then they are broken with an axial hydraulic press to measure the compressive strength[26].
It is possible to break specimens at different curing times (ex. 7,14,28,90) to have a compressive strength evolution curve. Results from this passage are essential to eliminate part of mix formulations.

3.6 Leaching tests

Leaching tests give the most important parameter, that answer the question of how much contaminants matrix can retain.
These tests are performed according to ANSI/ANS Standards [27], and consist in putting cubic specimens into a box filled with demineralized water for different standardized time intervals. Between one time interval and the next, part of water is collected and analysed with ICP-MS/ICP-OEM (Inductively Coupled Plasma Mass/Optical EMission Spectroscopy) or AAS (Atomic Absorption Spectroscopy, while the rest is replaced with new demineralized water (dynamic leaching test).
Quantities collected give a trend of how much contaminants can escape from matrix, considering a cumulative mass leached in the various time intervals.
A parameter to understand if the matrix can retain contaminants is the "leachability index", which in general must be greater or equal than 6 [28], [29] (ex. for Technical Guide N°33, the leachability index for Cs must be greater or equal than 7).

3.7 Freeze-thaw cycles and final tests

Freeze-thaw cycles are relevant to perform an accelerated aging for determining new performances of a degraded material.

Tests consist in placing cured specimens in a climate chamber that can change temperatures in short (or long) time intervals.

To reach the “nuclear grade”, at least of 30 cycles of 24h between -40°C to 40°C must be performed [30]. After cycling, if there are no cracks on the material, new compression and leaching tests can be carried out, thus completing the characterisation and determining its possible use for the immobilization of ILW radioactive waste.

4 Conclusions

This study demonstrated the effectiveness of a systematic approach for developing a simple cementitious matrix suitable for immobilizing ILW radioactive waste.

Through aggregate granulometric characterization, optimization of mixing ratios, and evaluation of the matrix physical and mechanical properties, it was possible to formulate a prototype capable of meeting long-term safety and functionality requirements.

In particular, the use of surrogate radionuclides allowed the simulation of the chemical-physical behaviour of radioactive elements while ensuring safety during laboratory operations. The focus on balancing workability and compressive strength of the mortar highlighted the importance of a careful selection of materials, including cement, aggregates, and additives such as superplasticizers.

The results obtained from compressive strength tests may suggest if mixes from workability tests are possible candidates for the matrix, but the confirmation is done after the leaching tests. Specimens that pass these tests are subjected to durability investigations performing aggressive freeze-thaw cycles.

If there are no cracks on surfaces, after the aging process, specimens are subjected to new compression and leaching tests, that can validate results obtained and indicate the better candidate for being an immobilization matrix.

As said, this is for a simple matrix formed by common materials easy to find, but future investigations could focus on approaches using matrices that use innovative binder materials, or more aggressive durability tests, or also tests with a different immobilized waste.

In summary, the approach developed not only provides a significant contribution to the safety of radioactive waste storage but also offers a methodological model applicable to other engineering contexts for managing hazardous waste.

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UAV-Based RFID localization of Pedestrian Workers and Machinery for Safety Applications

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Abstract
Radio Frequency Identification (RFID) technology offers versatility and benefits across sectors, extending beyond Industry 4.0, smart manufacturing, and Internet of Things (IoT). A key emerging application is RFID-based worker safety. Passive RFID tags, small and flexible, can be easily integrated into personal protective equipment (PPE) and are available in durable forms for challenging environments, such as construction sites. These cost-effective tags enable the creation of digital twins for various worksites, both indoor and outdoor. Applications include mapping hazards, managing machinery maintenance, and preventing collisions by tracking personnel and equipment. Besides target identification, also localization can be profitably implemented with the RFID technology. Among the best performing solutions, Synthetic Aperture Radar (SAR) localization with RFID systems stands out. Thanks to multiple measurements acquired by a moving reader antenna with respect to the tags, high accuracy position measurements are allowed.
This paper presents some guidelines to apply SAR-based RFID localization with an Unmanned Aerial Vehicle (UAV) in outdoor workplaces. The main requirements of the system are discussed and the system performance in a controlled outdoor scenario are shown for the case of static tags.

1 Introduction

Radio Frequency Identification (RFID) technology is highly adaptable and valuable across various sectors to perform identification of items, vehicles, or people, thus representing one of the key-technology of the incoming Industry 5.0. Beyond established use cases, e.g., smart manufacturing, access control and healthcare, new applications are continuously emerging. Among these, RFID-based systems for worker safety are particularly noteworthy
Passive RFID tags at Ultra High-Frequency (UHF) band have inlay or label formats and they are cheap, space-saving and battery-free. These features allow for easy installation on items, but also on Personal Protective Equipment (PPE). In such cases, they can be integrated during the manufacturing process or even woven. Special tags exist, i.e., on-metal tags, designed to work on metallic surfaces thanks to a higher thickness. Indeed, the wave-propagation at the UHF band is affected by the presence

of organic materials and liquids, and for this reason correct functioning is guaranteed only with a small distance from the surface. This flexibility of form factors means that personnel, machinery and vehicles (whether mobile or stationary) can be equipped with affordable RFID tags, enabling the creation of a digital twin of the whole working area, whether in an indoor industrial scenario or an outdoor site. Indeed, each actor can be identified through its RFID tag containing a unique code, by acquiring a univocal digital identity. This supports various safety functions, including mapping hazards, managing machinery maintenance, and tracking workers and vehicles to prevent accidents and collisions

Over the last decade, the chip sensitivity notably improved, thus allowing for tag detection up to 10-15 m. This crucial achievement led to the development of localization systems based on passive UHF-RFID technology. Each tag can be identified and localized by employing a proper infrastructure. There are many localization solutions including the use of multiple antennas or electronically scanned beam antennas. However, they are typically expensive and difficult to scale without a large investment, and their installation outdoors is not always easy.

More appealing solutions exploit mobile antennas through a handling system, a vehicle, a robot and even a drone Indeed, the antenna motion allows for the acquisition of multiple information from the tags for different relative positions. Several approaches exist for data processing, but the adoption of Synthetic Aperture Radar (SAR) principles stands out. These techniques are well-established for environmental monitoring through satellites, and they guarantee high accuracy in target recognition. Similarly, they are successful in locating tags communicating through backscattering communication. Recent advancements have made these methods computationally efficient thus enabling real-time localization of targets.

Thinking about the application of such SARFID (Synthetic Aperture Radar RFID) methods in outdoor scenarios, the exploitation of Unmanned Aerial Vehicles (UAVs) brings the greatest advantages. The UAV flight allows for great flexibility and scalability in large-scale scenarios such as agricultural-forestry or road construction sites. It can periodically fly over the area or take off when needed to go and monitor emergency situations. Navigation can be either autonomous or radio-controlled by the operator.

This paper explores the possibility to bring to service a RFID localization system based on Unmanned Aerial Vehicles (UAV) for safety applications in outdoor scenarios. The main features of the system will be investigated and analyzed. Moreover, the potential of the system will be shown in a general outdoor environment where a preliminary experimental campaign was carried out with a UAV equipped with commercial hardware and static tags. The trajectory of the UAV, required for the application of the SARFID localization is measured through a Differential Global Positioning System (DGPS) system, available with low effort in every outdoor setting. Finally, the method extension to the issue of localization of mobile agents will be discussed.

2 SARFID localization via UAVs in outdoor working areas

The proposed system is based on the adoption of a RFID-equipped UAV to monitor the position of items, vehicles, machinery, and people in outdoor working areas, through the principle of SARFID localization. In this way, by keeping track of locations of all involved agents, it is possible to build a solid foundation for an alert notification system. Fig. **1** shows an example of the main actors present in an open-air construction site flown over by a drone. To apply SARFID localization, the main requirements of the system are as follow: i) all elements to be located must be equipped with passive tags; ii) the UAV has to be equipped with a UHF-RFID reader connected to one antenna, that typically is facing downward, and it must be able to measure the phase of the tag backscattering signals; iii) the UAV trajectory must be known, for example with Differential Global Positioning System (DGPS) or with Real Time Kinematics (RTK) that outperform standard GPS measurements.

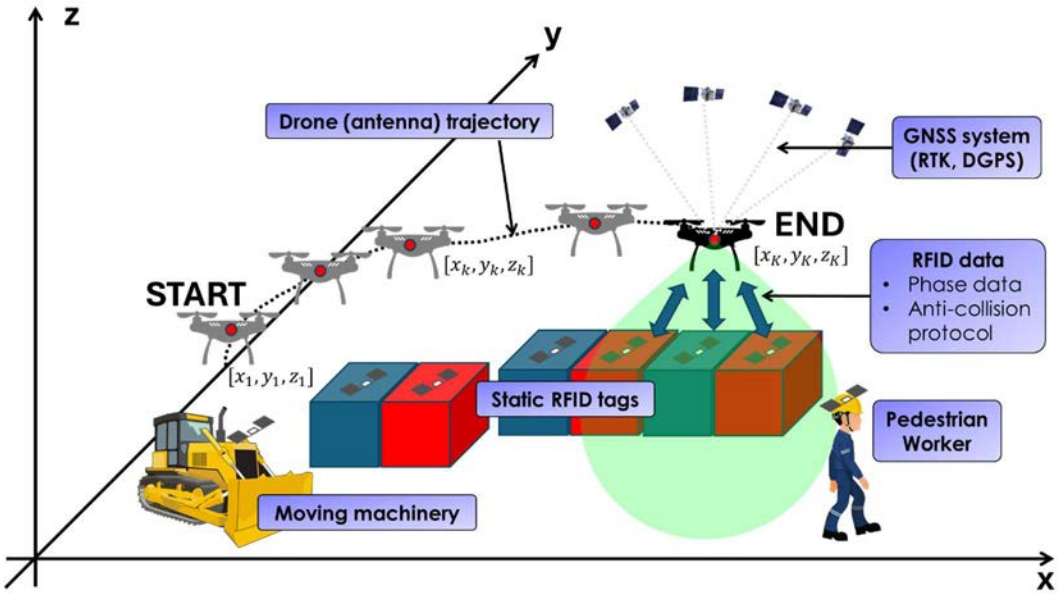


Fig. 1. Descriptive picture of a safety system based on UHF-RFID technology where a UAV is equipped with a reader and RFID tags are attached to pedestrian workers, machinery, and obstacles.

The UHF-RFID reader detect tags according to the Global Standard ECPglobal Gen2 (ISO 18000-63). It includes an anti-collision protocol that prevents multiple tags from replying at the same time to the reader query. This is particularly beneficial in complex or cluttered environments where multiple tags may be close to each other or where obstacles could interfere with Line-Of-Sight (LOS) detection. Moreover, tag discrimination is possible thanks to the unique Electronic Product Code (EPC) associated with each tag. To perform localization, it is sufficient to use one tag for each actor, but typically more tags are installed to increase the redundancy of the system. This choice allows for two main advantages. The first one is that when dealing

with mobile actors, the reader antenna could be in Non-Line of Sight (NLOS) with respect to a single tag, so reducing the probability of tag detection. Consequently, multiple tags at variable locations ensure the target identification. The second advantage is the possibility to get multiple estimations from tags attached to the same target, so they can be combined with several strategies, e.g., mean value operator or weighted average operator, to improve the accuracy of the actor localization.
During inventory the reader collects multiple phase information from the tags. Modern hardware, e.g., Impinj Speedway readers, can measure the phase in the [0, 2π] interval with a typical resolution of 0.0015 rad and an accuracy of 0.1 rad.

2.1 The SARFID localization method

When the UAV flights over the workplace, the reader periodically collects backscattered signals from passive RFID tags within its reading range. The flight of the RFID reader emulates a large "virtual aperture", intended as a large antenna array. This "synthetic aperture" enhances the resolution of the localization by combining data from multiple relative positions between the antenna and the tag along the path. All phase data measured from one tag are assembled in a "phase history" that represents the first input parameter of the method. The second input is the measured antenna trajectory that allows to build a set of "hypothetical phase histories", by assuming a hypothetical tag position. Then, the best matching between the measured phase history and the set of "hypothetical phase histories" allows to build a cost function, e.g., cross-correlation, whose maximum determines the estimated tag position. This methodology was patented by the University of Pisa. A detailed mathematical description can be found in the localization accuracy depends on the sizes of the synthetic arrays along the three main axes of the reference system. The longer the synthetic aperture, the better the localization accuracy. Since the UAV can easily flights over arbitrary trajectories with variable synthetic apertures along the three main directions, a high-accurate estimation of the 3D position of all involved targets is expected.
The reliability of SARFID localization was demonstrated in several scenarios, to locate stationary tags through an antenna moving with a handling system, a robot, or a drone. But it can be also applied to locate tags moving along conveyor belts with static antennas**Errore. L'origine riferimento non è stata trovata.**. This means that the possible fields of application are innumerable, provided that a relative motion between the reader antenna and the tag exists.
In a scenario like the one in Fig. **1**, both pedestrian workers and machinery can move with arbitrary and unpredictable trajectory with respect to the UAV flight and this complicates the issue. Indeed, it is required to perform a tracking of the mobile targets, namely an estimation of several positions over the time. This is currently an open research problem that is under development.

It is noteworthy that, if there is the need to extend the reading range, also semi-passive tags can be adopted, provided that they rely on backscattering communication. In the latter case a bigger encumbrance of the tag must be tolerated.

2.2 Particle Swarm Optimization (PSO) for real-time position updates

Another important aspect in safety applications is the estimation time required by the method to determine the target position. In particular, processing data for 3D positioning with SARFID localization may be computationally expensive when exhaustive approaches are applied to the maximum search of the cost function. So, real-time localization requires rapid processing of complex signal data, which can be challenging for embedded systems or resource-limited devices, especially if high resolution is desired. Therefore, algorithm variants have been developed to handle real-time updates, allowing for efficient tracking in dynamic scenarios. A possible solution is the integration of the Particle Swarm Optimization (PSO) in the SARFID method to get the PSO-SAR method**Errore. L'origine riferimento non è stata trovata.**.

PSO is an optimization technique inspired by the social behavior of birds flocking or fish schooling. It is used to solve complex problems by searching for an optimal solution through the collaboration and competition of a group of candidate solutions, called "particles," within a defined search space. Conventional SARFID method to determine the tag location through an exhaustive search, involves an assessment of every possible solution within a given search space to find the best one. This approach becomes impractical as the search space grows, meaning that high-resolution 3D localization requires large computation time.

PSO-SAR significantly reduces computation time by focusing on promising areas of the search space rather than evaluating every possible position. The method iteratively converges on an optimal or near-optimal solution, making PSO-SAR much faster and more scalable.

3 Experimental analysis with static tags in controlled outdoor scenario

This paragraph presents the application of the 3D-SARFID method in a scenario where a remotely piloted drone carries the UHF-RFID reader, and its trajectory is measured through a DGPS system. The location search is speed up through the application of the PSO technique (PSO-SAR) and perform offline on the measured data.

3.1 Experimental Setup

The experimental setup was realized by employing commercial UHF-RFID hardware and the commercial Colibrì IA-3 drone, depicted in Fig. 2a. The drone has a diameter of 81 cm, a height of 28 cm, and a payload of 1 kg. It was equipped with a Global Navigation Satellite System (GNSS) receiver Compact Dual Frequency Board TOPCON

B110, suitable for DGPS applications. By means of a simultaneous acquisition with a Leica GS15 GPS/GLONASS fixed station, it is possible to use a postprocessing kinematics (PPK) methodology to obtain the drone coordinates in a local reference frame with an error lower than 2 cm and with an update rate of 200 ms. The absolute position of the GNSS ground station was determined with the ITALPos network. The Impinj Speedway Revolution R420 UHF-RFID reader was installed on the drone together with the circularly polarized WANTENNAX019 antenna by CAEN RFID. The reader was fed through the drone battery and the transmitted power was set to 26 dBm. A synchronization between the reader clock and the GNSS acquisition timestamp was necessary to correctly aligned the measured trajectory of the UAV e the RFID data.

A grid of 5 × 5 UHF-RFID tags was deployed in an 8 m × 8 m area as shown in Fig. 2b. The tag spacing is around 2 m. Different tag typologies were used to demonstrate the independence of the method on the tag features, they have different antenna typologies and chips. Different tag orientations were also tested.

At the beginning of the experimental campaign, the actual tag positions were geo-referred through the GNSS ground station and the ITALPos network.

(a) (b)

Fig. 2. a) UAV equipped with DGPS receiver and UHF-RFID reader and antenna; b) measurement setup with passive UHF-RFID tags.

3.2 Experimental Results

As an example of a test case, Fig. **3** shows a drone trajectory in the local reference system. The antenna path width is around 8 m along both the x-and y-directions, and the drone speed varies between 0.1 and 1.3 m/s. The highlighted red trajectory portion represents the trajectory data during the detection of a tag placed at $\mathbf{p}_{\text{tag}} = \left[x_{tag}, y_{tag}, z_{tag}\right]^{T} = [-0.01, 1.95, 0]^{\text{T}}$ m.

The output of 3D-SARFID method is depicted in Fig. **4**. The 3D-SARFID method generates a 3D matching function that can be represented separately on each main 2D orthogonal plane (xy-plane, xz-plane and yz-plane). The maximum of the matching function (yellow color) corresponds to the estimated tag location.

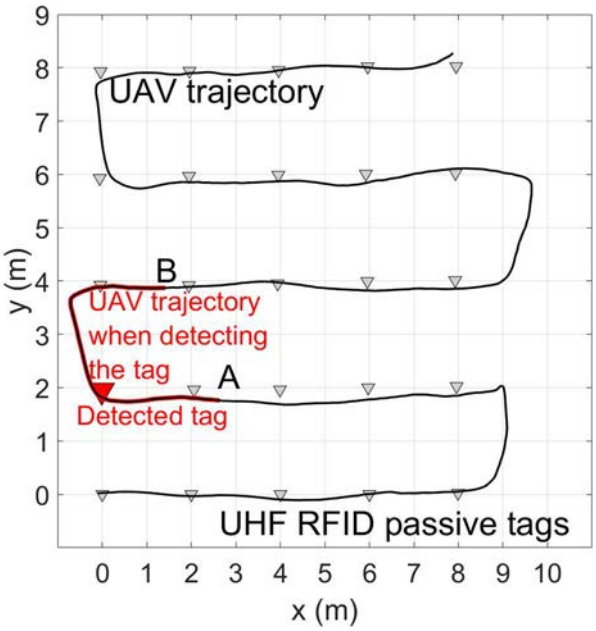
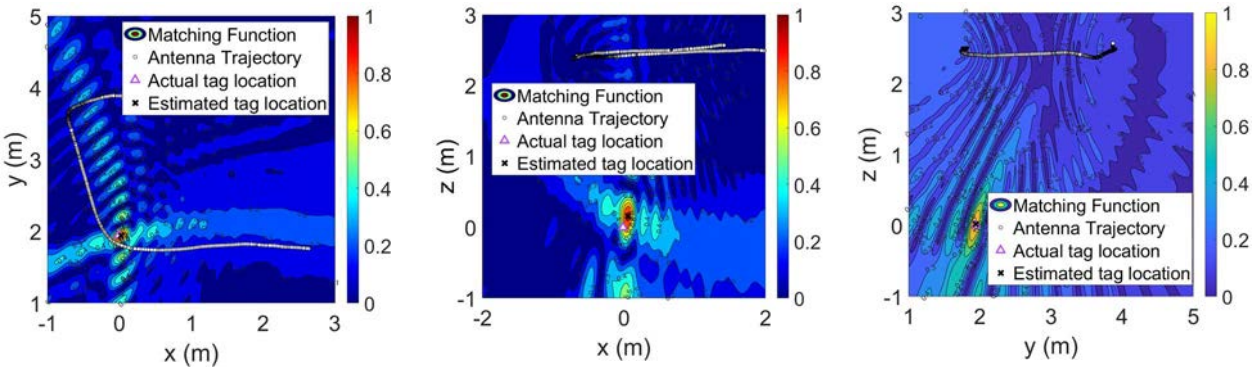


Fig. 3. Example of the drone trajectory measured with the DGPS receiver. The highlighted red trajectory portion represents the trajectory data during the detection of a tag placed at $\mathbf{p_{tag}} = \left[x_{tag}, y_{tag}, z_{tag}\right]^{T} = [-\mathbf{0.01}, \mathbf{1.95}, \mathbf{0}]^{\mathbf{T}}\ \mathbf{m}$.



(a) (b) (c)

Fig. 4. 2D matching function for the test described in Fig. 3: (a) xy-plane, (b) xz-plane and (c) yz-plane.

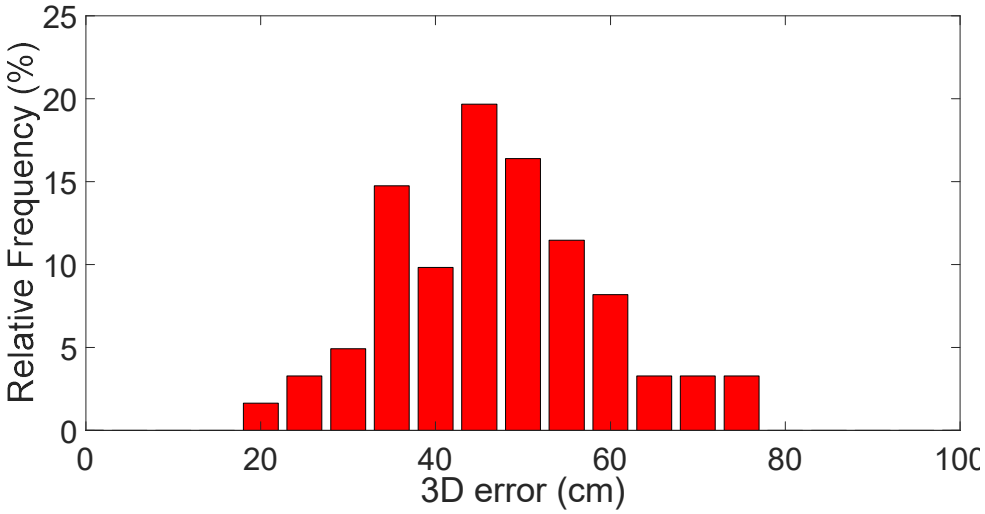


Fig. 5. Histogram of the global 3D localization errors for 318 analysed trajectories.

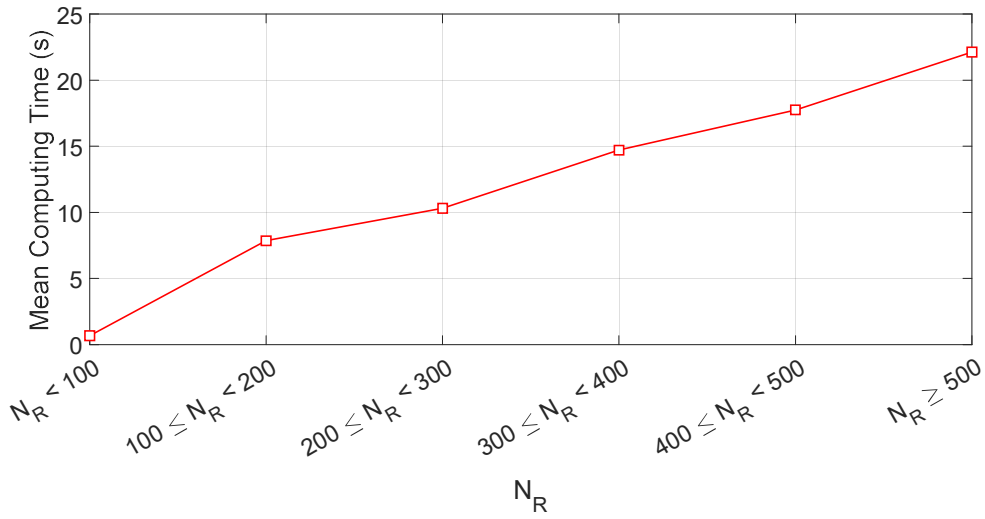


Fig. 6. Mean Computational time of the 3D SARFID method with respect to the number of available tag readings.

A measurement set composed by 318 different trajectories detecting all the 25 different tags was then analysed. The mean errors for each coordinate are $\mu_x = -4.6$ cm, $\mu_y = -0.2$ cm, and $\mu_z = -7.5$ cm, while the standard deviations are $\sigma_x = 16.9$ cm, $\sigma_y = 21.6$ cm, and $\sigma_z = 21.5$ cm.

The histogram of the 3D error is reported in Fig. **5**. The mean 3D localization error is $\mu_{3D} = 46.9$ cm, whereas the standard deviations is $\sigma_{3D} = 12.03$ cm. The obtained histogram shows the method effectiveness in terms of localization accuracy.

The computational time to perform the 3D localization depends on the number N_R of tag readings along the UAV trajectory and on the size and resolution of the search space, which determine the number of hypothetical locations $\mathbf{p}'_{\text{tag}}$ which are investigated for generating the matching function. A higher number of readings usually leads to better localization performance. In real-time applications, as soon as the UAV reached the minimum sizes of the synthetic arrays, the localization can be

performed, then, as soon as a new reading is available, the position can be updated. The computational time on all the 318 trials has a mean value of 7.7 s when the processing is done on a laptop with an Intel(R) Core(TM) i7-7700HQ CPU @ 2.80 GHz and 16 GB RAM. Fig. **6** shows the mean computational time of the 3D SARFID method with respect to the number of available readings.
As it can be noticed, the computational time ranges from a mean value of less than 5 s when 3D-SARFID runs on less than $N_R = 100$ readings, whereas it reaches a value greater than 20 s when more than $N_R = 500$ readings are available. Such an effort is not suitable for real-time applications. Consequently, the application of PSO-SAR was investigated.

3.3 Computation time optimization

Both 3D-SARFID with exhaustive search and PSO-SAR methods were applied to the previously described dataset. The PSO-SAR method was launched with $N_P = 100$, $N_P = 500$, $N_P = 1000$, and $N_P = 5000$ particles. The number of particles usually determines the accuracy of the method, since higher value of N_P is associated to a higher chance to get to the global optimization solution corresponding to the best tag estimated location. On the other hand, more particles lead to higher elaboration time.
The Cumulative Distribution Function (CDF) of the 3D localization for the standard 3D-SARFID with exhaustive search and the PSO-SAR method with different values of N_P is represented in Fig. **7**.
The PSO-SAR algorithm is not as performing as the exhaustive search, also because of the large search space in which the particles move, but it reaches acceptable performance by considering the sizes of the possible target involved in the worksite.
The mean processing time is shown in Fig. **8**. For PSO-SAR, a value of 0.4 s is reached as upper bound of the processing time, which is much lower than 7.7 s.
The advantage of the PSO-SAR method, regardless of the number of particles used, is that it has a much shorter delay due to data processing than the exhaustive search, making it suitable for safety applications.

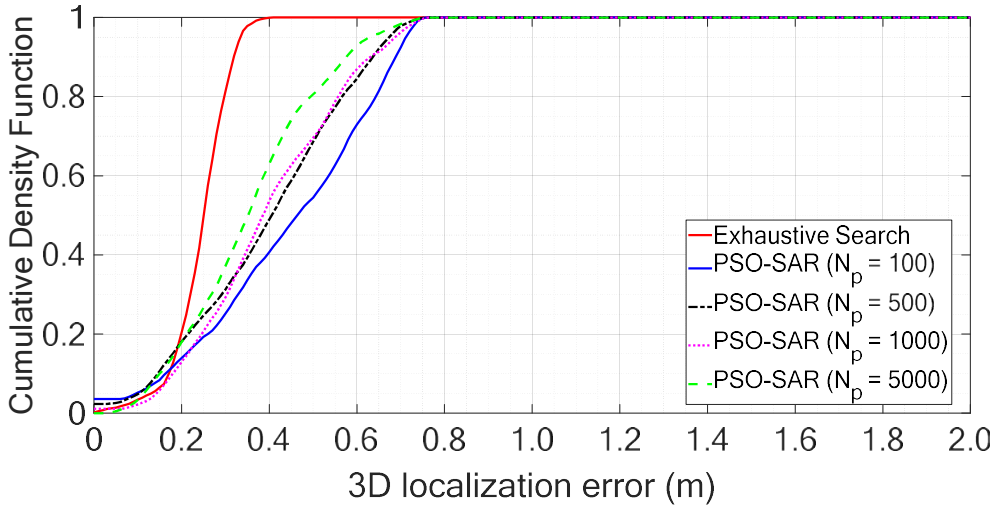


Fig. 7. Cumulative Distribution Function of the 3D localization error with exhaustive search and PSO-SAR for the analysed dataset.

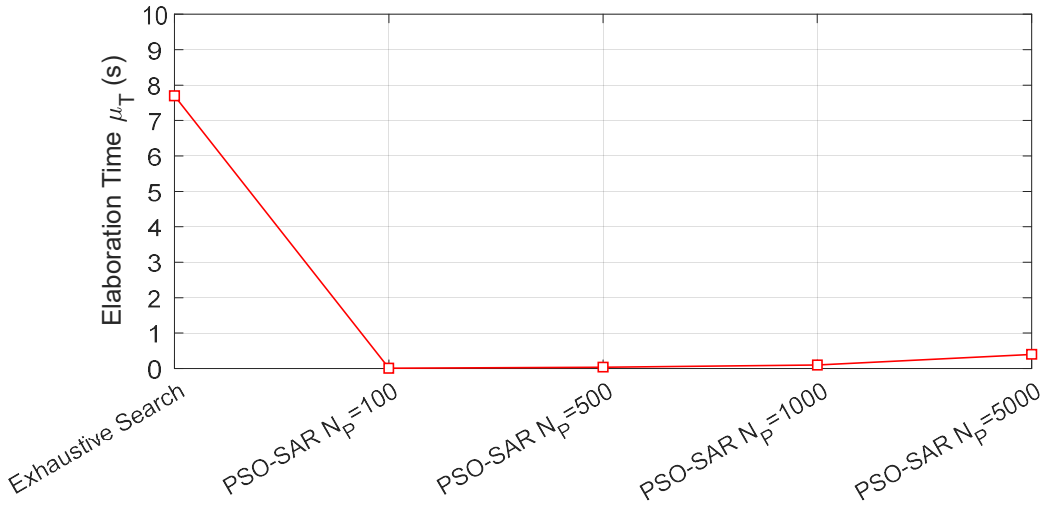


Fig. 8. Mean computation time with exhaustive search and PSO-SAR for the analysed dataset.

4 Conclusion and Future Works

The UHF-RFID technology can be profitably combined with Unmanned Aerial Vehicles to perform localization and tracking of items, vehicles, machinery, and people involved in outdoor workplaces.

In this paper, we presented a successful case-study application in an outdoor controlled environment with static tags. Besides, we discussed the extension of the proposed methodology to locate moving agents in real-time.

There are many possible applications. Drones can quickly inspect emergency equipment such as fire extinguishers, first aid kits, and personal protective equipment (PPE) to verify the right placement and to advertise operators if they are put in the wrong place. In emergency scenarios, drones can locate missing people or essential items in hazardous or hard-to-reach areas. In environments like mines,

construction sites, or chemical plants, drones programmed for monitoring can scan the tags on workers to ensure they are in safe zones during the working activities. In large industrial facilities, by tagging hazardous material containers or specialized tools drones can identify their locations and alert personnel if they are misplaced, damaged, or require maintenance.

Definitively, programming drones with automated flight paths could enable efficient scanning of all tagged assets, ensuring the area control in a short time. Integrating UHF-RFID technology into a safety management system could enable real-time notifications when issues arise, such as missing equipment or personnel entering restricted zones. Limitations of the technology regarding the reading range can be circumvented by utilizing semi-passive RFID tags, which ensure larger reading ranges while preserving a long battery life of the device.

To conclude, the combination of drones and UHF-RFID technology offers a new level of safety control, allowing for precise, real-time tracking of assets and personnel in hazardous environments. This proactive approach could enhance readiness, compliance, and response times, making workplaces safer and more efficient.

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Laser barriers to delimit and to alert work areas and prevent the risk of impact between workers and machines

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Abstract

This work describes a technology aimed to delimiting and alerting work areas and thus preventing collisions between machinery or vehicles and workers, as well as interference hazards, common in workplaces. We designed and constructed a prototype laser (Light Amplification by Stimulated Emission of Radiation) barrier consisting of a transceiver system that exchanges laser signals via a laser transmitter and receiver mounted on a stable base. The system can delimit risk areas; detect crossing of the interface between zones; alert vehicles, pedestrians, and workers; record data. An interruption of the laser signal between two transceivers is detected each time the barrier is crossed. Each transceiver detects laser breaks and sends a signal to a control unit able to activate devices emitting acoustic or optical signals. Each pass through the barriers triggers an audible signal (siren), which instructs workers to return to the safe zone, and an optical signal (traffic light) that instructs vehicles in transit to the site to stop.

The barrier's easy and quick installation mode makes it useful for short-term construction sites. It occupies a small volume both on site and on the road and is easily assembled and transported. It is easy to configure and intuitive, flexible in the configuration of the modular elements and adaptable to the shape of the area to be delimited and alerted. The system records data on activations and interruptions during use, without collecting data on persons, in full compliance with privacy regulations. The device, which is subject to patent, is intended to be tested in port areas and road works, to assess its ergonomics and reliability. The first tests concerned the monitoring of the alerts activated by the barrier. Further testing on the device is aimed at achieving a higher Technology Readiness Level (TRL) and greater system reliability. The system is promising as it assists workers during their tasks, intervening in the management of risks of interference with vehicles and equipment and, more generally, in the management of safety measures.

1 Introduction

Safety barriers have been used to protect humans and property from enemies and natural hazards since the origin of human beings. When human-induced hazards were created due to the industrialism, safety barriers were implemented to prevent accidents caused by these hazards [1]. No common definition of the term safety

barrier has been found in the literature, although different aspects of the term have been discussed. Different terms with similar meanings (barrier, defence, protection layer, safety critical element, safety function, etc.) have been used crosswise between industries, sectors, and countries. Safety barriers are categorized in numerous ways by different authors and the performance of the barriers is described in several ways. Although safety barriers are defined in variety of ways, we here accept the common features in the existing definitions of Sklet, that safety barriers are measures to prevent or protect against hazardous events [1]. Lauridsen et al. categorized safety barriers and their elements as physical barriers (such as firewalls), technical barriers (equipment and systems in realizing a barrier function), operational barriers (or activities that must be carried out to realize a barrier function) and organizational barriers (personnel with defined roles) [2]. Even though no universal definition is existing, safety barriers are always regarded as those physical or non-physical approaches to protect assets from the damage [1]. The concept of laser barriers with the purpose of the paper is briefly introduced in the first section; the second section discusses on occupational and transport sector accidents and gives an overview on the project and realisation of laser barriers with their function schemes. Such result of barrier application are discussed in section 3th with comments, a brief discussion of results and future directions.

2 Material and methods

In Italy, between 2013 and 2020, 830 road accidents involving pedestrians working on the roadway, protected (40%) or unprotected (60%) by road signs, were ascertained. As represented in Figure 1, these cases occurred mainly on urban roads (85%) and less frequently on extra-urban roads (13%) and motorways (2%) [3,4,5,6].

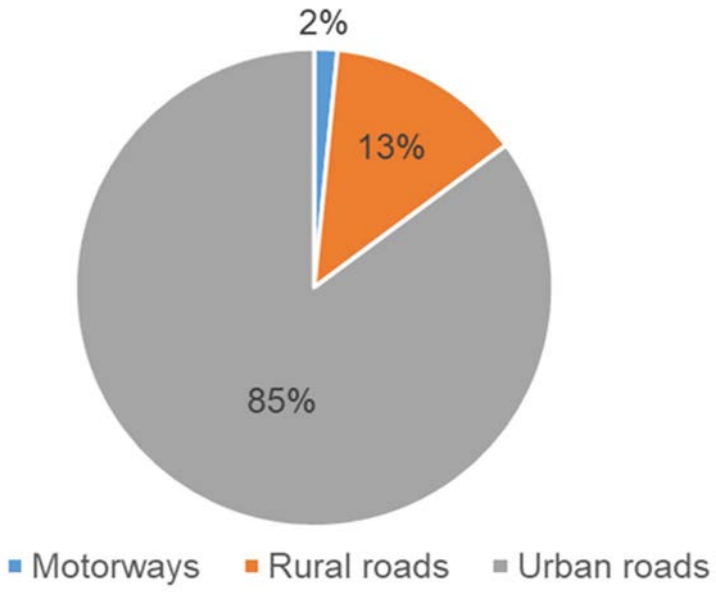


Fig. 1. Road accidents with pedestrian involved who worked on the working zones, by type of the road involved. Italy. 2013-2020. Source: Author processing by Istat data.

These results, although partial, show that the road construction site is a complex work environment that presents a multiplicity and variability of risks both for those who work there and for road users who meet the work area in some way [8,13]. By crossing the construction site-road interface, workers or pedestrians expose themselves to the risk of being run over.Temporary signs inform the road user by guiding and inducing him to behave (Figure 2) appropriate to the specificities of the road construction site, representing a tool for preventing this type of accident. The temporary signalling of road construction sites can be integrated with non-physical modular barriers.

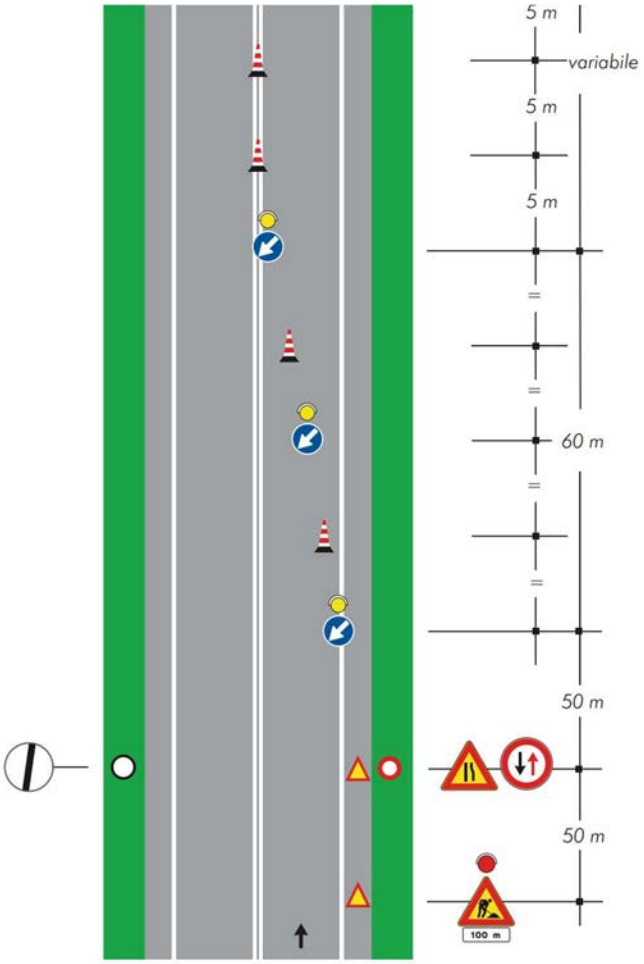


Fig. 2. Road construction sites. Example of delimitation proposed by Italian regulations. In the case of a construction site of more than two days, the cones are replaced by delineators. Temporary signs for roadside works. Source: Author processing on Italian Decree 10 July 2002 [7,9,10].

The laser immaterial barrier described in this paper can be considered an evolution of the temporary signs in use on road construction sites. Its flexibility allows it to be used to delimit construction site areas, quarries and other outdoor work environments. According to the “Italian Highway Code" [9] it is possible to use means of delimitation of road construction sites or depots on the roads, according to local

needs and conditions of the following type:
a. barriers;
b. special delineators;
c. flexible cones and delineators;
d. temporary horizontal signs and supplementary retro-reflective devices;
e. other means of signalling in addition to or in place of those provided, if they are authorized in advance by the Italian Ministry of Infrastructure and Transport.
The barrier in question, integrated with functions generated by a processor, detects the interruption due to the passage of a body and warns workers and road users of the danger, with acoustic and/or optical signals. The barrier consists of at least two identical modular transceivers mounted on cones and arranged "in series". Beam interruption results in an alarm and the opening of a contact. The control unit is the fulcrum of the system on which the signals coming from the modular elements of the laser barrier made with the transceivers connected in series converge and are interpreted. The control unit is connected to several barriers in series and can activate optical warnings (traffic lights) and acoustic warnings (sirens) when an interruption of the laser barrier has been detected (Figure 3).

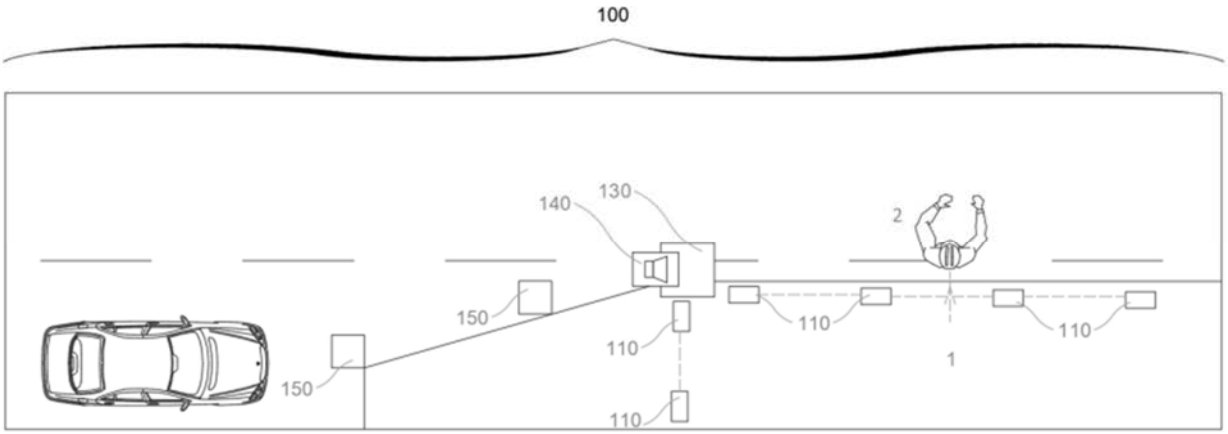


Fig. 3. Modular laser barrier (100) around the road construction site.1-2 The worker crossing the barrier. 110 The transceivers delimitating the working zone. 130 The control unit. 140 The acoustic alarm. 150 The traffic lights. Source: Inail. Authors'.

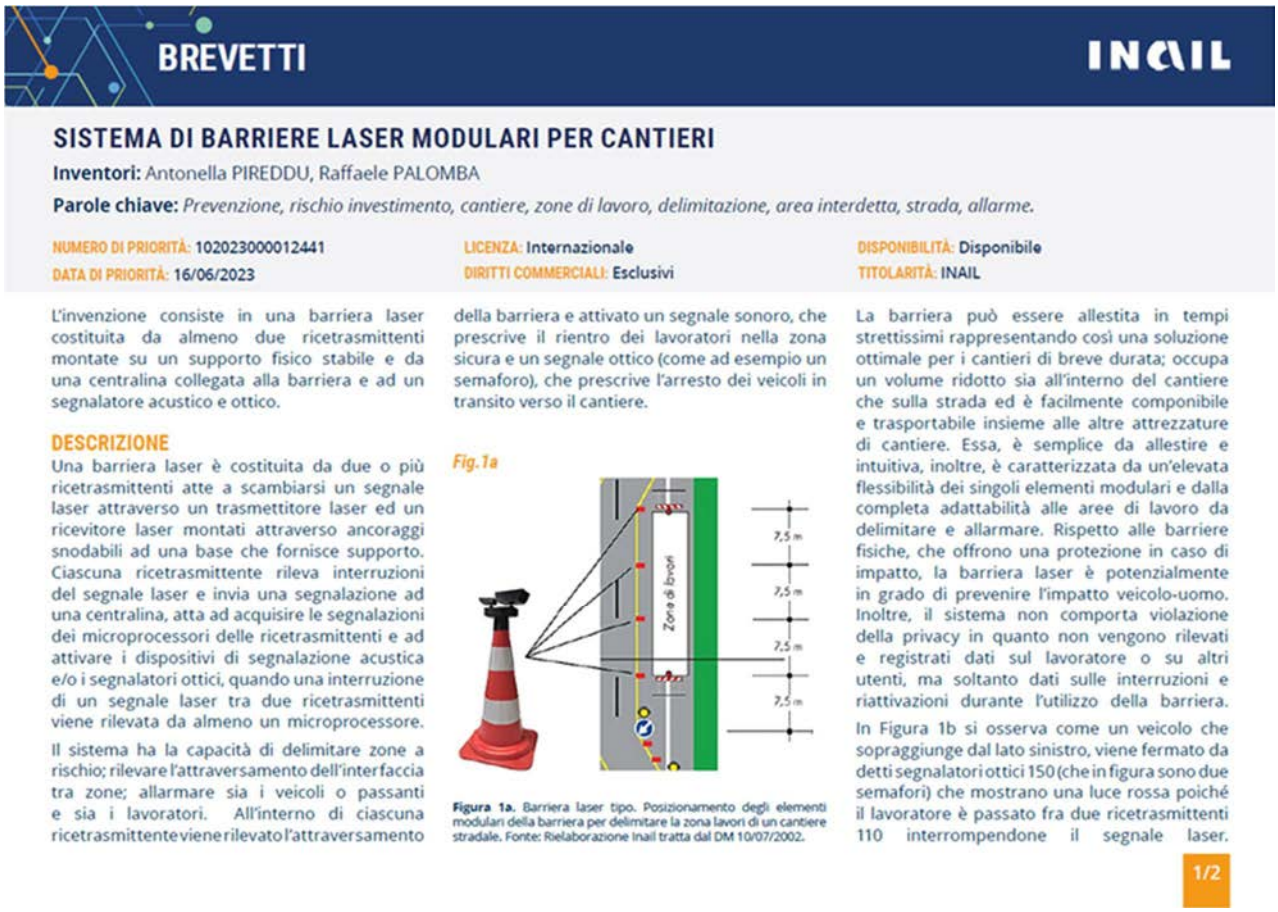
The alarmers are represented by acoustic warning devices (140 in Figure 3) and traffic lights (150 in Figure 3). The optical and acoustic signals are incorporated into the modular transceiver and warn the worker. A siren is instead positioned on the control unit. The optical warning device (traffic light), which must be positioned as the approach signs at an adequate distance from the beginning of the construction site [7,9,10], is activated by the control unit when the barrier is interrupted. The optical signaller has the purpose of prescribing the stop of vehicles while the siren is used to signal the return of workers inside the barrier (Figure 3). The supports are the elements on which to mount the components and with which to compose the laser

barrier. Due to its visibility and versatility, the support used in this application is a traffic cone for temporary road signalling. Each cone, once stabilized by means of a support at the base, is suitable for receiving both the transceiver and the control unit. Like temporary road signs, each module can be positioned appropriately on the construction site. Two elements in series positioned at 5 or 7.5 meters along the site-road interface, identify an elementary barrier. The traffic light activated by the control unit will be positioned together with the signs approaching the construction site and prescribes the stop of vehicles in transit. In the barrier installation and the positioning of traffic lights it needs to takes into account the braking distance and thus the permissible speed (e.g. 40 km/h), the condition of the road surface, etc. An example of calculating the *safe stopping distance* in meters (SSD) is provided below(1):

$$SDD = \left(t * \frac{v}{3{,}6}\right) + \left(\frac{0{,}5 + \left(\frac{v}{3{,}6}\right)^2}{D}\right) \quad (1)$$

Where t is the road user reaction time in seconds, v is the design speed in km/h, D is the deceleration speed in m/s^2. A barrier can take on different shapes and delimit areas of variable shape through the assembly of the individual elements, thus performing the following functions: 1. Delimiting the construction site or a part of it with an (invisible) laser beam; 2. Activate a continuous local alarm signal addressed to workers, whenever one of them crosses and interrupts the barrier; 3. Activate with wi-fi signal, an external control unit that activates a red light and a sound signal (siren) audible on site, associated with the local sound signal. This causes a vehicle moving towards the construction site to stop and the worker has time to return to the safe area. Immaterial barriers are elements that are easy to acquire and assemble. They can be set up in a very short time, thus representing an optimal solution for short-term construction sites. The proposed system occupies a small volume both inside the construction site and on the road. The barrier is easily modular and transportable together with the other construction site equipment, and finally it is easily manageable by all the workers present. The prototype of the laser barriers and its functionalities are currently under patent (Figures 4 and 5).

Fig. 4. Modular laser barrier. A transceiver prototype during the first test. Source: Authors



BREVETTI

INAIL

SISTEMA DI BARRIERE LASER MODULARI PER CANTIERI

Inventori: Antonella PIREDDU, Raffaele PALOMBA

Parole chiave: *Prevenzione, rischio investimento, cantiere, zone di lavoro, delimitazione, area interdetta, strada, allarme.*

NUMERO DI PRIORITÀ: 102023000012441
DATA DI PRIORITÀ: 16/06/2023

LICENZA: Internazionale
DIRITTI COMMERCIALI: Esclusivi

DISPONIBILITÀ: Disponibile
TITOLARITÀ: INAIL

L'invenzione consiste in una barriera laser costituita da almeno due ricetrasmittenti montate su un supporto fisico stabile e da una centralina collegata alla barriera e ad un segnalatore acustico e ottico.

DESCRIZIONE

Una barriera laser è costituita da due o più ricetrasmittenti atte a scambiarsi un segnale laser attraverso un trasmettitore laser ed un ricevitore laser montati attraverso ancoraggi snodabili ad una base che fornisce supporto. Ciascuna ricetrasmittente rileva interruzioni del segnale laser e invia una segnalazione ad una centralina, atta ad acquisire le segnalazioni dei microprocessori delle ricetrasmittenti e ad attivare i dispositivi di segnalazione acustica e/o i segnalatori ottici, quando una interruzione di un segnale laser tra due ricetrasmittenti viene rilevata da almeno un microprocessore.

Il sistema ha la capacità di delimitare zone a rischio; rilevare l'attraversamento dell'interfaccia tra zone; allarmare sia i veicoli o passanti e sia i lavoratori. All'interno di ciascuna ricetrasmittente viene rilevato l'attraversamento della barriera e attivato un segnale sonoro, che prescrive il rientro dei lavoratori nella zona sicura e un segnale ottico (come ad esempio un semaforo), che prescrive l'arresto dei veicoli in transito verso il cantiere.

Fig.1a

Figura 1a. Barriera laser tipo. Posizionamento degli elementi modulari della barriera per delimitare la zona lavori di un cantiere stradale. Fonte: Rielaborazione Inail tratta dal DM 10/07/2002.

La barriera può essere allestita in tempi strettissimi rappresentando così una soluzione ottimale per i cantieri di breve durata; occupa un volume ridotto sia all'interno del cantiere che sulla strada ed è facilmente componibile e trasportabile insieme alle altre attrezzature di cantiere. Essa, è semplice da allestire e intuitiva, inoltre, è caratterizzata da un'elevata flessibilità dei singoli elementi modulari e dalla completa adattabilità alle aree di lavoro da delimitare e allarmare. Rispetto alle barriere fisiche, che offrono una protezione in caso di impatto, la barriera laser è potenzialmente in grado di prevenire l'impatto veicolo-uomo. Inoltre, il sistema non comporta violazione della privacy in quanto non vengono rilevati e registrati dati sul lavoratore o su altri utenti, ma soltanto dati sulle interruzioni e riattivazioni durante l'utilizzo della barriera.

In Figura 1b si osserva come un veicolo che sopraggiunge dal lato sinistro, viene fermato da detti segnalatori ottici 150 (che in figura sono due semafori) che mostrano una luce rossa poiché il lavoratore è passato fra due ricetrasmittenti 110 interrompendone il segnale laser.

1/2

Fig. 5. Modular laser barrier as represented on the Inail website. Source: https://www.inail.it/portale/ricerca-e-tecnologia/it/terza-missione/valorizzazione-della-ricerca/portafoglio-brevetti/brevetti/brevetto.2024.07.barriere-laser-modulari-nei-cantieri.html

3 Discussion and future directions

Safety barriers play an important role in the risk management. Hollnagel states that "whereas the barriers used to defend a medieval castle mostly were of a physical nature, the modern principle of defence-in-depth combines different types of barriers—from protection against the release of radioactive materials to event reporting and safety policies" [11]. The concept of defence-in-depth was developed within the nuclear industry but is also used in other high-risk industries. The focus on the use of risk-informed principles and safety barriers in European regulations such as the Seveso II directive (EC, 1996), the Machinery directive (EC, 1998, 2006) and others, demonstrates the importance of safety barriers in order to reduce the risk of accidents. Discussions have emerged on what is a safety barrier. To clarify the terms will be useful to avoid misconceptions in communication about risk and safety barriers. In road transportation, where the term of safety barriers comes from, barriers originally refer to those concrete obstacles on bridges and road edges to avoid driving out of way, or central reservations of roads to prevent collisions (Szymanek, 2010) [12].

This paper showed a specific application of the barrier concept within industrial safety also relevant for the quarry or construction industry and for application areas such as the transport sector, focusing on occupational accidents in detail [6]. The characteristics and innovative elements of the barrier proposed in this work derive from the fact that, to date, there are no movable and modular intangible barriers available on the market that simultaneously perform the described functions. The most inventive aspects of the system are represented by the high flexibility of the individual modular elements and their adaptability to the work areas to be delimited and alarmed.

Such disadvantage of the device is related to the extreme conditions of the environment of use, which can compromise its resistance, integrity and reliability. The sensors are accessible and therefore subject to tampering or misalignment of the laser which can create system inefficiency. The use of road signs and other means of signalling in addition to or in place of those provided for Ministerial Decree of 10 July 2002 [7], must be authorised in advance by the Ministry of Infrastructure and Transport, which may also make technical or temporal changes to them. These provisions would also apply to laser barriers in case of industrial production and road use, for the use of which, the authorization process must be successfully concluded. In the area of interference between the work site and the transit road, there are risks that must be properly assessed before each intervention. Among the most frequent risks are the investment of workers working in the site-road interface, the investment of people outside the construction site (e.g. pedestrians, residents, passers-by, etc.), the collision between vehicles in transit, and operating machines, the fall into unprotected or unmarked excavations [8, 13, 14]. The danger of running over near the construction site-road interface can be mitigated by temporary signs that play an important role in the prevention of road accidents which, however, must be integrated with technological developments that increasingly involve vehicles and road infrastructures [14]. These technologies may also include systems of the type represented in our study.

Liu delimited the concept of safety barrier based on the existing studies and reviewed the research advances in the categories of barrier theory, barrier engineering and barrier management discriminating his research studies in different groups. The author stated that analysts and engineers related to safety barriers should have more collaborations with those experts in information techniques and data science, to address the challenges accompanying with technical development [15].

Our experimentation continues and aims to investigate further aspects of the device such as compatibility with the working environment, integration and impact with climatic aspects, usability and ergonomics perceived by users (handling, response to commands, etc.), the quality of data and information on violations of the barrier and nevertheless, the compliance of the product with applicable standards such as EU

Regulation 305/2011 [16] on construction products and related technical standards.

New technologies and inventions have an impact on the environment and standards applicable in the area where they are tested, produced, certified and marketed. A standard applicable to an invention is not always available and, in these cases, regulatory intervention is required; in other cases, the introduction of a new technology makes it necessary to update and define new or additional requirements for existing standards. In these cases, to fill the gap, the relevant organisations intervene by drafting new standards or by updating existing standards.

Inail is a public research organisation that conducts research to find technical solutions to occupational health and safety problems. For research institutions such as Inail, the so-called Technology Readiness Level (TRL), which classifies the technological maturity reached by an invention, generally only reaches the experimental stages. Therefore, the development, industrialisation and commercialisation phases of the prototype take place at external companies that transform the prototype into a “product”, suitable to be placed on the market and used in each territory. It is during these phases that the conformity of the prototype with the state-of-the-art standards in force in the same territory is certified.

Consistent with the previous considerations, some regulatory gaps have emerged concerning certain life stages of barriers, from design to production. Further developments in this study may help to fill some of the regulatory gaps that have emerged so far. However, in the design, production and testing phases of laser barrier prototypes, we have considered some technical specifications applicable in our country. Regulations on the intrinsic characteristics of the prototype (e.g. laser technology), regulations on construction sites and regulations on the safety of the road infrastructure for which the barriers are mainly intended were applied.

A concrete example of how this regulatory complexity influenced the design, construction and testing of the barrier concerns the laser emission power, which had to be completely “harmless” to workers. To this end, we opted for a Class I laser according to CEI EN 60825 (power < 0.04 mW), which at the same time was free of health risks for workers and sufficient to cover a distance between the barrier's transceivers of between 3 and 7.50 metres (Figure 2). The latter corresponds to the distance between two consecutive traffic cones (which we used as a support for the transceivers) required by the Italian Decree of 10 July 2002 on temporary signalling at roadwork sites [7].

As far as the subsequent phases of barrier testing are concerned, and thus from the moment when the prototype becomes a “marketable product” in a given territory, it will be possible to precisely define the applicable regulatory framework, linked either to the market rules in force in the chosen territory such as, for example, the European Construction Products Regulation [16] for Europe or, other standards for countries such as the United States or China. Similar considerations apply to standards for the use of barriers, whereby in Europe safety standards apply for products made available to workers, according to European directives and regulations [6] and

standards applicable to public roads according to national standards issued by the Ministry of Infrastructure and Transport [7, 9, 10].
INAIL's Department of Technological Innovations and Safety of Plants, Products and Human Settlements, as part of its research activities with institutional partners, has activated collaborations aimed at testing innovative solutions for the laser barrier described above. These integrate existing and innovative technologies applicable to work equipment.

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Agricultural Machinery Field of View Simulation Using Ray Tracing for Early Stage of Design Optimization

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Abstract
The issue of the field of view of work vehicles is a topic that is still being discussed in the regulatory field.
Although standards lay down minimum safety requirements and there are various arrangements such as manufacturers adopting cameras, or good practice requiring the site to be organized in advance or the presence of an external operator to coordinate the work, the issue remains topical and can be improved through the use of new technologies.
This paper presents an innovative method that employs Ray Tracing-based rendering to virtually analyze and verify the operator's field of view as required by the current reference standards as well as for the new one, which will be based on earth-moving machinery standards. Through this approach, tasks involving the interaction between agricultural machinery and nearby workers can be simulated to assess the operator's visibility during such scenarios. Moreover, this tool allows for the identification of potential issues early in the 3D design phase, eliminating the need to build physical prototypes in order to increase the possibility of detecting people in the vicinity of the vehicle and to reduce or eliminate the risk of investment.
In this way, the designer has the possibility to make the design optimization directly to the components that create masking effects or to opt for indirect vision systems, thus reducing machinery development times and costs.
In this paper, numerical and experimental results demonstrate the effectiveness of the approach used for field of view verification will be presented. Additionally, the limitations of the standard concerning the rectangular boundary visibility field (RB) will be discussed.

1 Introduction

Various standards lay down minimum safety requirements of agricultural, industrial and earth moving machinery field of view. Some manufacturers use tools such as

video cameras and good practice that could require the site to be organized in advance or the presence of an external operator to coordinate the work, but the issue remains topical and can be improved through the use of new technologies. Data from INAIL highlights the critical issue of reduced field of view, particularly in areas closest to these machines [1-2]. Tractor's structural components, along with other elements, can contribute to the creation of blind spots that are difficult to monitor.

The issue of visibility in tractors is reported in the ISO 5721-1:2013 [3] and ISO 5721-2:2014 [4] standards that define the requirements and methods for evaluating the field of view, considering different areas: front, side, and rear. These standards, applicable to agricultural and forestry machinery, use similar procedures to identify and assess masking effects, but they differ in testing surfaces. Likewise, ISO 5006:2017 [5], which has the same goal but applies to earth-moving machinery, adopts a similar approach, requiring checks on specific surfaces such as the Visibility Test Circle (VTC) and the Rectangular Boundary (RB), see [6].

In both cases, the test consists of installing lights on supports in strategic positions, placing them at a certain distance from the Seat Index Point (SIP), which is determined using a standardized device as described in ISO 5353:1998 [7]. Subsequently, it is evaluated whether these lights are visible in a mirror positioned in specific areas of the test surface. This method allows for the detection of masked areas in a simple way, but it is neither very precise nor reproducible as it depends on the operator's skill. For this reason, recent studies have looked to improve the accuracy of the field of view evaluation using more advanced technologies.

In one of these studies, Zvěřina et al. [8] used a LiDAR scanning system placed on the tractor seat to simulate the operator's eyes, performing two scans (one for the right eye and one for the left) with reference spheres positioned in a semicircle located twelve meters in front of the machine. The data obtained from the scan are processed in 3D modeling software, where points above the working plane and beyond the reference distance are ignored, generating a graphical model of the field of view in .DXF format. This method offers high accuracy compared to ISO standards but involves high costs for equipment and analysis.

Another advanced approach was proposed by Bayran et al. [9], who used a virtual simulation of the field of view based on a CAD model of the tractor. In this method, visibility is simulated using a digital human model inserted into the "Jack" simulation software, which allows for a 20 mm diameter sphere to be traced around the machine to identify masking areas. This virtual method is particularly useful in the design phase of the machine, as it allows for identifying and reducing masking effects before the production of physical prototypes.

Similarly, Teizer et al. [10] introduced the use of Ray-Tracing algorithm to simulate and evaluate blind spots generated by forklift components. In this case, Ray-Tracing allows tracking light paths to identify areas shaded by vehicle parts. The test was

conducted on two models: the first obtained via CAD and the second from a LiDAR scan, comparing the results obtained from both systems.
Thanks to the review of the current state of the art presented so far, a virtual simulator has been created based on the Ray-Tracing algorithm to simulate the field of view during the design phase of tractors, as indicated in [11]. The results from this simulation have been compared with those from physical tests, showing a good match and greater accuracy compared to the methods currently described in the state of the art.
This article aims to deepen the analysis of the field of view in areas close to the tractor, which presents the greatest safety challenges for the operator, using the system described in the aforementioned research. By using the Ray-Tracing-based simulation method, the masking effects in these areas will be analyzed in detail, with the goal of improving safety and contributing to the update of technical standards while optimizing the tractor design process and reducing the need for physical testing on prototypes.

2 Development of the Virtual System for Visibility Testing

As mentioned in the introduction, the goal of studying the visibility around the tractor was achieved using a virtual FoV simulator. The system was developed following the procedure and guidelines of ISO 5006:2017, which sets the requirements to ensure that the operator of an agricultural machine has an adequate field of view from their seat, to work safely, minimizing blind spots and visual obstructions. Specifically, the standard requires the SIP, as defined by ISO 5353:1998, to be used as a reference point for positioning measurement tools and lights during visibility tests, which are performed on specific surfaces: the VTC and the RB.
Using these guidelines, a virtual environment was created in Autodesk Inventor software to simulate and evaluate the field of view for agricultural machines, using an existing high-power tractor as a reference model, which we will henceforth refer to as Tractor D (Figure 1). However, the system is designed flexibly so that it can be adapted to any other agricultural machine and used on any testing surface.
The virtual system relies on several key components, integrated into a parametric structure, which allows the test setup to be easily adjusted. The main component is the unified device for determining the Seat Index Point (SIP), which is added to the 3D model of the tractor and serves as the reference for calculating visibility from the operator's perspective. This device is placed parametrically, allowing for quick adjustments to fit the test specifications.
Another essential part is the light support structure, which simulates the operator’s binocular vision. Two light colored sources are mounted on this support, one red and one green, to distinguish areas of monocular vision from areas of binocular vision. The structure is designed to rotate 360° around the vertical axis, allowing for full coverage of the field of view.

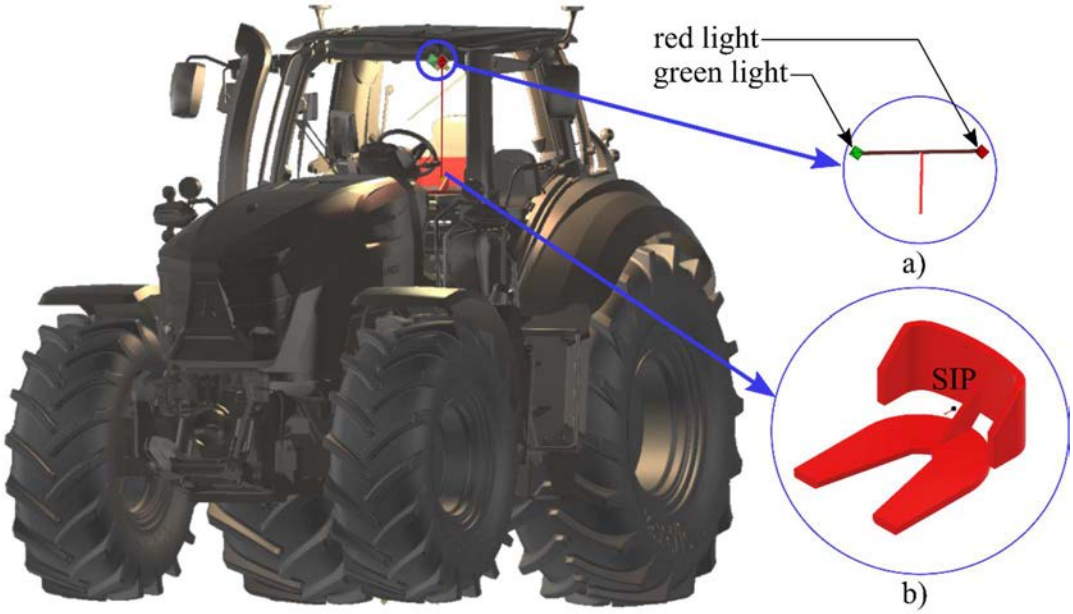
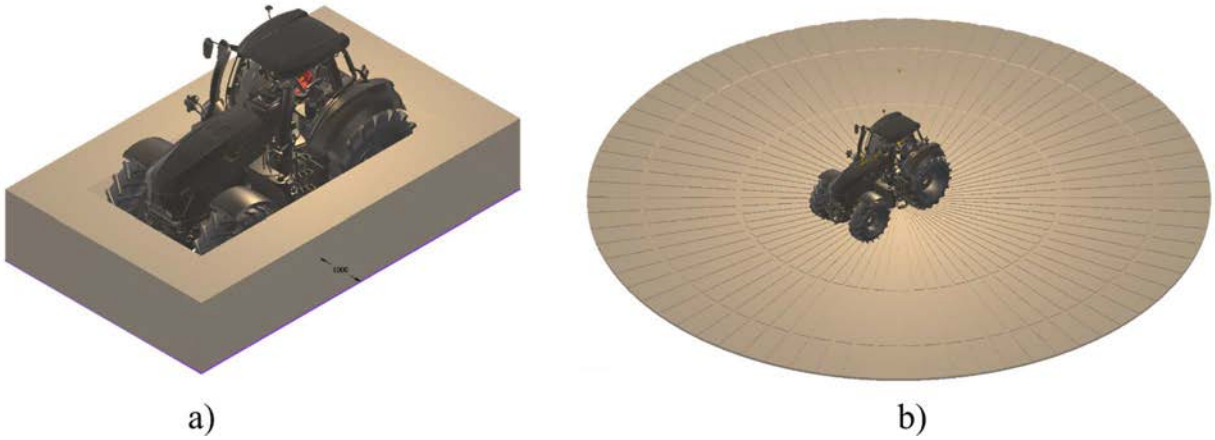


Fig. 1 - 3D model of the test vehicle representing a high-power tractor. a) Lights support; b) ISO 5353:1998 unified device for determining the Seat Index Point (SIP).

The system accurately reproduces the test surfaces required by the ISO 5006:2017 standard. The first surface is the VTC, which is a circle with a radius of twelve meters drawn on the ground reference plane, with its center aligned vertically below the reference point of the lights (Fig. 2-b). The VTC is essential for identifying visibility areas that are blocked by the vehicle. The second surface, the RB, is a rectangle placed one meter from the edge of the machine, with height parameters that vary based on the type of vehicle being examined (Fig. 2-a). This surface allows for evaluating visibility at ground level, especially near the machine.
The simulation process is carried out using the Inventor Studio module of Autodesk Inventor, which employs Ray-Tracing rendering to visualize masking effects. Areas with complete visibility are colored yellow (binocular vision), while areas with monocular vision appear red or green, and masked zones are represented as dark areas. This representation helps in identifying blind spots and critical areas of the field of view.



a) b)

Fig. 2 - Virtual test environment Tractor D. a) RB; b) VTC.

The renderings were precisely scaled and annotated within the software to ensure accurate measurement of the masked areas, allowing for a clear assessment of visibility limits as per the requirements of ISO 5006:2017.

The operation of this virtual system was validated in [11], where it was used to assess the field of view of another commercial tractor, Tractor A, as well. In that study, the results from the virtual tests were compared with real-world field tests to verify the accuracy of the system. Specifically, the real tests were conducted following the same procedure outlined in ISO 5006:2017 and under controlled conditions. The visibility of the tractor was analyzed using both the VTC and the RB methods. The masking effects and blind spots identified in virtual simulations were compared with the physical measurements, confirming the system's reliability and accuracy. In this article, the same validated system was used to conduct tests on Tractor D, following the procedures outlined in ISO 5006:2017 (Fig. 3). Additionally, the study further investigates the field of view in the areas close to the tractor, with the goal of enhancing operational safety by addressing the blind spots near the machine.

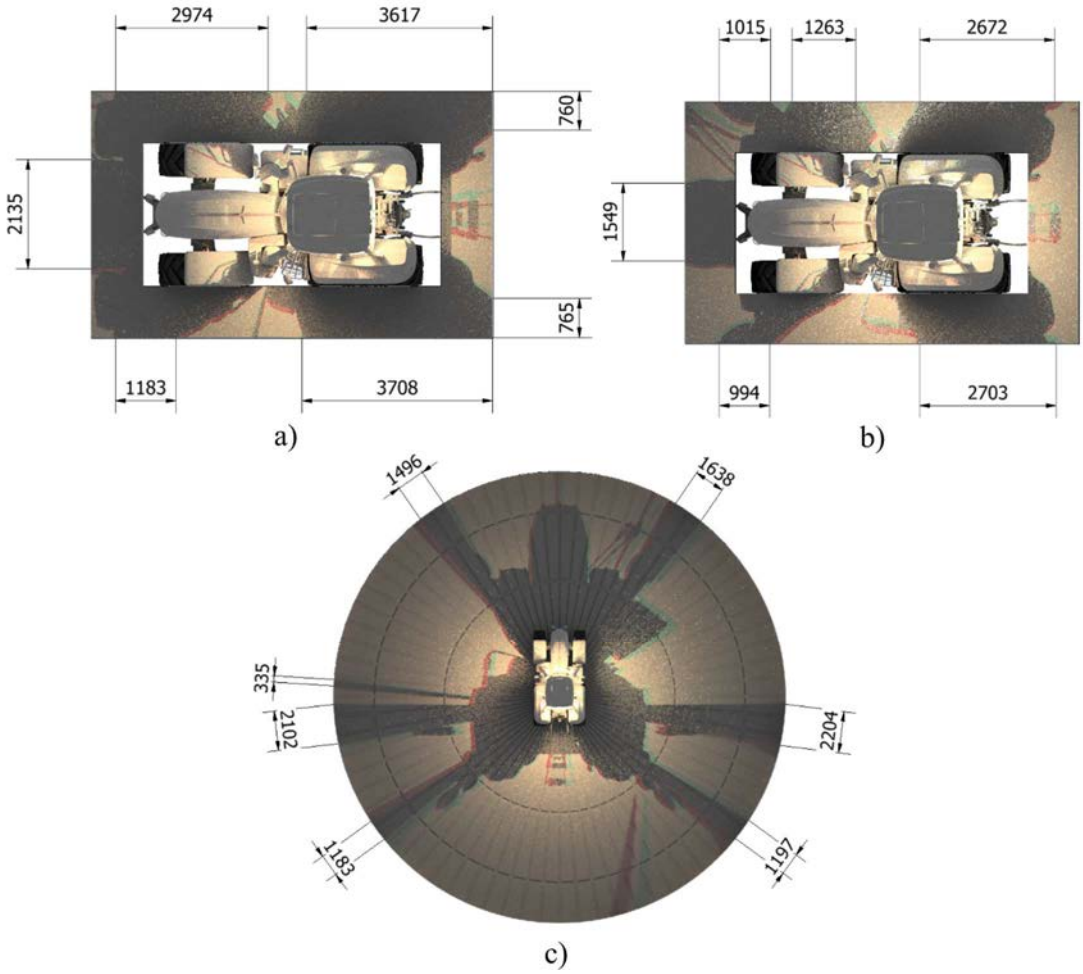


Fig. 3 - Measurement in mm of the masking effects on different test surfaces, Tractor D. a) RB at a height of 1 m; b) RB at height of 1,5 m; c) VTC.

3 Short-Range Field of View Further Analysis

As shown in Figures 3-a and 3-b, the field of direct visibility near Tractor D has completely shadowed areas. The visibility changes depending on the height: when the reference surface was placed at 1.5 meters, 40% of the RB was masked, but when it was lowered to 1 meter, the masked area increased to 60%. This suggests that shorter people or operators sitting down are much harder for the driver to see directly, and in some cases, it may even be impossible.

To better understand this problem, we decided to test direct visibility not only as described in the ISO 5006:2017 RB test but also by using dummies or other test objects useful to represent workers on the ground while they perform typical tasks near a tractor. It has been decided to carry out some visibility tests using a dummy that follows the basic measurements from the ISO 7250-2:2011 standard, based on the 5th percentile female [12] and utilizing the "Human Dummy II," which represents the 50th percentile male. This approach allows for a more comprehensive

assessment of the operator's ability to see people of different sizes and in different postures near the tractor.
First, we placed two dummies in specific positions. In the first instance, the dummy representing the 5th percentile female (shortest, as it reflects a particularly challenging scenario) was positioned near the lift arms to simulate a worker performing an operation at the Power Take-Off (PTO) (see Figure 4). Meanwhile, the dummy representing the 50th percentile male was placed near the right wheel, simulating a worker ready to press the switches that control the lift arms (see Figure 5). These situations represent an operator connecting an implement, or when maintenance is required.
Both figures include two images. Part a) shows the rendering from an angle near the rear window of the tractor cabin, allowing for an assessment of the illuminated portion of the dummy. Part b) shows the rendering made using a camera with a 120° field of view (corresponding to standard binocular visibility), positioned at the center of the lights support. It is important to note that in both figures, the dummy has been intentionally colored blue to make it easier for the reader to detect.

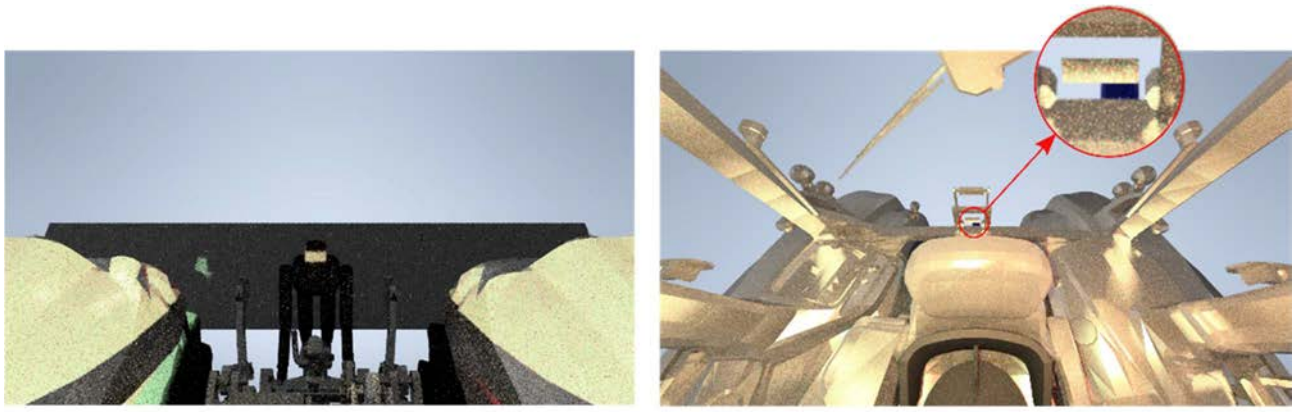


Fig. 4 - Assessment of the field of view of a 5th percentile female dummy operating at the PTO through rendering. a) Evaluation of masking effects; b) direct view from the lights reference point.

a) b)

Fig. 5 - Assessment of the field of view of a 50th percentile male dummy ready to press the switches through rendering. a) Evaluation of masking effects; b) direct view from the lights reference point.

This tests highlights two important aspects: on the one hand, the virtual system provides visibility information both through the analysis of masked areas and through the direct simulation of the operator's field of view; on the other hand, it shows that both images, despite using different approaches, present the same results, demonstrating that areas close to the tractor are heavily obscured by direct visibility, significantly limiting visibility and making the use of indirect systems necessary to improve safety.
Additional tests were conducted following the guidelines of the ISO 18497-1:2024 standard, which addresses the safety of partially automated, semi-autonomous, and autonomous agricultural machines and tractors [13]. This standard introduces the concept of a "hazard zone", defined as the area where, if an obstacle is present, there is a risk of injury. For demonstration purposes, we chose to define the hazard zone as the area outlined by the RB perimeter, as suggested by the ISO 5006:2017 standard regarding the field of view around the tractor. This zone includes the entire area enclosed by the smallest rectangle that can surround the machine's edge, with a one-meter outward offset. During the test, the dummy representing the 5th percentile female was positioned standing and moved so that, at first, the head was touching the edge of the RB perimeter and then the arm was touching the inner edge of the hazard zone, simulating movement around the tractor (Figure 6a-6b).

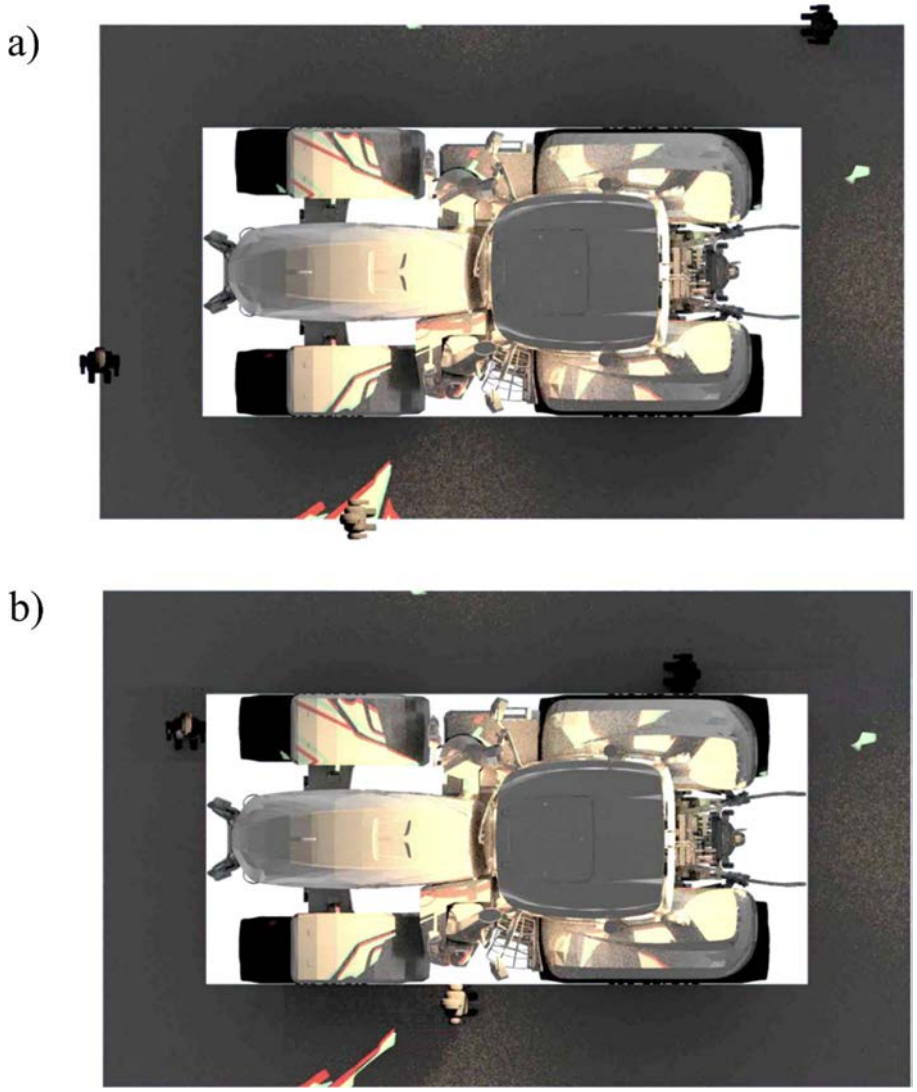
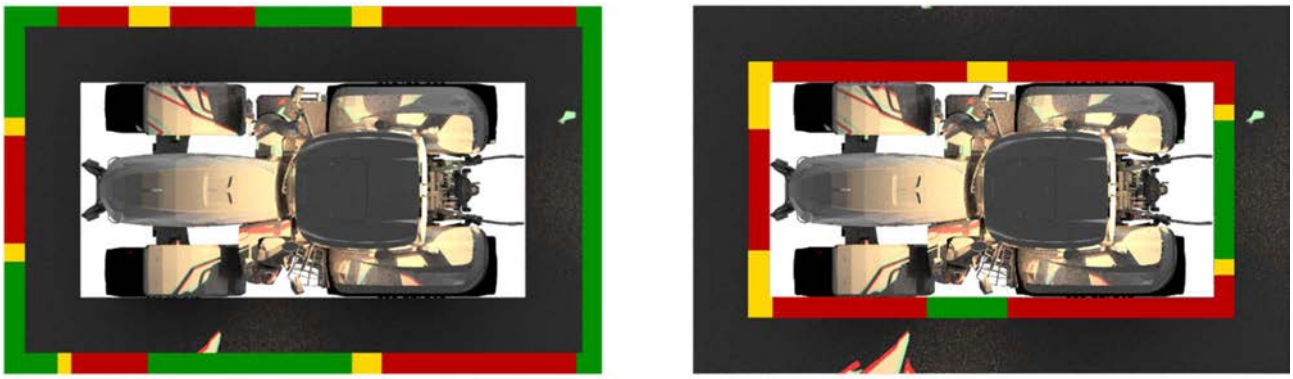


Fig. 6 – Some frames from the animated rendering tests. a) Dummy at the edge of the RB perimeter; b) Dummy touching the edge of the tractor.

The animated renderings obtained from the tests were analyzed to define the visibility of the dummy during the previously described paths. A color-coding system was adopted to represent different visibility conditions: areas where the dummy is completely invisible are colored red, while those where only the head is visible are highlighted in yellow, and zones where both the head and at least one other limb are visible are colored green. Figure 6 illustrates, for clarification purposes, all three conditions for both paths, while Figure 7 presents the results derived from the evaluation of the animations.



a) b)

Fig. 7 – Results from the visibility assessment of the animated rendering tests. A) Dummy at the edge of the RB perimeter; b) dummy touching the edge of the tractor.

The second test confirmed the results of the first, highlighting once again the shadowed areas in the immediate vicinity of the tractor. In fact, a significant variation in visibility percentages is observed: at the rectangular RB perimeter (Fig. 7-a), there are 54% green areas, 38% red areas, and 8% yellow areas. In contrast, when the dummy approaches the edge of the tractor, these percentages change, showing 68% red areas, 17% yellow areas, and only 15% green areas.

4 Limitations of Current Standards and Proposals

As described in the introduction, current standards require the validation of the operator's field of view (FoV) by analyzing the number and size of obscured areas at specific heights and in certain zones (such as RB and VTC according to ISO 5006:2017). These masked areas are defined by the zones that are blocked from the light emitted by bulbs positioned from the machine's SIP.

However, as previously highlighted, the placement of lights during physical tests is often challenging. Using the virtual system, we examined the close-range field of view of the Tractor D within the RB perimeter, not only under ideal conditions with correct lights placement (Fig. 3b), but also simulating a SIP drop of 10 and 20 mm. These variations are commonly observed in physical testing. The analysis of the results in Figure 8 compared with Figure 3a shows that even small deviations in the positioning of the light support can lead to significant differences in masking, with a maximum variation, in our specific case, of 246 mm.

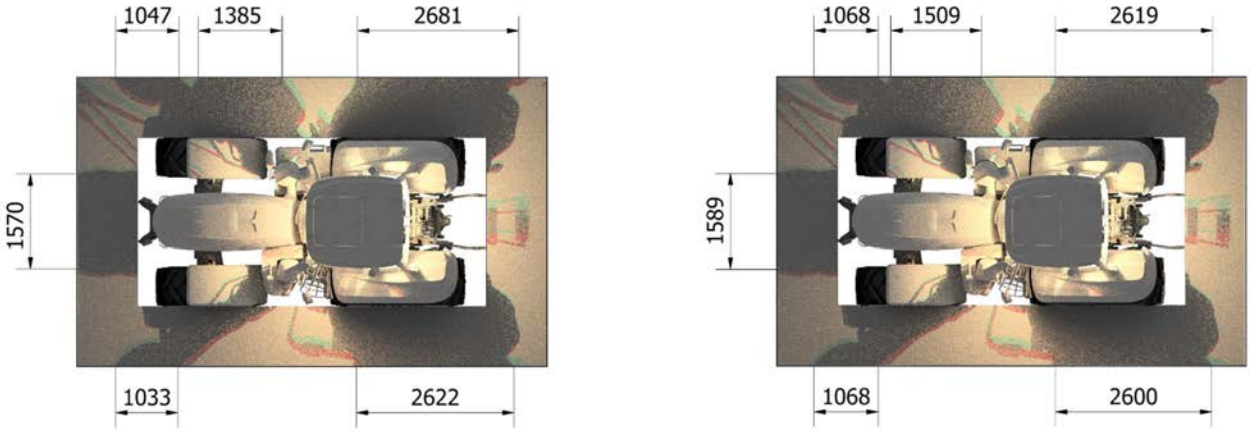


Fig. 8 - Measurement in mm of the masking effects on RB with different SIP heights. a) SIP lowered by 10 mm; b) SIP lowered by 20 mm.

This shows that current tests rely heavily on the operator's skill and how even minor positioning errors can significantly impact results, leading to considerable variations in visibility assessments. Additionally, a purely numerical approach may be less effective, as it could indicate that a part of the operator's body is visible but not necessarily recognizable. Therefore, in the future, it might be more useful to adopt a system that verifies whether a minimum portion of the operator's body is clearly identifiable, rather than just visible.

5 Conclusion

This article introduces a virtual system for checking the field of view of agricultural and forestry machines, using Ray-Tracing rendering. This system allows visibility to be evaluated during the design phase, helping designers to improve the FoV before the physical machine is built.
The visibility tests performed on a representative tractor, following ISO 5006:2017 for the VTC and RB zones, showed that areas close to the machine are particularly problematic. Further tests confirmed that these zones have the greatest visibility limitation. Additionally, it was found that measuring the masked areas in millimeters can be inaccurate due to the difficulty of precisely positioning the testing equipment. Moreover, this approach can be misleading, as some body parts may be visible but not easily recognizable. For this reason, future standards could consider new methods, such as assessing a specific body part of a dummy that should be visible. Despite these limitations, the system presented in this article can be a valuable tool for regulatory bodies, as it allows different environments and configurations to be easily simulated, helping to create safer standards. It's also clear that full safety for operators working near huge machines can only be achieved using indirect vision systems. An improvement to the system is being developed to virtually simulate how these vision systems improve visibility, using the same technology.

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Improving safety through innovation: how Inail's financial support to companies can promote the adoption of innovative machines

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Abstract
Since 2010, INAIL has been supporting companies in enhancing workplace safety and health through funding initiatives known as ISI (Italian acronym standing for "Incentivi di Sostegno alle Imprese"). Over time, the evolution of these funding calls has increasingly emphasized the purchase of new machinery alongside the replacement of used machines already owned by the companies, both in the industrial and the agricultural sector.
Two aspects underpin this trend:
renewing work equipment enhances safety conditions, as machines naturally deteriorate over time,
newly manufactured machines are safer by design, as they meet the latest safety requirements, which are aligned with new available technologies.
This paper aims to deepen this last item, i.e. how regulations (Machine directives, harmonised standards) represent the meeting point between technological innovation and economically compatible solutions and, consequently, how the ISI calls contribute to encouraging the application of technological innovations and stimulate the market to make available work equipment updated with innovative devices.

1 Introduction

INAIL, the Italian Institute for insurance against accidents at work and occupational diseases, has among its institutional aims the prevention of occupational risks in terms of both accidents and illnesses. To achieve this goal, INAIL carries out various activities, including:

- the provision of statistical data and risk assessment tools,
- participation in technical standardization activities,
- economic support to companies–for the improvement of health and safety conditions at work.

This latter activity is carried out through funding calls called ISI, aimed at supporting micro and small companies, which have a particular numerical importance in Italy and which have fewer resources to invest in safety.
The primary purpose of the ISI calls, issued annually starting from 2010, is the documented improvement of health and safety conditions at work compared to pre-

existing conditions. To this end, the calls have made 3,600 million euros available to companies until 2023, thus leading to the request for financing for over 50,600 projects aimed at reducing the different types of occupational risk.
Given the significant resources involved, ISI calls require a careful design in order to maximize the effectiveness of projects taking into account the following priorities:

- the funds must be directed preferentially to the riskiest production sectors and to the most significant risks both in terms of magnitude and frequency;
- the projects must be carried out within the times established by the call;
- applicants must be able to demonstrate improved health and safety conditions resulting from the implementation of the project.

Among the occupational risks, those linked to the use of machinery and work equipment are of particular importance. It can be estimated that in Italy over 50% of fatal accidents with confirmed professional origin are due to the total or partial loss of control of vehicles, machines, handling equipment and manual tools.
While the ISI calls exclude the purchase of vehicles, it is possible to request financing for new machinery and work equipment to replace obsolete models, i.e. machines built before the transposition of the first Machinery Directive 89/392/EEC, consolidated by the Directive 98/37/EC. For this type of project, the ISI calls presuppose an *a priori* improvement so that companies are not required to demonstrate it, with a notable simplification of the evaluation process.
This concept of *a priori* improvement is based on technical considerations that take into account the close interconnection between technological innovation and technical regulations as will be analyzed in the following paragraphs.

2 The importance of renewing working equipment

When referring to working equipment, the passage of time plays an important role. In fact, it affects not only the improvement of the performance of working equipment, but also their level of safety. Moreover, the latter is sometimes enhanced, for specific types of machines, by changes in safety requirements of dedicated harmonised standards. Thus, with reference to what aforementioned, the granting of financial support for the renewal of working equipment takes a significant meaning.
In fact, while compliance with fundamental requirements introduced by an EC directive generates a general change in the manufacture of all work equipment, the standards harmonised to the same directive refer to a single type of machine. The directive prescribes the mandatory safety and health protection requirements for work equipment in general terms, while the European harmonised standards provide the technical specifications to meet these requirements. Work equipment built according to a harmonised standard is considered to comply with the requirements specified by the standard. Standards generate improvements of such equipment more frequently than a directive.
Indeed, harmonized standards are affected by closer technical updates. Furthermore, these standards follow the concept of updating to the state of the art.

A harmonised standard provides an indication of the state of the art at the time of its adoption. It indicates the level of safety that can be expected from a given type of equipment.
The standards report the technological innovations available at that time and adopt those that are technically and economically possible. Technical solutions to meet health and safety requirements must use the most effective technical means currently available at reasonable costs. The reasonable cost is the one that which considers the total cost of the category of machinery in question and the necessary risk reduction. The standards thus allow an improvement of the equipment for the prevention of accident risks (tipping, overturning, shocks, etc.) but also of those that generate health problems due to long exposures (noise, vibrations, chemical agents, etc.).
Not all equipment is covered by a specific harmonised standard, especially for innovative machines not already on the market. When harmonised standards are not available, other technical documents can provide help in applying the safety and health requirements of the Machinery Directive, such as international standards or national standards. Often, pending the implementation of specific standards, similar machine standards are used.

3 Some examples

3.1 The agricultural tractors

Agricultural tractors fall under the so called “type approval” approach. Since 2018 all tractors placed on the market or put into service must be approved according to Regulation (UE) 167/2013 (Mother Regulation). This regulation replaced the Directive 2003/37/EC. Comparing these two legislative references, it appears that Regulation (EU) 167/2013 improved the safety level of tractors in many aspects, such as:

- braking devices - some important innovations concern the braking devices of trailers and equipment. The Mother Regulation, in fact, establishes in detail all the cases in which it is necessary to use inertial, mechanical, hydraulic or pneumatic brakes, depending on the weight;
- coupling devices - to ensure the correct coupling of tractor and trailer, the Mother Regulation provides for the type-approval of the various hooks that can be installed on tractors (fixed pin, pivot pin, hook, piton, ball and drawbar) and their respective eyelets for trailers and towed equipment: swivel, fixed, toric and ball types;
- operator presence control - tractors shall have an audible and visible alarm that alerts the operator when he leaves the driving position with the park brake not engaged;
- roll over protective structure (ROPS) and seat belt – all tractors, even those having a mass of less than 600 kg, must be equipped with a ROPS and seat belt;
- engines – from 2020 all tractor engines will have to comply with Stage V, in order to reduce emissions.

Considering the examples above summarized, it appears that the safety level of new tractors has significantly improved with respect to tractors placed on the market before the entry into force of the Mother Regulation. This is more relevant in Italy, where the agricultural sector is characterized by a significant number of obsolete tractors still in use. For instance, referring to Figure 1, it appears that many old tractors still in use are not equipped with the relevant mandatory safety devices such as roll-over protective structure (ROPS) and seat belt.

Fig. 1. Example of old tractor not provided with relevant safety devices

Thus, granting financial support for renewing tractors and dismantling the old ones leads to an improvement in terms of safety and prevention at work.

3.2 The hydraulic excavators

As regards hydraulic excavators, regulatory developments have led to the introduction of increasingly safe products on the market. In this regard, the new edition of ISO 5006 introduced an improved static test method to determine and evaluate the operator's field of view around the machine. In particular, it establishes visibility performance criteria on a rectangular boundary (RB) close to the machine and on a visibility test circle (VTC) with a radius of 12 meters centered on the driving position (see Figure 2). The updated version, ISO 5006:2017, came into force on May 17, 2018, replacing the previous 2008 edition and making significant changes to test methods and performance criteria.

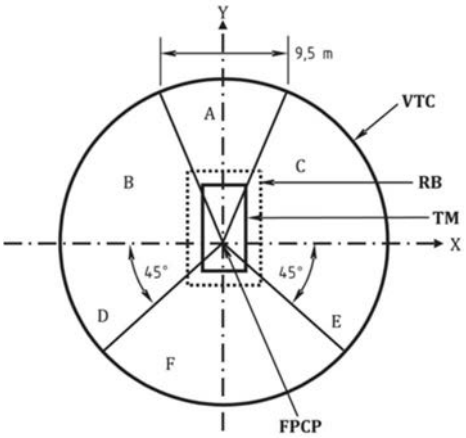

Fig. 2. Example of rectangular boundary (RB) and visibility test circle (VTC)

The ISO 5006 edition 2017 introduced significant innovations compared to the previous version dated 2006, with a particular focus on the evaluation of the operator's visibility for earthmoving machinery:

- the new standard with the new static test method ensures a more accurate assessment of visibility;
- stricter requirements have been introduced to increase visibility on the rectangular boundary, thereby enhancing operational safety and reducing the risk of accidents during operations;
- new guidance regarding obstructions caused by the movements of excavator arms has been included, addressing one of the critical aspects of visibility during operations.

As regards the risk of overturning/tipping over, there are important regulatory developments which have defined stringent requirements regarding the type of protective structures with which excavators must be equipped when placed on the market. In particular, the reference standard in force until November 2008 was EN 474-5:1996. This edition of the standard required a tip-over protective structure (TOPS) only for compact excavators (i.e. hydraulic excavators having a mass less than or equal to 6,000 kg) when equipped with a cabin. TOPS was not mandatory for compact excavators not equipped with a cabin (see Figure 3). Only starting from March 2012, with the amendment A1 of EN 474-5:2006, the harmonised standard required a TOPS for compact excavators, without any exception, and a roll-over protective structure (ROPS) for excavators having a mass greater than 6000 kg up to 50 ton. Moreover, in addition to the presence of a TOPS or ROPS the recent editions of the standard provide requirement for operator protection from falling objects where necessary (e.g. demolition activities), by means of a falling object protective structure (FOPS).

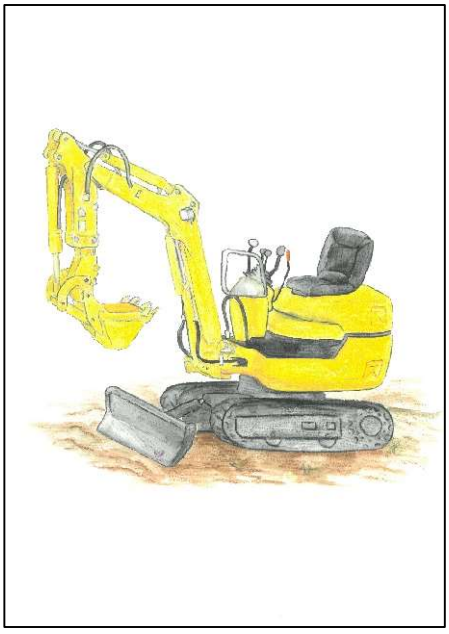

Fig. 3. Example of compact excavator without cabin

3.3 Rough terrain Work Platform for Orchard operations (WPO)

Another important example to consider is Rough-terrain Work Platforms for Orchard's operations (WPO). This type of machinery was initially placed on the market without a harmonised standard with Directive 2006/42/EC. Thus, there were no homogeneous requirements and, in some cases, the WPO could be considered as Mobile elevating work platforms (MEWP) falling into the scope of harmonized standard EN 280. However, there were some significant differences as concern type of use, heights and loads. When EN 16952:2018 on WPO was published, it defined specific safety requirements for off-road work platforms used in agricultural operations, particularly fruit harvesting. The main innovations introduced by the standard are summarized below:

- stability requirements, focusing on the need for platforms to maintain stability on uneven terrain. This includes:
    - enhanced stability requirements, such as automatic slope control that stops the machine if it exceeds a specified maximum slope;
    - detailed testing protocols for dynamic and static stability, including overcoming obstacles tests that simulate uneven ground conditions, ensuring that platforms can operate safely in agricultural environments;
- physical barriers that can be inclined towards vegetation, allowing operators to work safely while reaching for branches without the risk of falling;
- enhanced control systems that ensure the activation of safety mechanisms in various operating scenarios, such as automatic braking when the machine is in neutral;
- guidelines for design calculations related to stability considering the weight of fruits and bins carried on the machine platform.

A revised version of the standard EN 16952 has been published in 2022.

Therefore, considering that the old WPO do not have such requirements (see Figure 4) (such as stability tests, rigid falling protective devices, etc.), the ISI funding calls have an even greater impact because they allow the replacement of even recent machines that are not in line with the state of the art required by harmonised standards.

Fig. 4. Example of old WPO

a. Data on the age of scrapped work equipment

The ISI calls also constitute a tool for understanding the current consistency and type of work equipment currently in use by companies.

For example, a survey of the financing applications presented by agricultural companies with the ISI 2022 tender highlighted the following data:

- the applications submitted by 742 companies concerned the purchases of 548 tractors and 421 agricultural machines;
- approximately 40% of the applications included the scrapping of an old owned tractor;
- approximately 36% of the applications included the scrapping of an owned agricultural machine, similar in type to the one to be purchased.

The age of tractors to be scrapped, highlighted in the following graph (see Figure 5), reaches a peak around 50 years, but there are older ones, that reach up to 70 years. This means that the safety level of this work equipment does not reflect the actual safety level neither in terms of improvements in safety standards/regulations nor in technological upgrade.

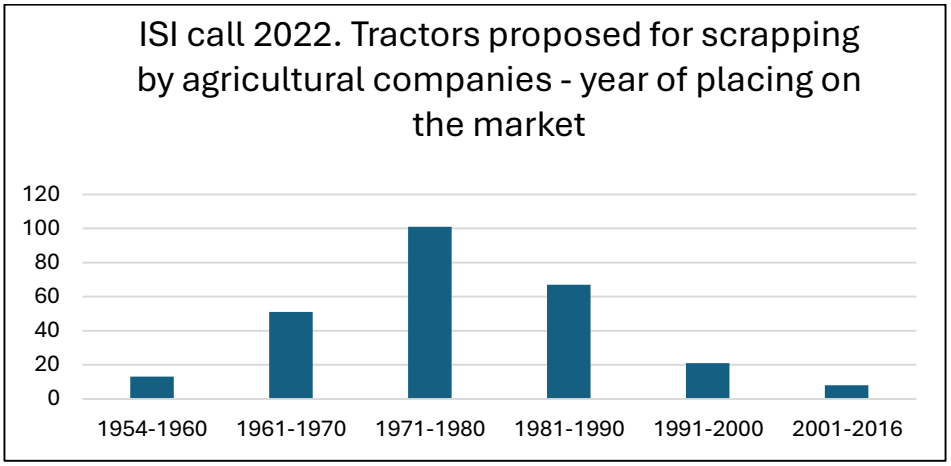

Fig. 5. Age of tractors to be scrapped by agricultural companies applying for financing

4 Conclusions

With reference to the proposed examples, it is clear how the development of safety harmonised standards or, even more so, the introduction of new regulations leads to an improvement in the safety level of working equipment. This is much more relevant when compared to machines placed on the market before any safety legislative reference.

Data reported above show that many old tractors are still in use in Italian agricultural sector and the same happens for agricultural machinery, motorized or not. This causes the permanence of occupational risks that have been faced and resolved over the years through technological innovation.

The financial support offered by the ISI calls thus achieves the dual objective of demolishing older work equipment, removing it from the companies' availability, and on the other of introducing into the work environments equipment with an intrinsically higher level of safety with a positive effect on accident prevention.

INAIL therefore remains committed to supporting the renewal of working equipment, also by promoting additional safety features that go beyond current regulatory requirements, in order to have as much impact as possible on improving the health and safety of operators.

PPE integrated with IOT technologies: an innovative Italian Standard

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Abstract
The introduction of IoT technologies in the health and safety at work field has been studied for some time and, currently, there are some applications that allow access to procedures or information, to give assistance in case of accident, to report directly and immediately the proximity of a danger. Now there are new possibilities to monitor the use of personal protective equipment (PPE), to interface with the work environment (for example to allow access to an area) and to also be able to transmit data on the worker's condition.
Certainly, these innovative technologies represent an opportunity to improve the role of personal protection equipment (PPE) in ensuring health and safety of workers.
Anyway, there is the CE certification aspect that, although it may seem formal, represents an obstacle to the widespread adoption of PPE integrated with IoT. In fact, the certification of a PPE follows precise, defined community rules by EU Regulation 425/2016, and requires an approval by a Notified Body (for 2nd and 3rd Category PPE) for technical and functional characteristics.
Adding an IoT system to already certified PPE, is considered a product modification and could, formally, result in the loss of certification. We do not have a standard for PPE integrated with sensors and the possibility of adding an IoT system to PPE is not contemplated in the standardization. In Italy, first in Europe, UNI has started a virtuous path and drafted the technical report 11858:2022 on the use of IoT technologies to the world of PPE. At the moment it is published in Italian and it has been translated into English. In this work we describe UNI TR 11852:2022 with an overview of the UNI working group. It is hoped that this document will support the regulatory adaptations needed to allow the use of IoT systems applied to PPE.

1 Applications of IoT Technology in Personal Protective Equipment for Occupational Health and Safety

The technological evolution of Personal Protective Equipment (PPE) has historically focused on improving protective capabilities through new materials and mechanical features. However, the advent of the Fourth Industrial Revolution, marked by increasing digitalization and the adoption of Internet of Things (IoT) technology, has

opened a new chapter. PPE, traditionally designed to mitigate the consequences of accidents, can now be transformed into proactive prevention tools. This technological shift is currently supported by European policies, such as those promoted through Horizon and EU Cordis programs, which encourage the integration of Industry 4.0 into safety devices to enhance occupational health and safety. These initiatives aim to develop integrated ICT solutions for smart PPE, with specific applications for firefighters and first responders in emergency scenarios.

The concept of IoT relies on the ability of physical objects to communicate and collaborate through digital connections, facilitating increased efficiency and safety. Within Industry 4.0, IoT integrates with cyber-physical systems to create a decentralized network capable of dynamically managing information. This synergy enables PPE to collect and transmit real-time data, monitoring environmental or physiological conditions of workers and activating reactive measures in hazardous situations. For instance, embedded sensors can detect the presence of toxic gases or anomalies in vital parameters, immediately alerting workers or emergency teams.

The application of IoT to PPE offers numerous benefits, including real-time monitoring of health and environmental conditions, GPS tracking for emergencies, and training opportunities through virtual reality simulations. Additionally, the collection of big data from these devices allows for detailed analyses to prevent future incidents, improving the effectiveness of occupational safety systems. However, adopting these technologies also presents significant challenges. Training workers for proper use and addressing privacy concerns are critical issues. Risks of device malfunction, variable reliability of wireless communications, and the high cost of smart equipment can also hinder widespread implementation. Furthermore, electromagnetic emissions and vulnerability to cyberattacks require careful management.

PPE remains essential for mitigating residual risks when collective and engineering controls are insufficient. Common devices include respiratory protection, eye protection, body protection, and limb protection. IoT integration expands PPE's protective capabilities, transforming them into intelligent tools capable of adapting to varying risk conditions. For example, smart PPE can utilize advanced materials that change properties to absorb impacts or shield against extreme heat, with sensors continuously monitoring both device and worker status.

The European Agency for Safety and Health at Work (EU-OSHA) acknowledges the revolutionary potential of smart PPE but emphasizes the need to address the complexities of their adoption [1]. In various documents, the agency evaluates the benefits of these tools, such as enhanced protection and comfort, while highlighting the necessity of ensuring regulatory compliance and data protection. EU-OSHA underscores the importance of a balanced approach that considers both opportunities and limitations, advocating for research to maximize the benefits of digitalization without overlooking ethical and practical implications.

The introduction of IoT technologies into PPE represents a wave of innovation aimed at ensuring greater safety, enhancing worker performance, reducing long-term costs, and improving operational efficiency. The primary goal of these applications is to provide integrated solutions combining protection and prevention in work environments with medium to high-risk levels.

Technological innovations transforming the PPE sector are based on several core principles. Wireless communication technologies such as WiFi, Bluetooth, and Radio Frequency Identification (RFID) form the fundamental infrastructure for data transmission. These systems enable devices to collect, process, and share real-time information, ensuring a continuous flow of data between workers, machinery, and control centers. Biometric sensors facilitate continuous monitoring of physiological parameters, while smart textiles offer advanced properties such as adapting to changing environmental conditions or reacting to physical stress. These advancements are further combined with innovative visual methodologies like Augmented Reality (AR) and Virtual Reality (VR), enhancing risk perception and worker training.

Wireless transmission systems are essential for the effectiveness of smart PPE. Technologies like Bluetooth and its Low Energy (BLE) variant provide secure and efficient short-range communication, ideal for localized applications. WiFi ensures broader connectivity, while advanced solutions such as RFID and Near Field Communication (NFC) protocols excel in precise short-range data transmission. For complex scenarios, long-range technologies such as UMTS and WiMax maintain connections even in remote areas. The diversity of wireless technologies allows PPE to adapt to various operational contexts, making them versatile and highly effective tools.

IoT-enriched PPE introduces significant advancements in workplace safety. Key functionalities include GPS-based worker tracking, real-time communication with supervisors, and continuous monitoring of worker physical conditions and environmental characteristics. Some devices incorporate heating or cooling systems to adjust internal temperatures based on external conditions. Additional innovations include luminescent materials or visual signals for emergencies and emergency stop mechanisms to prevent incidents near hazardous equipment.

IoT technologies have opened new frontiers for worker safety. Advanced systems leverage RFID and Bluetooth sensors to monitor proper PPE use, enable or restrict access to high-risk zones, and provide alerts in case of anomalies. These systems can verify in real-time that operators are wearing the required devices, recording each event in a centralized log. Other applications include Physical Safety Information Management (PSIM) platforms that collect and analyze data from PPE and work environments to anticipate and prevent dangerous situations. For instance, smart textiles with conductive ink not only monitor biometric parameters such as heart rate

and muscle exertion but also transmit data to external platforms for a comprehensive view of worker status.
The integration of Artificial Intelligence (AI) in PPE is a cornerstone innovation for Industry 5.0. Projects such as SENSE-RISC, developed by INAIL, highlight AI's potential to enhance safety. This device, equipped with environmental and biometric sensors, employs machine learning algorithms to adapt to changing conditions, identifying signs of fatigue or stress that may precede an accident. AI also allows advanced customization of PPE, improving effectiveness and adaptability to various work environments. However, AI should complement existing processes rather than entirely replacing them.
Adopting AI in PPE raises ethical issues, such as privacy protection, data transparency, and addressing algorithmic biases. The recent AI ACT of 2024, the first of its kind globally, promotes a uniform framework for developing and using AI systems in the European Union. This regulation seeks to balance technological innovation with the protection of fundamental rights, emphasizing principles like inclusivity, sustainability, and accountability to ensure safe and ethical AI implementation.
IoT and AI technologies applied to PPE mark a significant breakthrough in worker protection, offering advanced solutions for accident prevention and workplace condition monitoring. However, the adoption of these innovations requires careful management of ethical, technical, and regulatory challenges.

2 CE Marking

Regardless of their category, Personal Protective Equipment (PPE) must comply with the Essential Health and Safety Requirements (EHSR) outlined in Annex II of European Regulation EU 2016/425. This regulation establishes the standards for the design and manufacture of PPE to be made available on the market. At the time of market entry, manufacturers are required to ensure that PPE has been designed and manufactured in accordance with the EHSR and to prepare the "technical documentation." They must also conduct or commission the relevant conformity assessment procedure to demonstrate compliance with the applicable EHSR. If conformity is established through the appropriate procedure, manufacturers draft an EU declaration of conformity in compliance with Article 15 and affix the CE marking.
For Category I PPE, the conformity assessment procedure involves internal production control. Under their sole responsibility, manufacturers must:

- Prepare the technical documentation as outlined in Annex III;
- Take all necessary measures to ensure that the manufacturing process and its control guarantee the PPE's compliance with the technical documentation and the Regulation's applicable requirements;
- Affix the CE marking to each unit of PPE;

- Draft a declaration of conformity and keep it, along with the technical documentation, available to national authorities for ten years from the date the PPE is placed on the market.

For Category II and III PPE, the conformity assessment procedure involves an EU type-examination conducted by a third party, known as the notified body. This body evaluates the technical design of the PPE to verify and certify its compliance with regulatory requirements. Specifically, the notified body assesses the adequacy of the technical design against applicable provisions of relevant harmonized standards or, in their absence, alternative technical specifications. This process includes examining a representative production sample and conducting or commissioning tests to verify compliance with harmonized standards or other specifications adopted by the manufacturer. The notified body then prepares an evaluation report, detailing the activities performed and indicating whether the PPE meets the applicable EHSR. If successful, the body issues the manufacturer an EU Type-Examination Certificate.

3 The UNI 11858:2022 technical report

The UNI technical report (RT) 11858:2022 aim is to target and support employer in choosing PPE integrated with IoT technologies; it is the first Italian technical document about interactive technologies applied to PPE and, in this sense, it documents the contribution that standardization can give to the technological transformation process identified as "industry 4.0" or “industry 5.0”.

The report, in fact, describes several aspects: characteristics of IoT technologies into PPE, their management and interaction with the wearer and the working environment, the compliance with essential health and safety requirements of integrated PPE, the information and training, the description of the possible applications in the health and safety at work and the related potential new risks.

Table 1 shows the index of the UNI TR 11858:2022.

Paragraph	
	Introduction
1	Scope
2	Normative references
3	Terms and definitions
4	Description of IoT system
5	Compliance of integrated PPE with essential safety requirements
6	Information, training and on-the-job training
7	Potential safety application of IoT in safety at work
8	Information provided and/or collected by devices
9	Management of data relating to PPE

10	Management and control of PPE
11	Risk assessment related to the use of IoT system
	Bibliography

Table 1 – Index od UNI TR 11858:2022

3.1 Compliance of integrated PPE with essential safety requirements

It's known that there is a general request of appropriate standards in the field of smart PPE but, at the moment, in Europe we have only few publicised standards and just one is about selection and use of smart garments[1]. Moreover, as long as no standardized method exists for the testing of these elements, neither employers nor employees will have confidence in technical solutions of this kind – even if the added value is universally recognized [2]. The Uni Technical report gives an answer to these requests describing roles and responsibilities of manufacturer, employer, notified body and focusing on some specific items.

Relating to compliance with Essential Health and Safety Requirements, the Uni document distinguishes three cases to fit/integrate tags or sensors to PPE:

- Inclusion: tag/sensor is applied or integrated by PPE manufacturer during the production process;
- Compatibility system: the manufacturer prepares specific areas to subsequently accommodate the tag/sensor having specific characteristics;
- Customization: employer personalizes the PPE with tag or sensor having specific characteristics, according to its needs and usage requirements.

For each of these cases, the technical report suggests what to do in order to have the necessary compliance of integrated PPE with European Regulation 2016/425 (Essential Health and Safety Requirements).

Actually, some smart PPE used in industries are the result of an idea of employer and a collaboration with a technology solution provider that supports companies to define the path of digital transformation. In recent years, several research institutes and companies have worked on projects concerning smart PPE but only few products are on the market. So, it's important to make it clear that some factors (position od sensors, materials, etc.) can reduce the effectiveness of the protection.

In general, if the tag/sensor is not designed and inserted by the PPE manufacturer, the person who is responsible for supplying the PPE with the tag, undertakes to provide the unaltered protective efficacy of PPE and the absence of additional risk from the PPE use.

In general, when the tag/sensor is not designed and integrated by the PPE manufacturer, attention must be paid to ensuring that the smart and the traditional protective elements work well together and do not interfere with each other [1]; in particular the Uni report underlines that who is responsible for supplying the PPE

[1] EN 17673:2022: protection against heat and flame – Requirements and tests methods for garments with integrated smart textile and no textile elements.

with the tag, have to ensure the unaltered protective properties and the absence of additional risk for the user.
In the particular case of a customized system, the employer must contact both the tag/sensor manufacturer and the PPE manufacturer in order to have all the necessary information. The tag/sensor manufacturer has to provide the information to be sure that the tag/sensor is compatible with the conditions to which it will be exposed once it is integrates into the PPE.
The PPE manufacturer has to assess whether adding the tag/sensor changes the PPE. If appropriate, the manufacturer can contact the notified body for an integration of the certification, following the procedure provided for by the European Regulation 2016/425.
If the PPE manufacturer does not respond or does not consider the change feasible, the employer still has the right to proceed with the addition of the tag/sensor, if the change does not affect compliance with the essential health and safety requirements. In this context, he can contact a notified body and proceed to the certification of the integrated PPE, following the procedure provided for by the European Regulation 2016/425. In this case the employer becomes the manufacturer of the new, integrated PPE.

3.2 Information, training and on-the-job training

Another important aspect of the UNI technical report is represented by the tripartite approach. In fact, the working group is composed of experts from different backgrounds: PPE manufacturer, tags/sensors manufacturer, notify body, industries that have already applied smart PPE, Institutions and social partners (employer organisations and trade unions). A constant collaboration between institutions and social partners is certainly the way to build solid programmatic and regulatory foundations for a sustainable future, especially looking at work contexts [3].
In PPE field, the technology adoption results in a change that, if not accompanied by correct, careful and adequate training, is often refused by the workers: in fact, the use of devices with technologies is often considered invasive of privacy by workers. The consequence is to miss the opportunity for greater protection during the work, specifically offered by PPE with IOT.
The UNI Technical report, in order to overcome this criticality, suggests integrating training and on-the-job training already provided for traditional PPE, with al least the following topics:

- purpose of introducing the IoT system;
- functionality of the IoT system;
- communication technology adopted;
- data collected, transmitted, processed and archived and the policy for data managing;
- specificities relating to the PPE with the IoT system;

- any changes to business procedures following the introduction of the IoT system;
- improvement in the management of safety and emergencies;
- the impact and consequences on the operator as regards health protection following the use of PPE with IoT system.

For smart PPE that is capable of data collection, the users must be well informed about what data are collected and what is done with them (with regard to evaluation but also storage). In particular, when it needs to handling workers' data, the general data protection regulation (GDPR) and the worker's contract rules has to be followed.

3.3 Risk assessment related to the use of IoT system

Using smart PPE provides some opportunities but also brings some challenges and the possibility to introduce new risks.
The document shows both:

- technical and technological aspects related to the devices analysed highlighting the innovative prevention aspects of PPE;
- new risks to which the operator could be exposed. These risks must be adequately assessed to prevent potential damage and to prevent resistance, often strong, to the use by workers.

It is important to draw attention to carry out adequate risk assessment related to the use of IoT system, as reported in the par. 11. In particular, it must be considered exposure of wearer in vulnerable situations because of pacemakers or other prostheses and devices equipped with electronic circuit. Medical implants that may be disturbed by the electrical components because of the characteristics of devices, the anatomical localisation of implants, etc.; moreover, sensor may be disturbed by medical implants and do not work well.

3.4 Management and control of PPE

The risk of failure must be considered, too. The device equipped with tags needs to be managed similar to PPE, also considering the following activities:

- tag integrity check and periodic verification by means of tag reading device;
- checking the status of batteries for PPE with actives tags and any associated charge level control/alarm system;
- scheduled periodic maintenance of hardware components, if feasible.

4 Conclusion

Smart PPE is supposed to provide new possibilities for using PPE and to offer a higher level of protection, however, as described above, there are some obstacles their diffusion on the market. The first obstacle is the lack of test methods to ensure compliance with European Regulation; another is that Smart PPE is often associated with data capture, collection and transfer. Anyway, supported by appropriate

changes in the legislation and by workers' training, smart PPE has a great potential to make workplaces safer and healthier in the future. In Europe, the Uni Technical report 11858:2022 is the first document that offers solutions to these critical issues.

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Innovative technologies for radioactive waste management and treatment

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Abstract

Radioactive waste arises from all activities related to nuclear energy production (nuclear power plants and fuel cycle). Smaller, but significant amounts are produced in other activities such as medical diagnosis and therapy, production controls and scientific research.

Currently, most of the radioactive waste in Italy comes from the past nuclear program and is located at the four nuclear power plants, permanently shutted down in the 1980s (Trino, Garigliano, Latina and Caorso), and at the plants of Saluggia, Trisaia and Casaccia, which are no longer operational and are thus subject to their respective decommissioning programs. In addition to these sites, there are also all the healthcare facilities where radioactive substances are used, which generate a non-negligible amount of radioactive waste. In Italy Sogin is the State-owned company responsible for the decommissioning of Italian nuclear plants and for the management of radioactive waste, including those produced by industrial, research and nuclear medicine activities. Sogin is also involved in the siting, designing, building and operating of the National Repository and the Technology Park for radioactive waste long term storage and final disposal. It should be considered that while the so-called "energy" radioactive waste will end, once the decommissioning of all plants is completed, the healthcare-related production of radioactive waste will continue over the years. Therefore, these wastes require an ongoing management to guarantee citizens' safety, the safeguard of the environment and the protection of workers and future generations from radiological risks.

The work aims to examine the main technological, regulatory and safety aspects related to the management of radioactive waste produced in hospitals, industries and nuclear plants.

Current practices for waste classification, innovative technologies for their treatment and volume reduction, as well as requirements for safe storage or disposal will be examined.

1 Management and processing of radioactive waste

In Italy, Legislative Decree no. 101/2020 [1] establishes safety standards to protect people from risks associated with exposure to ionizing radiation in the industrial, medical, research and exposure to particular sources of natural radiation. It also regulates the safety of nuclear plants, installations and activities in which radioactive materials are used as well as the management of spent fuel and radioactive waste. Moreover the provisions of the Decree apply to shipments of radioactive waste, fuel and radioactive materials.

Radioactive wastes produced from the operation and decommissioning of nuclear facilities and from the application of radionuclides in industry, medicine and research, are classified by the Italian Ministerial Decree of 7 August 2015, accordingly to the type and quantity of radioactivity they contain and to their final destination. Five categories are considered: Very Short-Lived Waste (VSLW), Very Low Level Waste (VLLW), Low Level Waste (LLW), Intermediate Level Waste (ILW), High Level Waste (HLW). Each category corresponds to different management methods and disposal solutions of the radioactive waste.

Radioactive waste must be processed to make it safe for disposal. Processing actions includes treatment (such as mechanical, thermal or chemical processes of wastes) and conditioning (such as immobilisation). Secondary waste streams that may result from the processing of the primary waste stream must also be handled in a safe and efficient manner.

The final goal is to minimise the quantity and volume of radioactive wastes (via treatment processes) and put them into a form suitable for disposal or for long-term storage (via conditioning processes).

The selection of the different approaches and technologies for waste processing should be based on appropriate consideration of the characteristics of the waste and of the demands imposed by the subsequent steps in its management (transport, storage and disposal).

IAEA International Safety Standards provide fundamental safety principles and requirements, that must be met to ensure the protection of people and the environment, and recommendations and guidance on how to comply with the requirements.

At national level, ISIN (National Inspectorate for Nuclear Safety and Radiation Protection) Technical Guide No. 33 [2] establishes the safety and radiation protection criteria that must be respected, according to a graduated approach, for the correct and safe management of radioactive waste, considering the nature and radiological risk associated with each type of waste. The guide defines the minimum requirements of radioactive waste packages for the purpose of their management in the storage facilities at the production sites, as well as their future transferability to the long-term Italian National Repository.

2 Treatment and conditioning of radioactive waste

The main objective of radioactive waste management is to reduce the volumes to be disposed of, through efficient treatment and decontamination processes. This involves the use of appropriate techniques to reduce the quantity of waste to be disposed of and then perform a conditioning process in the final form, to ensure safe disposal. [3][4] Each type of radioactive waste undergoes different processes before disposal, mainly based on its characteristics. Treatment involves preparing the waste for the conditioning and/or disposal phase, reducing its volume through various techniques [5]

2.1 Chemical decontamination techniques

The objective is to remove surface contamination using water and steam (to dissolve chemical species by eroding and washing away loose debris), strong mineral acids, acid salts, organic/weak acids, alkaline salts, complexing agents, redox agents, organic solvents, detergents and surfactants. The removed wastewater may be further treated using ion exchange resins (to trap radionuclides) or evaporative processes (to separate liquids from radioactive sludge which is reconcentrated);

2.2 Mechanical decontamination techniques

Contamination is removed using methods such as water flushing, steam cleaning, dusting, CO_2 blasting, wet ice blasting, hydroblasting, ultra-high-pressure water cleaning, shot blasting, scrubbing, scarification, drilling, and spalling. Residual liquid waste can be further treated, while solid waste is ready for conditioning. Other decontamination techniques include electropolishing, ultrasonic cleaning, and vibratory finishing.

Large volumes of waste may need to be reduced using cutting techniques, such as thermal cutting and hydraulic cutting combined with mechanical methods.

In cases where workers cannot handle waste directly, due to the high levels of radiation to which they could be exposed, remote decontamination techniques are used using robots, drones, remotely operated vehicles (operating in confined spaces under negative pressure) and mechanical manipulators (installed in hot cells).

After treatment and before conditioning, radioactive waste volume can be further reduced using two main techniques:

- Compaction: the most commonly used technique [6] , involving pressing the waste to minimize its volume;
- Incineration: organic radioactive waste can be burned, transforming it into a more stable form (ashes) [7]. This technique is not accepted in some countries.

When waste volume cannot be minimized, the final step is the conditioning phase. Residual radioactive waste can be immobilized using three methods [8]:

- Cementation: widely used method [9]; it involves encapsulating waste in cementitious matrices to provide structural stability and limit radionuclide migration;

- Bituminization: radioactive waste is embedded in bitumen [10], which acts as a hydrophobic barrier and limits radionuclide migration;
- Vitrification: radioactive waste is converted into a glassy matrix through high-temperature processes[11], providing long-term durability and chemical stability. This process is used mainly for HLW radioactive waste.

After the conditioning process, radioactive waste can be disposed following the properly route.

3 Management of radioactive waste produced in hospital

Medical applications of nuclear physics are distinguished according to whether they use sealed or non-sealed sources: in the first case these are mostly radiotherapy applications oncology, in the second diagnostics and therapy with radiopharmaceuticals (nuclear medicine).

While the former involves managing disused radioactive sources, the production of waste radioactive materials that must be disposed is normally associated with the second activity.

The activity of a Nuclear Medicine Unit is divided into therapy and diagnostic sections. In both cases, patients are administered with radiopharmaceuticals, that are radioactive pharmaceuticals for diagnostic or therapy purpose.

The 2022 Inail guidelines “Design of a site for handling of unsealed sources and for production of radiopharmaceuticals” provide practical suggestions, in compliance with Italian Legislative Decree n. 101/2020, about the design of a ward of Nuclear Medicine, including radiation protection aspects related to contaminated waste.

3.1 Diagnostics sector

The acquisition of diagnostic examinations, such as PET/CT and SPECT/CT, requires the administration of specific radiopharmaceuticals. The correct dosage of radiopharmaceutical is prepared by a trained technician of nuclear medicine, based on the prescription of a nuclear medicine physician.

After administration and until the exam acquisition, the patients wait in a dedicated room inside the nuclear medicine unit for an interval of time compliant with the pharmacokinetics of the radiopharmaceutical. Throughout this time, patients and workers produce a variety of waste, which can be contaminated by the most used radioisotopes in a nuclear medicine unit or by radio-activated substances (as in case of induced radioactivity produced by cyclotrons).

The most used isotopes in a traditional diagnostic section are 18F, 68Ga, and 99mTc (half-time respectively: 1,83h, 1,13h, 6h). They do not evaporate easily and their disposal (as solid, liquid or gaseous waste) from the regulatory regimen occurs in most cases in compliance with the non-radiological relevance criterion, which is respected when: the practice is justified; the risks caused to individuals from the practice are low enough to be considered negligible; the practice can be considered intrinsically safe, with no significant chance of occurring situations, that conduct to

the non-compliance of the previous points. Hence, a practice can be considered without radiological relevance, when in all realistic possible situations, the effective dose to any persons of the public is inferior or equal to 10 μSv.
Thanks to their short half-times (lower than 60d), the solid waste contaminated with these radioisotopes can be stored in a dedicated storage for a time estimated by the Radiation Protection Expert, a central figure defined at Article 7 of Legislative Decree n. 101/2020, to ensure the safeguard of people against the risks derived from ionizing radiations, who has competence, education and experience necessary and compliant with Article 130 of Legislative Decree n. 101/2020. This waiting time is necessary so that the activity concentration decays below the limits indicated by the Italian law, respecting in this way the non-radiological relevance criterion.
Before the disposal, it is recommended to perform a measurement of the solid waste with an appropriate device, such as a contamination monitor or a gamma spectrometer, to confirm that the procedure of management of the contaminated waste has been correctly applied. It is even possible to use compact systems for the measurement of solid waste containers, which at the same time work as contamination monitor and scale.
As regards the liquid waste, the most representative example is the contamination with isotopes with very long half-times (e.g. radioinduced activity with half-time higher than 60 days originating from cyclotron activity and following pharmaceutical synthesis), which do not permit to store the waste for a limited time in a storage and to respect the activity level required by the Italian law for disposal. Hence, whenever the non-radiological relevance criterion (and any disposal equation) cannot be respected at all or in an appropriate time of decay by keeping waste in a storage inside the hospital (e.g. solid waste produced during maintenance of a cyclotron contaminated by isotopes with a very long half-time, or liquid waste of a radiopharmacy lab contaminated by isotopes with very long half-life, radioisotope generators whose parent isotopes have long half-lives, etc.), these materials should be committed to an operator specialised in transport and logistic services of radioactive materials/waste.
As regards the gaseous waste, they are particularly important where an installation for the production of radioisotopes, such as a medical cyclotron, is present. In this case a monitoring system of the air collected by the different rooms of the installation is necessary, with the aim to control that the potential contamination of the air inside the installation cannot be disposed in the environment. Specific pre-alarm and alarm thresholds can be set in the monitoring system, so that the radioactivity in the air disposed through the chimney (after filtration) can respect the non-radiological relevance criterion. In case of alarm, the air inside the installation should be confined in the unit, until activity values decrease to authorized limit, defined through a disposal equation.
In a traditional diagnostic ward, instead, the gaseous contaminants in air are not common and they are hold by high efficiency filters (e.g. HEPA or activated carbon

filters, periodically replaced and disposed of correctly after the decay of any residual radioactivity) installed in the manipulation cells and in the chimneys, before the disposal in the environment.

3.2 Therapy sector

Nuclear medicine therapy is a medical specialty that uses radiopharmaceuticals to treat various diseases, primarily cancer; Iodine-131, introduced into clinical practice in the 1950s and 1960s, has always been considered the primary radionuclide used in nuclear medicine therapy.

The last few decades have seen the introduction into clinical practice of new radiopharmaceuticals labelled with radionuclides that emit alpha or beta particles, such as 177Lu, 223Ra, 225Ac. The growing interest in alpha particles is due to their ability to deposit high energy per unit path and to their ability to produce the breakage of both DNA strands and therefore a greater cytotoxic effect on the tumour cell.

In compliance with Legislative Decree n. 101/20, in case of administration of activity of 131I greater than 600 MBq, the hospitalization in a protected room and the collection of radioactive fluid are necessary. In all other cases of radiopharmaceutical administration for therapeutic purposes, the need of hospitalization is assessed by the medical specialist on an individual basis, after consulting the medical physicist and the radiation protection expert.

A nuclear medicine department for therapy must guarantee adequate spaces for workers and patients, such as protective rooms with toilets connected to the radioactive waste collection system, adequate spaces for the storage and decay of the produced waste, radiation monitoring system for patients and operators, adequate shielding.

The radioactive waste produced in the nuclear medicine therapy unit consists mainly of solid waste (such as waste from hospitalisation, waste from the preparation of radiopharmaceuticals, biological waste produced by patients, waste from the decontamination of surfaces), liquid waste (any residues of radiopharmaceuticals or liquid effluents) and gaseous effluents.

Solid and liquid waste produced in the context of nuclear medical therapies is, in almost all cases, classified as biological and infectious waste, and must be compliant with Legislative Decree n. 101/20, since it contains radioactive substances at the time of their packaging. It is particularly important to carry out a collection of waste containing traces of radioactivity as more differentiated as possible, depending on the half-life and characteristics of the contaminants.

The solid waste produced can be kept in a temporary storage before the disposal as solid hospital waste, in accordance with authorization regimen (Article—54). Alternatively, they can be committed to an operator specialised in transport and logistic services of radioactive materials/waste, who requires compliance with the obligations in Article 56 (labelling, correct packaging, STRIMS compliance etc.).

In compliance with Legislative Decree n. 101/20 a special register of radioactive waste should be established. The register should contain all data relating to the disposal of solid waste, such as the list of radionuclides present in the solid waste, the activity of each radionuclide at the date of the disposal and the mass of the solid waste.
Patient excreta collected during hospitalization are directed in a system of decay tanks before being released into the public sewer system. The volumetric dimensions of the tanks must be calculated based on the expected workload, in terms of isotopes used and their quantities in authorization. A subsequent spectrometric analysis of the content of each tank after an adequate decay allows to verify the achievement of the permitted activity levels and the subsequent discharge into the public sewer system, thanks to an automatic sampling chain.
In addition, Legislative Decree n. 101/20 requires the evaluation of the effective dose to the representative person of the population resulting from the release of radioactive waste into the environment.
The environmental impact assessment is carried out through the application of models that consider all the critical pathways of return to humans of radioactive substances released into the environment [12].
The definition of the disposal formula that demonstrates the non-radiological relevance is calculated starting from the estimate of the activity released into the environment directly from the structure and applying the screening factors that consider all the critical pathways of return to humans for each route of release of radioactive substances into the environment.
Nuclear Medicine therapy activities do not normally involve the production of gaseous radioactive effluents of appreciable amounts that do not guarantee compliance with non-radiological relevance.
The air exhaust chimney of the areas at major risk of contamination are equipped with absolute and/or activated carbon filters capable of intercepting any gaseous effluents, periodically replaced and disposed of correctly after the decay of any residual radioactivity. The rooms of the unit are generally equipped with an environmental radioactivity monitoring system equipped with alarms to measure the levels of radioactivity inside the rooms of the section in which radioactive substances are handled and/or used, and in the extraction ducts.
However, it is possible to carry out some precautionary estimates to demonstrate compliance with radiological non-relevance, through compliance with the discharge formula.
Recently, alternative solutions for waste collection have been introduced to the market, i.e. toilets equipped with filters with a high filtering power for 177Lu (up to 99.95%).
These filters are shielded with lead and it is possible to store them for an adequate time until they are removed in compliance with the non-radiological relevance.
This type of product can be connected to the tanks in the nuclear medicine department. By introducing filtered water into the tanks, this solution is particularly

useful in cases where the volume and therefore the decay time of the existing tanks is not sufficient to handle an increase in radiopharmaceutical therapies.

4 Management of radioactive waste in industrial activities

Industrial activities generate various types of radioactive waste, which require specific treatments to ensure proper disposal and environmental safety. The main sectors involved include the nuclear industry, which produces waste from the decommissioning of facilities, including metallic components, resins, sludge, and liquid waste. Fuel reprocessing plants also contribute, generating high-activity liquid waste and solid materials.

Oil and gas industry with mining activities produce naturally occurring radioactive materials (NORM), such as sludge and scale.

Quality control and food sterilization industry, which employs radioactive sources for product irradiation, also add to this waste stream.

Finally, other industrial sectors, such as electronics manufacturing, generate waste from measuring devices containing small radioactive sources. This waste is usually collected, treated, and temporarily stored in anticipation of a final disposal site.

The following is a more detailed overview of radioactive waste from industrial activities.

4.1 Nuclear Industry

The nuclear industry is one of the main sources of radioactive waste, generated from various stages of the nuclear fuel cycle and from decommissioning activities. Waste varies in type and radioactivity level, and includes solids, liquids, and gases, each requiring specific management methods.

Most part of radioactive waste in the nuclear industry comes from the decommissioning activities of nuclear power plants, in particular, in addition to process fluid, there are contaminated metallic components and irradiated concrete structures. After decontamination and treatment, part of these materials can be recycled and/or considered as “normal waste” (through clearance process) [13], while the radioactive part is conditioned and disposed taking into account its activity level. Some materials, as resins used for filtering liquids and sludges from water treatment, are directly conditioned and disposed.

Another source is everything that comes out of reprocessing plants and fuel manufacturing, for the most part HLW type. In this case, it is possible to recover and recycle also part of treatment waste, as depleted uranium and other materials useful for activities involving radioactive sources [14],[15].

4.2 Oil and gas industry

The oil and gas industry is another important source of industrial radioactive waste [16], generated both from the use of radioactive sources for industrial purposes and the management of Naturally Occurring Radioactive Material (NORM). The waste

produced varies in type and radioactivity levels, including solids, liquids, and sludges, each requiring specific management methods.
Most radioactive waste in the oil and gas sector comes from maintenance and decontamination operations on infrastructures. For instance, scale deposits and sludges contaminated with NORM accumulate during hydrocarbon extraction and transport activities. These materials contain natural radionuclides such as 226Ra, 228Ra, 210Pb and 210Po [17], that require specialized treatment for equipment decontamination and subsequent disposal in suitable facilities.
Another significant source of waste arises from the use of sealed and unsealed radioactive sources for industrial purposes. Sealed sources, such as 192Ir, 137Cs and 241Am-Be, are used for industrial radiography and well-logging measurements [18], [19]. Once depleted, these sources must be safely disposed of according to strict regulations or returned to suppliers for recovery or treatment. Unsealed sources include radiotracers and radioactive markers used to monitor fluid flows or detect leaks in systems, generating contaminated waste that requires specific handling and disposal.
Finally, maintenance processes and accidents may contribute to the production of additional radioactive waste, such as contaminated materials or residues resulting from recovery and decontamination interventions. Depending on their activity levels, such waste is treated, conditioned, and disposed of following rigorous safety standards to protect workers, the public, and the environment.

4.3 Radioactive waste from mining and milling activities

The management of radioactive waste from mining and milling activities presents a complex challenge due to the large volumes of material and the presence of long-lived radionuclides, such as those associated with uranium and thorium ores [20], [21]. The waste generated includes processing residues (tailings), mineralized rocks, process water, and emissions of radon and dust.
Managing this waste involves several options, including disposal in surface or underground facilities with low-permeability barriers, engineered covers to limit infiltration, and the stabilization of contaminants by cementation (up to ILW) and/or vitrification (HLW). It is essential to implement measures that restrict access and limit radionuclide dispersion over extended periods, thereby minimizing environmental impact and health risks.

4.4 Quality control and food sterilization industry

The quality control and food sterilization industry frequently use sealed radioactive sources to ensure product safety and extend shelf life. Technologies such as gamma irradiation, often employed to eliminate microorganisms and parasites, utilize radioactive isotopes like 60Co. Once depleted, these sealed sources become ILW or LLW, depending on their residual radioactivity. Such waste requires specific

management methods, including adequate shielding and disposal in authorized facilities, to minimize risks to the environment and public health.

4.5 Radioactive waste in electronics and other industrial activities

Radioactive waste in electronics and other industrial activities (different from those mentioned) represent an underestimated environmental and health risk. On some occasions, radioactive elements found in electronic devices, waste produced from the processing of sources for medical use and scraps from gauges utilized for process control in industry have been recycled accidentally without proper precautions, leading to contamination of the entire recycling facility [22], [23], [24]. Devices such as smoke detectors, lightening emergency exit signals and old luminous watches, contaminated medical equipment, and industrial instruments could contain traces of radioactive elements (as 241Am for smoke detectors, tritium for signals and watches, etc.).

In recent decades, some of these devices, while still in use, are no longer produced, or their production has been significantly reduced. However, the risk persists, especially with older devices that might be improperly disposed of. The main challenge in managing this type of waste is to identify the radioactive sources in devices, as not all of them containing radioactive isotopes are easily identifiable, and due to a lack of adequate knowledge, some were disposed of as ordinary waste, thus becoming orphan sources [25].

Once identified, these sources can be decontaminated and treated in the most appropriate way.

5 Research and Innovation in Radioactive Waste Management

Technologies and practices for radioactive waste management are well advanced but further optimisation can bring more economical, sustainable and environmentally friendly waste processing practices. In addition, some challenging waste streams (e.g. graphite, organic waste, reactive metals and future generation wastes, like molten salt reactors) have not yet a mature and consolidated treatment technologies and RD&D activities are needed to develop solutions for such problematic waste management.

Research should be aimed at developing, in a short time, concrete solutions to demonstrate the feasibility of appropriate treatment processes and the possibility of adapting techniques used at industrial level on conventional waste to the nuclear field should considered.

The needs for R&D are, in most of the cases, common to many countries and the sharing of experiences between countries with more advanced programs and countries that have limited quantities of waste and less advanced nuclear programs should be encouraged.

The Directive 2011/70/EURATOM establishing a community framework for the responsible and safe management of spent fuel and radioactive waste. Adopted by

the Council of the European Union on 19 July 2011, it provides binding legal force to the main internationally endorsed principles and requirements in this field.
The Directive explicitly requires (Article 8) that "Member States shall ensure that the national framework require all parties to make arrangements for education and training for their staff, as well as research and development activities to cover the needs of the national programme for spent fuel and radioactive waste management in order to obtain, maintain and to further develop necessary expertise and skills".
Dedicated R&D programmes and Knowledge Management activities are usually initiated by the relevant stakeholders at the national level and in addition to this, the Euratom Research and Training Programme has been implemented by the European Commission, under the provisions of the European Atomic Energy Community (Euratom) Treaty, to supplement and coordinate the Member State programmes to perform joint cutting-edge research and to support knowledge generation and preservation.
A 5-year framework programme (with a 2-year extension) is implemented via annual or biannual work programmes publishing calls for proposals which are evaluated by independent experts. The selected research projects are then funded up to a duration of five years.
Italy via Sogin is participating to different EU Research funded projects and among the others the following two are focused on R&D activities for Radioactive Waste Management:

- PREDIS (Predisposal Management of Radioactive Waste): 4 years project ended in August 2024, aimed at identifying, developing, and improving innovative technologies in predisposal of low and intermediate level radioactive waste. The project targeted metallic wastes, liquid and solid organics and concrete waste packages long term monitoring.
- EURAD-2 (European Partnership on RWM): started on October 2024, it is a 5 years project that gathers 120 organisations from across 21 European countries and 23 International partners. In accordance with the Waste Directive, EURAD-2 is supporting the Member States in developing and implementing their national RD&D programmes for the safe long-term management of their full range of radioactive waste taking into account the various stages of advancement of national programmes. EURAD-2's vision is deployed into a set of 18 Work Packages and covers all phases of the Waste Management programme, including predisposal and disposal, through the development of a robust and sustained science, technology and knowledge management programme that supports timely implementation of RWM activities and serves to foster mutual understanding and trust between Joint Programme participants.

In addition to the EU Research funded projects, to solve some specific issues and find solutions for the safe management of specific waste streams existing in some of the Sogin sites, dedicated R&D activities have been conducted on-site, and innovative solutions have been internally developed and briefly reported in the following:

- In Bosco Marengo site, a multiphase radioactive liquid waste, characterized by the presence of three different stratified phases (oil, water and sludge), posed significant challenges to waste management because of the presence of hazardous and non-standard components. In order to enhance the safe waste management on site and to fulfil the criteria for the future transport to the National Repository for final disposal, a specific test program has been developed. It is based on the use of two different solidifying agents: high technology polymers for the oily phase and cement for the aqueous one. The design and realization of the mixing system has been included in the project. The final product obtained at the end of the solidification process is a monolithic solid material that can be managed as a solid radioactive waste ready to be conditioned for the final disposal. After the approval of the process by the Italian Safety Authority, the activity started, and the radioactive waste treatment and conditioning has been completed in December 2021.
- To find a solution for the management of small volume of alpha contaminated liquid waste existing in the Sogin Casaccia Plutonium Plant, an innovative treatment and conditioning system consisting of equipment and components installed in a small volume process system inside a glove box, has been designed and developed. The system allows, in an enclosed alpha-sealed environment, to perform semi-automatic handling operations aimed at cementing alpha contaminated aqueous liquid waste and consists in the simplification and reduction of components and equipment normally used in large industrial plants. It offers the nuclear decommissioning sector a solution to treat and condition small volumes of liquid waste without having to build complex industrial plants that involve long authorization procedures, environmental impacts and significant construction and management costs. The process components and the process operation scheme have a great flexibility to be adapted for treatment and conditioning of different type of liquid radioactive waste and the full system has been designed to be easily decontaminated in order to be reused for future conditioning campaign and finally easily dismantled.

6 Conclusions

The innovations introduced by Legislative Decree no. 101/2020 and subsequent amendments, ISIN Technical Guides and sector-specific Italian standards [26] represent an important step forward in the safe and transparent management of radioactive waste produced in Italy, aligning the country with international and European standards.

One of the difficulties in managing radioactive waste is the progressive decrease in available storage space; this leads to the proliferation of temporary storage sites across the national territory.

Technologies and practices for radioactive waste management are well advanced but further optimisation can bring more economical, sustainable and environmentally

friendly waste processing practices. In addition, some challenging waste streams (e.g. graphite, organic waste, reactive metals and future generation wastes, like molten salt reactors) have not yet a mature and consolidated treatment technologies and RD&D activities are needed to develop solutions for such problematic waste management. Research should be aimed at developing, in a short time, concrete solutions to demonstrate the feasibility of appropriate treatment processes and the possibility of adapting techniques used at industrial level on conventional waste to the nuclear field should be considered. The needs for R&D are, in most of the cases, common to many countries and the sharing of experiences between countries with more advanced programs and countries that have limited quantities of waste and less advanced nuclear programs should be encouraged. Modifications will be soon introduced in the radioactive waste management program, according to the requests of the European Commission (ref. doc n.2020/2266). Therefore, it is crucial to develop effective techniques for reducing the volumes and isolating the radioactivity of radioactive waste, as well as the timely construction of the National Repository.

7 References

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Using augmented and virtual reality, integrated with ai, as tools for occupational health and safety training. considerations from a regulatory point of view

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Abstract
The use of augmented and virtual reality technologies is on the rise in several European countries also as learning tools for occupational health and safety training. Without doubt, this is due to the growing combination of such technologies with artificial intelligence which enables the creation of realistic simulations of complex conditions, allowing users to practice and interact in safe environment. However, there is still no specific regulation, at national or European level, regarding the validity of using these tools for occupational health and safety training, unlike the case of AI: the AI Act, published in the Official Journal of the European Union, regulates exactly and punctually the planning and use of new information systems, also guaranteeing an uniform regulation activity. This paper focuses on this deficiency. The main reasons for assessing the validity of the use of augmented and virtual reality will be analysed, obviously in accordance with the requirements of Directive 89/391 ("framework directive" on OSH); the first step will be the analysis of the Italian regulatory background in which the INAIL research activities is recalled by the Ministry of Labour in support of how these new technological solutions can contribute to training in health and safety at work.

1 Introduction

The use of Virtual Reality (VR) and Augmented Reality (AR), integrated with Artificial Intelligence (AI), has seen significant development in workplace safety training, especially in environments that require continuous updates and management of complex risks. These technologies make training courses more immersive, personalized, and interactive, improving their effectiveness and safety. VR/AR, in fact, keeps attention higher than traditional courses, enhancing the retention of information through practical experiences. Workers can experience dangerous situations firsthand and repeat modules until they master them. Furthermore, AI allows training to be tailored to individual needs, making it accessible at various levels of language proficiency and education, detecting potential difficulties and intervening with simplifications or translations. In this sense, workers who do not speak Italian properly could benefit from specific explanations in their native language, also

supported by graphs or images that improve the understanding of concepts. Additionally, multilingual technology can enhance the training experience through the use of interactive avatars, which are further revolutionizing learning. Interactive avatars, which can simulate, for example, safety experts giving instructions or providing suggestions, make training and education more accessible through clear and specific communication. AI can analyze progress and suggest additional modules for those who need to delve deeper into specific topics.

To date, however, there is still no specific regulation at national or European level regarding the legitimacy of using such tools for mandatory training, unlike what has happened with AI: the new European Regulation, published in the Official Journal of the European Union, precisely and clearly regulates the programming and use of new computer systems, also ensuring a unified legal framework. This paper focuses on this gap. It will analyze, both from a jurisprudential//legal and technological perspective, the use of AR/VR tools, in compliance with the requirements set forth by Directive 89/391 ("framework directive" on OSH), starting with an examination of the Italian context, where, among other things, the activities of INAIL within the memoranda of understanding signed with major industrial groups are referenced by the Ministry of Labor to support how these new technological solutions can contribute to training on health and safety at work. Moreover, the Commission for inquiries on health and safety at work of the Ministry of Labor and Social Policies intervened on the issue of using VR in training courses on health and safety at work, following an inquiry proposed by the University of Siena.

In the inquiry no. 3/2024 submitted by the University, it is highlighted how new technological methods could also respond to the guidelines set by Article 20 of the Decree-Law of April 30, 2022, no. 36, in which immersive vision devices and AR are identified as possible tools to face accidents in the implementation of the National Recovery and Resilience Plan and to improve health and safety standards at work. In response to the aforementioned inquiry, the Commission clarified the possibility of using "virtual reality as a learning method and the effectiveness of mandatory training and updating courses pursuant to Article 37 of Legislative Decree no. 81/2008." The Commission clarified that virtual reality can indeed be used in mandatory training and updating courses on health and safety at work. In formulating its response, the Commission refers to the current regulations and agreements in this area, starting with an analysis of Article 37 of the above-mentioned decree, which establishes that each worker must receive from the employer "sufficient and adequate training in health and safety matters." The same Commission then refers to the "methods of delivering training and teaching/learning methodologies" outlined in the Agreement of December 21, 2011, between the Minister of Labor, the Minister of Health, and the regions and autonomous provinces of Trento and Bolzano. For ensuring an adequate training in health and safety, the agreement provides, among other aspects, to promote "innovative learning methodologies, including e-learning and the use of multimedia languages, ensuring the use of IT tools as a means by which to

disseminate training content, also to better reconcile professional and personal life needs of both learners and teachers."
In essence, therefore, in Italy the Ministry of Labor has granted substantial authorization to use new technologies in the field of mandatory training according to the Consolidated Law on Health and Safety at Work, but the teaching and learning methodology, already provided for, is always respected, namely: balance between lectures and exercises, development of interactive methodologies, provision of simulations and practical demonstrations and, where possible, the use of eLearning methods. Not only that. Article 20 of the Legislative Decree of April 30, 2022, no. 36, entitled: "Measures to face the accident phenomenon in the implementation of the National Recovery and Resilience Plan and to improve health and safety standards at work" is also referred to. In this context, INAIL promotes "specific memoranda of understanding with companies and large industrial groups" with respect to training in health and safety, which may also include research and experimentation of new technological solutions: advanced robotics, exoskeletons, sensors for monitoring work environments, innovative materials for work clothing, immersive vision devices and augmented reality are the new frontier of evolution in this field which, among other things, can also contribute to improving sustainability, which has now become an essential objective for any organization.

2 Definitions of Virtual Reality, Augmented Reality and Artificial Intelligence

A review of the concepts and terminologies related to VR, AR, XR and the metaverse reveals an heterogeneous use of several terms to describe the same types of hardware and applications. This is confusing for scholars and experts reading the published literature, as it is not immediately evident what type of technology is being referred to in a given context.There have been recent efforts to standardise the terminology. In this paper we have chosen and used the following:
VR is defined as an immersive experience in a visually isolated three-dimensional space, without meaningful interaction of the user with the physical world outside the simulation;
AR is defined as an experience that integrates virtual elements into the user's physical space, with varying degrees of integration of the virtual elements into the physical space;
An *AI system* is a machine-based system that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments. Different AI systems vary in their levels of autonomy and adaptiveness after deployment.

3 European and national legislation for mandatory training of workers and use of innovative technologies

In order to use VR/AR tools integrated with artificial intelligence in workers' training, it is necessary to comply with various regulations, ranging from workplace safety to personal data protection, as well as considering legal and ethical implications. Below is a summary of the main references at the European and Italian levels.

3.1 Health and safety regulations at work

Article 153 of the Treaty on the Functioning of the European Union gives the EU the power to adopt directives in the field of occupational safety and health. The Framework Directive, with its broad scope, and the additional European directives focusing on specific aspects of occupational safety and health lay down minimum health and safety requirements. Member States are free to adopt more stringent rules for the protection of workers when transposing EU directives into national law. Therefore, legal obligations in the field of occupational safety and health may vary between EU countries. At European level, the Framework Directive on Safety and Health at Work (Directive 89/391/EEC), adopted in 1989, was a milestone in improving safety and health at work. It ensures minimum health and safety requirements throughout Europe, while Member States, as as already highlighted, are allowed to maintain or establish more stringent measures. It requires companies to provide continuous and adequate training on occupational risks and therefore VR and AR technologies, although innovative, must be used in full compliance with the adequacy prescribed by the Directive itself. In Italy, Legislative Decree 81/2008 (Consolidated Law on Health and Safety at Work) transposing the Framework Directive, establishes that worker training is a fundamental requirement to ensure their health and safety. The introduction of AR/VR and AI in training programs, must respect the safety principles provided for by law.

3.2 Technology Safety Requirements

The adoption of AR/VR devices or AI solutions in mandatory training programs requires that these technologies be safe and compliant with European and national safety standards. For example, devices such as AR glasses or headsets must be certified to ensure they do not harm users and do not pose dangerous interference in the work environment.

3.3 GDPR Compliance and Data Collection and Security

AR/VR and AI technologies must be designed to protect the collected data by employing advanced security measures, such as encryption, to ensure sensitive information is not vulnerable to breaches or unauthorized access. Using AR/VR and AI technologies involves the collection and processing of workers' data, including biometric or behavioural information, which may relate to their health, training performance and progress. In this context, personal data protection must strictly

comply with Regulation (EU) 2016/679 (GDPR), which establishes stringent rules on personal data protection, requiring companies to ensure the security and privacy of processed data even during training. Specifically, GDPR requires companies to:

1. *Collect only necessary data:* During training with AR and AI, data collection should be minimized. For example, only errors in learning processes could be recorded instead of collecting more detailed information about worker behaviour.
2. *Provide informed consent:* Before collecting and processing data, companies must inform workers about the data to be collected, how it will be used, and who will have access to it. In general, explicit consent from workers must be obtained; this requirement should also be implemented during the training process.
3. *Ensure data security:* Companies must employ security measures to protect sensitive data, such as encrypting data collected during the use of AR/VR and AI technologies. Access to data must be restricted to those with legitimate training or safety monitoring needs.
4. *Facilitate data subject rights:* Workers must have easy access to information about their data, request correction of inaccurate ones and, in some cases, request deletion or limitation of their data processing. These rights must also be ensured for workers during the training activities.

Moreover, AR/VR technologies can be combined with IoT (Internet of Things) sensors and monitoring systems to detect workers' behaviour in real time during training. These devices can collect data on body movements, stress levels, posture, and task completion. AI systems can then analyze this data and adapt the training based on specific needs.

If the AI system, used in training, collects such data (e.g., analysing workers' facial expressions or posture to monitor their reactions or safety during training), the GDPR requires that they must be handled with particular care, as it is considered sensitive data. This necessitates an additional level of protection, a clear justification for its use and explicit consent from the workers involved.

3.4 Ethics of Artificial Intelligence: AI Act

Another critical dimension concerns the ethical implications of the use of AI. Although AI can optimize personalized learning, the collection of large amounts of data on workers can raise concerns about surveillance and control. It is essential that companies balance the use of advanced technologies with the protection of workers' dignity, ensuring that the data collected is used exclusively to improve training and not for the purposes of excessive surveillance or automated decisions. The first ever comprehensive legal framework on AI worldwide is the AI Act is (Regulation EU 2024/1689). It sets out a clear set of risk-based rules for AI developers and deployers regarding specific uses of AI. More specifically, it assigns applications of AI into four risk categories: *unacceptable risk* (AI systems considered a clear threat to the safety,

livelihoods and rights of people), *high risk* (AI use cases that can pose serious risk to health, safety or fundamental rights), *limited risk* (associated with a need for transparency) and *minimal risk* (there aren't rules introduced for AI systems that are deemed minimal or no risk).

3.5 Civil and criminal liability

Another aspect to consider regarding the use of AR/VR tools are the implications that may arise in terms of civil and criminal liability. Just think of the case in which an accident was to occur precisely because of a malfunction of an AR/VR device or in any case for a cause strictly linked to the technology used. In such a situation, in fact, problems relating to civil or criminal liability would arise, which would require a careful evaluation of the existing regulations, without neglecting that a regulatory adjustment would probably be desirable, in order to fill the gaps in this area.

4 State-Regions Agreement and mandatory training

The Consolidated Act establishes that the duration, minimum content and methods of training must be defined through an agreement within the Standing Conference for Relations between the State, Regions, and Autonomous Provinces, following consultation with social partners.

The use of AR/VR tools, as well as AI systems, in mandatory worker training programs could be considered valid under the State-Regions Agreement of December 21, 2011 (as updated in 2012 and 2016), provided that certain fundamental principles outlined by regulations and workplace safety guidelines are respected. The State-Regions Agreement establishes guidelines for worker training concerning health and safety risks in the workplace. It defines the training objectives and minimum content for mandatory training, as well as the course delivery methods, trainer requirements, and documentation to be provided.

Specifically, mandatory training must be tailored to the specific risks of each sector and include both theoretical and practical components. Simulation techniques (such as those provided by AR/VR) are allowed but must be applied in such a way that workers can face and understand real risks and correctly implement safety procedures.

It should be noted that the approval of the new State-Regions Agreement on Mandatory Training is still pending. The agreement was initially expected to be issued by June 30, 2022. A draft of the State-Regions Agreement framework, sent by the Ministry of Labor to the Department for Regional Affairs and Local Autonomies on October 17, 2024, outlines the new training paths for health and safety under Legislative Decree 81/2008. While it permits the use of simulation techniques, such as augmented reality, it does not address potential critical issues, such as reliability, transparency, vulnerability, and privacy protection.

These aspects must be carefully evaluated by the legislator to balance the benefits brought by AI without compromising data protection and transparency safeguards.

4.1 Personalization of Training with AI

An AI system can be used to personalize the training path, monitoring progress and adapting training content based on the needs of the worker. For example, AI can analyze a worker's performance in an AR simulation, detect errors and provide immediate feedback. As already said, the use of AI to track learning and personalize training is not in conflict with the current provisions of the State-Regions Agreement, as long as the objective of ensuring that every worker receives adequate training is respected. Furthermore, AI could also be useful for monitoring the effectiveness of training. Through the analysis of performance data, it is possible to continuously improve training courses, ensuring that all workers acquire the skills necessary to work safely. Technologies must be integrated so that the mandatory content and skills established in the State-Regions Agreement are respected, without altering their content or the method of practical application. The use of AR/VR tools and AI should, in fact, only be an innovative complement and not a substitute for the practices required by the legislation.

Moreover, according to the State-Region Agreement, training must be verified through a final assessment to ensure that the worker has acquired the specific skills mandatory to operate safely. In this context, AR/VR technologies and AI systems play a fundamental role, as they allow for tests and simulations within training courses in highly innovative ways. However, to comply with the prescribed regulations, the final assessment (intended to verify the assimilation of theoretical concepts and practical skills and the effectiveness of the training) must always follow traditional methods. From a jurisprudential perspective, in fact, the effectiveness of the training is closely linked to its actual effectiveness: training is not effective if it has not allowed the worker to concretely and genuinely assimilate the transmitted content, which must then translate into consistent and appropriate behaviour within the work environment.

5 Conclusions

The combination of AR/VR and AI represents an innovative frontier for training workers in terms of improving their effectiveness and personalizing training paths. However, the use of these technologies requires a solid regulatory basis that protects workers in terms of safety, privacy, and guarantees their rights. Innovative technologies with which training courses are delivered, including mandatory ones, must therefore be designed, implemented and adopted in accordance with current regulations and in consideration of all the issues that arise on the ethical level that must be addressed carefully to avoid abuse and ensure the well-being of workers. Therefore, it seems imperative that a solid regulatory construct be created that, like what has happened with e-learning training, clarifies the modalities, requirements, and even technical characteristics for this modality to be considered valid. It must also be ensured that such technologies do not create new risks, such as disorientation

or stress for workers when using AR/VR or managing AI algorithms that could cause poor decisions in critical contexts. Most of the literature on OSH implications of the use of VR at work focuses on ergonomic issues associated with the hardware that facilitates the VR experiences. Other OSH risks, especially those related to the psychosocial aspects associated with VR technology use and related to workers' mental health and wellbeing, generally less represented in the scientific literature, are presented below and can be divided into four areas (as described in "EU-OSHA" discussion papers):

Physical and ergonomic risks relate to the HMD's ergonomics (weight, form factor, wearability), blue light emission close to the eyes, the reduced need for physical movement during XR operations and potentially malfunctioning technology. Furthermore, cybersickness can be experienced due a combination of physical and ergonomic factors of HMDs.

Psychosocial risks relate to the potential of these technologies to cause stress due to the need to learn new skills and interact with new equipment, reduced physical interactions and interaction with peers, and isolation and risks related to the interaction with and between avatars. These also include sensory or cognitive overload, difficulty distinguishing between virtual and real environments leading to disorientation, and impacts on cognitive functions (attention, memory, spatial awareness).

Ethical-legal risks relate to the new and unregulated nature of the technology, the ethical implication of digital interactions, and the technical features of the technology that make them prone to privacy breaches.

Biological risks relate to potential pathogen contamination of the equipment worn by the user.

According to Legislative Decree 81/2008, the employer must ensure that mandatory training is adequate and that workers acquire the necessary skills to work safely. If VR/ AR and AI are used in this regard, the employer must ensure that these technologies are safe and do not expose workers to new or unforeseen risks; the training complies with current occupational health and safety regulations; the technologies do not replace practical training sessions but complement them; and workers are adequately informed about the use of the technologies, including the management of their personal data.

Without prejudice to the primary responsibility of the employer, who under current regulations is responsible for safety at work, as well as an active participant in a process of improving safety conditions in the workplace through periodic risk assessment, it must also be said that other figures must certainly be involved in this process.

Among these, certainly the Safety Manager, the Prevention and Protection Service Manager and the Responsible for Safety play a key role in the field of safety at work.

However, in the face of activities that cannot be delegated by the employer (such as the drafting of the document that follows the assessment of the risks present in the

working environments, contained in the "risk assessment document" and the appointment of the Prevention and Protection Service Manager), all other tasks can be delegated and the Employer remains obliged to supervise the activity of the delegate. Moreover, even the jurisprudential evolution in the field of safety at work, over time, has been characterized by a significant tightening of the position of the judges for all the figures involved and towards whom the legislation places a series of obligations (employer, responsible for safety, safety manager), precisely with a view to making as stringent and punctual as possible all those obligations incumbent on people charged with compliance with the rules designed to ensure safety and prevent accidents at work.
Therefore, in the light of the above, in anticipation of a necessary regulatory adjustment that codifies the usability of the new VR and AR devices (also integrated with AI) in the training courses on health and safety at work, it is desirable to involve all the subjects above mentioned and not only the employer.

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Inail research activities for enhancing safety in agricultural sector

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Abstract
The agricultural sector is one of the most affected by injuries and fatalities related to the use of tractors and the mobility of agricultural machinery. For this reason, Inail is focusing research activities on specific issues in this sector. In particular, the main activity focuses on the reduction of roll-over risk both for tractors and for self-propelled machines. For tractors, the design and implementation of an innovative foldable roll-over protective structure (QROPS) is described. QROPS is based on a four-bar linkage mechanism and equipped with sensors and controls to activate the foldable function by the operator from the seating position on tractor. Safety configuration (upright) is ensured by two innovative automatic locking systems. For what concern self-propelled machines, a digital terrain model (DTM) and a geographic information system (GIS) have been used to analyse areas with a high risk of roll-over, acquiring topographic parameters which allow to implement a digital terrain model with a resolution of 0.5 m. The digital terrain model has been used for the identification of the slope angular variations deemed to be significant with respect to machines stability. The result of the analysis consisted in false colours images according to the level of roll-over risk, superimposed on the aerial view in order to predict the stability of agricultural self-propelled machines prior they are used on the field. Finally, it is described the project Mobi.Ru.D. (Rural Mobility for Disabled Persons)is described, established with the aim of designing and building an electric-powered vehicle to promote the inclusion and reintegration in employment of physically disabled people with impaired mobility in agricultural and rural contexts.

1 Innovative foldable roll-over protective structure (QROPS)

In order to provide a more effective way to move foldable ROPS in upright configuration, an innovative highly automated ROPS has been designed. This foldable ROPS is based on a four-bar linkage solution equipped (hence QROPS) with an automated locking system and actuators for folding/unfolding controlled by the operator from the driving position on tractor. To assure a suitable strength in case of overturning, the QROPS was conveniently sized, taking into account the reference mass of the heaviest tractor model on which it will be fitted.

The study consisted of three main phases:

A- structure design;
B- selection of the best actuator system;
C- manufacturing of the ROPS and execution of experimental strength tests.

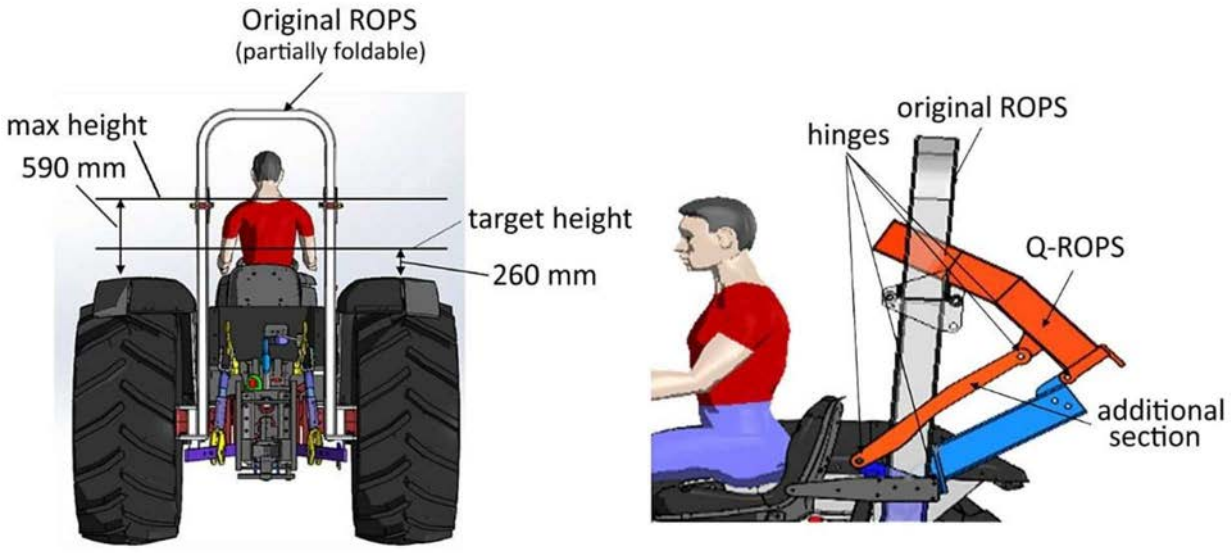


Fig.1. Original manufacturer partially foldable ROPS with respect completely foldable Q-ROPS.

A Phase

Taking into account the minimum height with the ROPS in upright (safety configuration) and the target height when the ROPS is folded down (see Fig.1) the original manufacturer's ROPS has been divided into three sections, determining the location of the hinge joints. A structural element was then added, to obtain a four-bar linkage with one-degree of freedom to be managed thanks to only one actuator.

B Phase

In order to maintain a low overall cost of the structure is provided with just one actuator easily connected to the tractor battery, without any need of further devices, apart the electrical wiring.

The electric actuator applied was supplied by a 12 V DC, 20 A current, developing a speed of 33 mm/s max and a load up to 18,000 N.

Functional and structural tests

Later, the prototype was subjected to a virtual test using Abaqus software for structural analysis following the requirements of the corresponding OECD Code. After this research step, a physical specimen of the rollbar, conveniently fitted on the tractor, was subjected to a real test, consisting in some horizontal and vertical loads. The only requirement for the positive outcome of both the virtual and real tests is that the so called "clearance zone" (i.e. a volume representing the driver's position normally placed on his/her seat and grasping the steering wheel) is protected against

the entry of any ROPS structural component and any possible terrain interference. Particular attention was devoted to the devices executing various movements of the QROPS, to assure maximum robustness in case of overturning and the best reliability in the time.

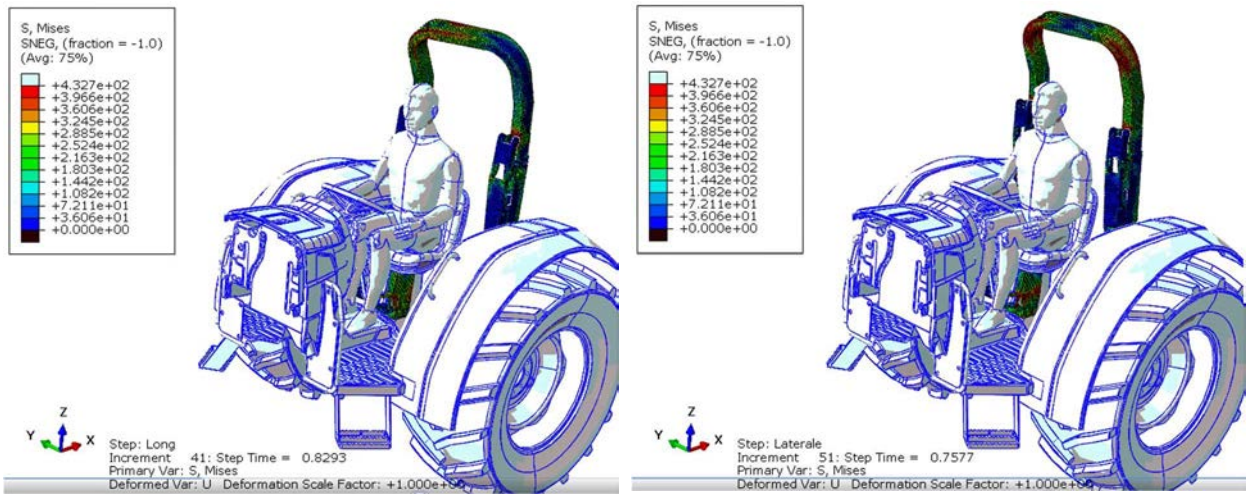


Fig. 2. Virtual test at maximum load value: side loading (on the left) and rear loading (on the right).

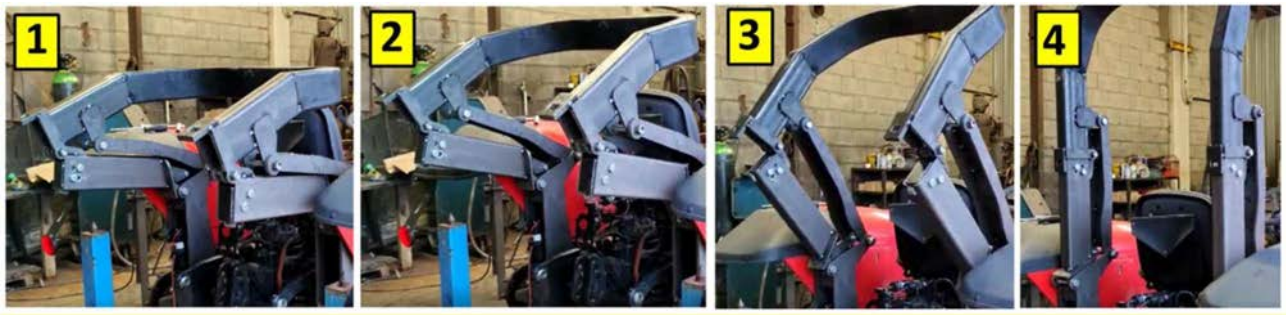


Fig. 3. Functional tests with the structure maneuvered by electric actuator.

Thus, the assisted system demonstrated its capacity to function as a fully deployable assisted rollbar; the Fig. *3* depicts the raising phases controlled by the actuator without the human intervention.

2 Roll over risk for self-propelled agricultural machines

The risk of roll-over for self-propelled machinery is unfortunately high in agricultura, with dramatic consequences for workers, as reported by numerous studies [1-3]. Thus, Inail developed a specific research activity which aims on one hand to design specific roll-over protective structure (ROPS) for aged agricultural machines still in use and, on the other hand, to determine in sample agricultural working areas the roll-over risk percentage when using self-propelled machines.

2.1 Material and methods

For what concern retrofitting ROPS on old agricultural self-propelled machines, the main steps of the applied methodology can be summarized as follows:

(1) by means of reverse engineering, the self-propelled machine is acquired and virtually prototyped in a CAD environment;
(2) the ROPS is designed and fitted onto the virtual model of the machine to check for consistency and suitability with respect to the geometrical features of the machine and its functionality;
(3) ROPS is virtually tested according to applicable testing codes or harmonized standards by means of finite element method in order to verify the structural strength and the capability of protecting operator's deflection limiting volume;
(4) ROPS geometry is then optimized according to results of step (3), if necessary.

Details of the steps above mentioned and examples of application can be found in [4].

However, the application of ROPS on self-propelled machines is not always possible or even necessary according to the series of harmonized standard EN ISO 16231. In these cases, the stability limits of the self-propelled machines play a relevant role. In fact, the machine shall not be used on slope higher than the prescribed static stability angle. For this reason, the Inail research activity focuses on how to detect the actual terrain slope before the machine moves on it. Thus, a digital terrain model (DTM) and a geographic information system (GIS) are used to analyse areas with a high risk of roll-over for agricultural self-propelled machines. This approach could be also applied to predict the risk of roll-over even for agricultural tractors. The result of the analysis consists in mapping the surfaces where self-propelled machines work on, in order to have a false color image with respect to the level of roll-over risk, superimposed on the aerial view. First of all, airborne LiDAR data of the area are acquired in order to develop a HR-DTM (High resolution Digital Terrain Model) of the area of interest.

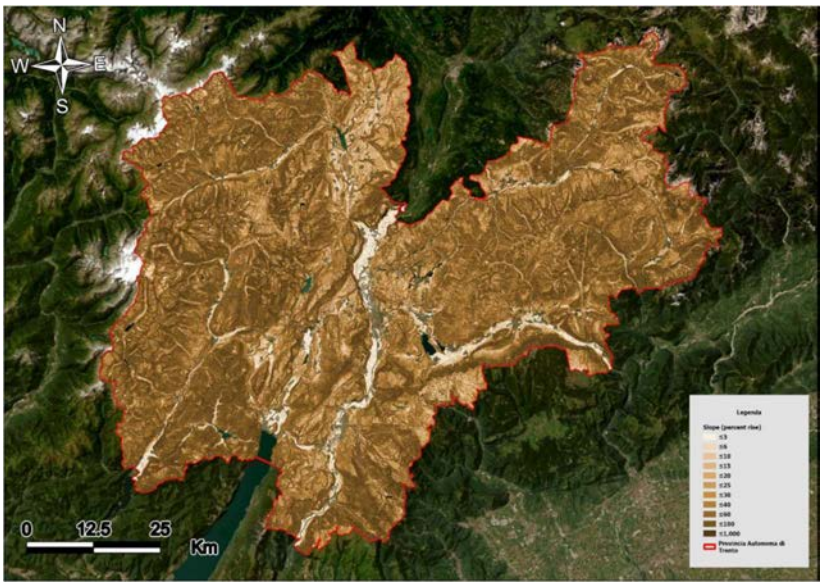


Fig. 4. Example of area of interest and relative slope

The methodology mainly required four processing steps:

(1) the automatic evaluation of a preliminary slope in percentage from the HR-DTM (Fig. *4*);
(2) reclassification of the preliminary slope dataset with respect to level of roll-over risk for each kind of agricultural machine, according to machine typology as per EN ISO 16231-2;
(3) statistical analysis of the acquired data for each machine's category;
(4) developing a zonal histogram on the vector parcels, to associate the amount of the area potentially exposed to roll-over/tip over risk (or tipping over) when using specific agricultural machines according to crop type.

As an example, represents the false colour diagrams for combine harvester without slope compensation system (type 1 machine) and for combine harvester with body levelling system (type 2 machine). The red area represents terrain where slope exceeds the lateral and/or longitudinal stability limits for the machine. Yellow area represents slope where only lateral stability of the machine is exceeded. Green area is where the machine can be used within its stability limits.

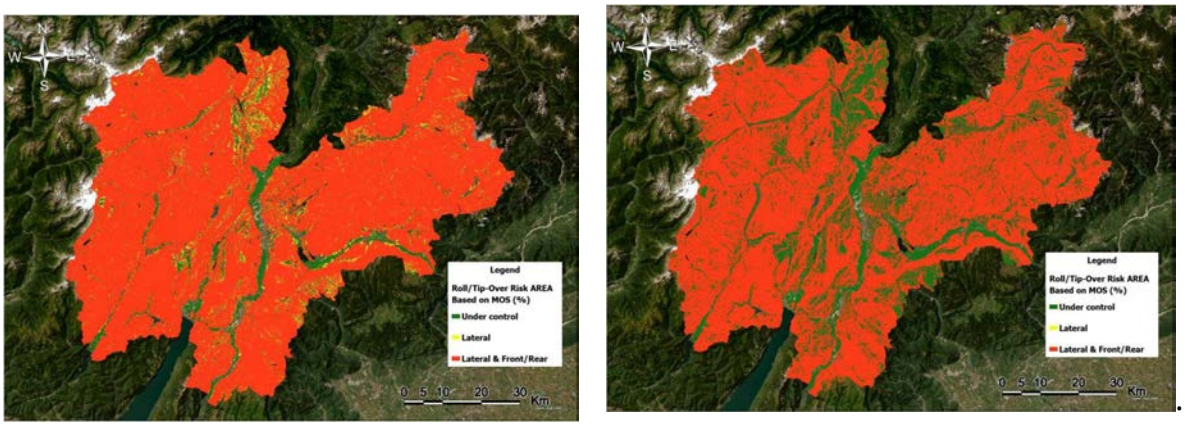


Fig. 5. – False colors images of digital terrain for detecting stability of combine harvester without (on the left) and with slope compensation system (on the right).

2 Mobirud

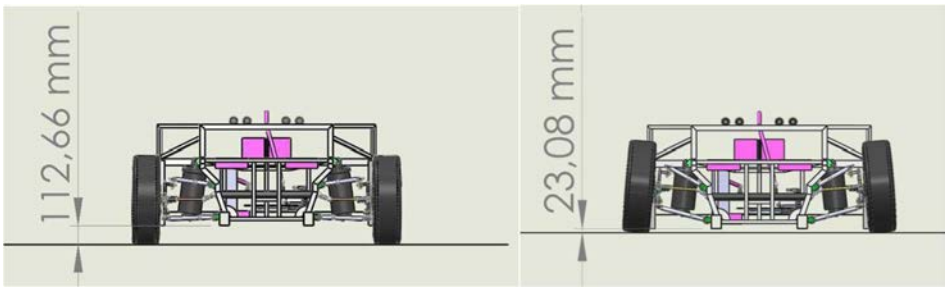
The high number of accidents caused by the overturning of tractors and self-propelled agricultural machinery in the agricultural sector causes dramatic consequences for workers, as reported by numerous studies [1-3], very often, even if the consequences are not fatal, they cause injuries with permanent damage to operators who are therefore no longer able to return to work activities by reusing agricultural vehicles.

Inail has therefore promoted, through the Bric 2019 call, a specific research activity aimed at the Rural Mobility of the Disabled to design and create an Full electric-powered vehicle (AWD) to promote the inclusion and reintegration into work of

people with physical disabilities and reduced mobility in agricultural and rural contexts. The Developed project called Mobi.Ru.D was therefore carried out with a collaborative research call financed by INAIL, which saw CREA - IT Research Centre for Engineering and Agro-Food Processing based in Monterotondo (RM) as the institutional recipient.
The vehicle is designed to give the indicated personnel the opportunity to carry out a series of work activities (for example, crop monitoring; active participation in harvesting operations; technical control and coordination of various company activities). The peculiarity of the vehicle is that it allows users to access the driving position with their own wheelchair, avoiding the need to move from the wheelchair to the driving position, in complete autonomy and safety.

Fig. 6. Prototype "Mobi.Ru.D."

The vehicle in question has fundamental technical characteristics for use in agriculture such as the 4-wheel drive, all steering, the pneumatic suspensions which allow the vehicle to rise and lower from the ground both to facilitate the operator's ascent/descent and to move easily on agricultural land.



Fig,7. The vehicle has a lowering of approximately 90 mm

The vehicle was tested by operators with lower limb disabilities, who appreciated its functionality and manageability. Overall, the vehicle proves to be a potential resource for making field activities accessible again.

3 Conclusions

This article provides an overview of INAIL research activities focused on mobility issues in the agricultural and for each topic covered the following considerations can be highlighted:

- The prototype of QROPS was designed for fitting onto a well-defined tractor model; however, the design guidelines and kinematic synthesis could be extended to other ROPS, allowing them to be fitted on tractors of different architectures. The strength tests of the Q-ROPS, conducted following the OECD Code, were successfully completed. Therefore, the two-post, three-section foldable rear roll-bar can be considered a viable safety device
- The rollover risk associated with self-propelled machinery remains significant in agriculture. Currently, these machines are not equipped with ROPS structures since the EN ISO 16231-2 standard defines the minimum stability angle required for not having a rollover protection structure fitted on the machine. The results of the research activities revealed that, in some cases, typical operative slope (TOS) values do not accurately reflect the real angles present in specific plantations. Furthermore, this approach allows for predicting the slope of specific areas concerning plantation types and correlating it to the static stability angles of the machines used on that cultivated land. Consequently, it is possible to define a slope map for specific areas relative to particular machines, enabling preliminary checks to ascertain whether a machine can operate safely on that slope before reaching it.
  This represents a significant added value for preventing accidents and potential injuries and serves as a valuable risk assessment method tailored to each specific case.
- The Mobi.Ru.D project was primarily designed to encourage the reintegration of operators who, following accidents resulting in permanent injuries, cannot return to field activities. Additionally, it promotes professional integration for individuals with reduced mobility within the agricultural context. Following positive feedback from users, the vehicle has proven to be an appreciable product in terms of technical content and psychosocial impact. The vehicle created in this project, which is currently a first prototype, could be improved in future versions by implementing additional operational functions.

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New technologies to protect machine operators and workers from mechanical hazards: challenges and opportunities

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Abstract
The Machinery Directive and the new Regulation that will replace it from 2027 provide for the use of guards (i.e., physical barriers designed as part of the machine to provide protection) or protective devices (types of protection other than guards, i.e., sensitive protective devices, active opto-electronic protective devices) to reduce risks associated with the presence of moving parts. They also require that protection against mechanical risks associated with the movement of transmission parts must always be provided by fixed or movable guards, while allowing the use of protective devices where such risks are associated with the moving parts involved in the process (EHSR 1.3.8). The moving parts directly involved in the process which cannot be made completely inaccessible during their operation, can also be protected by fixed guards preventing access to those parts which do not need to be reached and by adjustable guards restricting access to those moving parts which need to be reached for the process.
However, access to moving parts involved in the process, although recognized as necessary by the legislator itself, still poses a significant residual risk to the machine by exposing the operator and any other worker in the immediate proximity of the machine. In the case of operating machines, mobile machines, etc., the risks due to their mobility (translation) or the mobility of their parts (e.g., rotation or extension of arms) must also be considered.
The article will focus on hypothesis to introduce new technical solutions aimed at further reducing residual risks associated with moving parts involved in the process and not completely segregable or with mobility; the analysis of challenges and opportunities will be carried out mainly by referring to construction and/or handling machinery.

1 Introduction

The rapid increase in the use of sensors in various industrial sectors, particularly through wireless technologies, leads to a need for a specific analysis of their applicability in relation to the machine safety. In particular, the massive use of sensors highlights the possibility to mitigate risks currently considered to be residual, such as risks of collision between the machine (or part of it) and objects or obstacles, including workers or certain risks arising from contact between parts of the worker's

body and moving parts of the machinery involved in the process that cannot be made completely inaccessible during their operational activity.
This paper aims to analyze the opportunities arising from the use of sensors and the challenges inherent in their adoption, with a focus on the construction and load handling machinery sectors.

2 Mechanical risk reduction approach for machines

The general definition of machinery given in the Machinery Directives 98/37/EC [1], the 2006/42/EC [2] and the Machinery Regulation (EU) 2023/1230 [3] is "*an assembly, fitted or intended to be fitted with a drive system other than directly applied human or animal effort, consisting of linked parts or components, at least one of which moves, and which are joined together for a specific application*". Mechanical hazards in machinery are therefore associated with all possible hazardous movements of the machine, whatever they may be, and more specifically with all hazards due to the presence of potential or kinetic energy. The hazards may be associated with movements, controlled or uncontrolled by the operator, of the machine as a whole or of individual components.
In general terms, hazardous movements can be divided into three macro-areas: i) movement of the moving transmission parts, ii) movement of the moving parts involved in the process and iii) machine mobility. Each of them must be approached differently for the purposes of risk assessment and the search for technical measures to protect the operator. Even the Machinery Directive and the Machinery Regulation, in the Essential Health and Safety Requirements (EHSR), indicate different approaches and technical solutions to be adopted in the three cases.
To reduce risks for the operator or other exposed persons associated with the presence of hazardous moving parts, they require (EHSR 1.3.8) that only guards, i.e., physical barriers designed as part of the machine to provide protection, fixed or movable (when frequent access to the parts is required), shall be used for moving transmission parts. When the risks are associated with the hazardous moving parts involved in the process, they allow the use of protective devices, namely types of protection other than guards, such as enabling devices, travel control devices, two-hand control devices, sensitive protective devices, active opto-electronic protective devices, mechanical restraint devices, limiting devices, and limited motion control devices. Furthermore, moving parts directly involved in the process that cannot be made completely inaccessible during their operation, can also be protected by fixed guards preventing access to parts that must not be reached and by adjustable guards that limit access to moving parts that cannot be made inaccessible for the process.
Similarly, the legislator recognizes that it is generally not possible to completely protect with “physical” barriers the operator or other people exposed to risks due to the mobility of the machine as a whole. Therefore, he provides for different technical solutions and relies heavily on the visibility of the danger zone by the operator (EHSR 3). In addition, other dangerous situations are related to uncontrolled movements of

the machine or its parts, due for example to accidental starts, loss of stability, structural failures, and so on.
Furthermore, the new Machinery regulation introduces EHRS to consider the increasingly widespread diffusion of machines designed with a fully or partially self-evolving behavior or logic conceived to operate with different levels of autonomy.
Therefore, the hypothesis of introducing innovative technical solutions aims at further reducing the residual risks associated with exceptional situations (e.g., breakdowns, misuse), moving parts involved in the process and not completely segregable (e.g., tools, arms), the mobility of the machine (e.g., self-propelled, towed) or at mitigating risks arising from the adoption of "advanced" machines, such as autonomous and self-evolving ones (e.g., robots, autonomous machines).

3 State of the art for construction and load handling machines

As reported in the Construction Ateco F sector infographic published by Inail [4], the data on accidents reported in Italy over the period 2019-2023, show that the construction sector remains at the top of the list in terms of accident incidence, with an accident frequency index per 1000 workers of 18. It is second only to agriculture at 20 and well ahead of manufacturing at around 12. The same publication shows that a large number of accidents depend on the "Total or partial loss of control of a machine, a means of transport/handling equipment, a hand tool or object, or an animal" (var. Esaw/3 causes and circumstances), which represents approximately 23% as a cause (first place) and about 30% as a circumstance of the accident (second place).
Despite the evidence of such accidents suggests the need for targeted intervention strategies, the current state of the art in the construction and load handling machinery sector is not characterized by a widespread use of enabling technologies. The reasons for this gap compared to other more advanced sectors, such as industry, can be found in various contingencies in the employment sectors.
Firstly, the companies in this sector are often very small and the structural and organizational characteristics do not favor a frequent renewal of the fleet and the acquisition of modern technologies and machinery. Also, the limited number of employees, often with poor professional qualifications, makes this process of technological replacement more difficult.
However, the difficulty is not only due to the limited ability of construction companies to engage in the innovation process, but also to the reduced availability of innovative machinery and systems designed to operate effectively in the specific sector. Indeed, the construction sector is characterized by some morphological (temporal and geometric variability of the site configuration), environmental (extreme weather conditions, dust, vibrations, noises, etc.) and organizational (concentration of numerous activities, companies and workers in a small space) characteristics which, in addition to leading to a high accident index, make it more difficult to spread

innovative technologies useful for worker safety, already used in other production sectors or under development.
In recent years, there has been an increase in the use of sensors in the construction and load handling machinery sectors, to detect position and configuration and avoid the risk of collisions between machines, between machine and obstacles or between machine and one of its moving parts, e.g., between the boom of a work platform and the driver's cab of the vehicle (to this last aim, sensors typically employed are encoders and angle-measurement devices). Nevertheless, their adoption is very limited, and activity automation is almost non-existent. The effect of the sensor measurement is usually an alert or a stop of the movement, less frequently.

4 Technologies to be introduced in construction and load handling machinery applications

Solutions for construction and load handling machinery are being explored, with a view to exploit enabling technologies consolidated in more advanced sectors, such as industry and services, which have then been applied in indoor scenarios. Similarly, innovative technologies that are still under development could be profitably applied in the construction and load handling machinery sectors and deserve particular interest.
These include solutions for the prevention of collisions between machines, or between machines (or parts of them or the load being handled) and workers or obstacles, the issue of visibility, but also the protection of the operator (driver) from hazards present on board due to various possible dangers. The latter can be multiple: dangerous events relating to access (slipping, falling, etc.), unintentional or uncontrolled movements, overturning due to incorrect use of the machine in relation to the characteristics of the terrain or the environmental conditions (weather, disturbances, etc.), incorrect use of the machine in relation to its performance (rated load capacity), incorrect coupling of accessories or interchangeable equipment, without excluding ergonomic factors (incorrect posture, noise, vibrations, etc.). Another issue may be the protection against contact with moving parts that could injure the operator or other workers in the vicinity of the machine.
For all the above-mentioned issues, technologies are available, or are being developed or improved, that can provide real benefits in reducing the residual risk currently considered “acceptable”, but that is still associated with a significant number of occupational accidents and illnesses. However, applying these technologies in the construction and materials handling sector turns out more difficult due to the influence of specific factors, e.g., climatic, microclimatic and meteorological factors, less regular and predictable site conditions with respect to indoor environments, variability and changing nature of site configurations and, in some cases, the increasing difficulty of controlling access to work areas. Anyway, experimentation is very active in the latter areas and it is hoped that reliable solutions will be more massive available in the near future.

In the following, we will analyze and discuss some technologies that, in the authors' opinion, have the greatest potential for providing solutions and mitigating the above-mentioned risks. Particularly, technologies to improve visibility and collision avoidance, and technologies to create semi-autonomous and autonomous machines will be investigated, since they are considered to have a high impact on the accident phenomenon in the considered sector.

5 From improving visibility to avoiding collisions to semi-autonomous and autonomous machines

Improving visibility and preventing collision can be achieved by means of single devices capable of replacing the machine operator's eyes in areas where visibility is not guaranteed. Cameras or sensors based on various technologies as radio frequencies, ultrasounds, infrared, and so on, can be profitably adopted. The results of the detection made in these areas can be returned to the operator, for example, by means of images shown on a display or in the form of acoustic or visual warnings. The integration of one or more of these devices is an improvement over the state of the art in terms of safety in the construction and load handling sectors, where the residual risk of collision between the machine, or parts of it, with workers or obstacle is significant and the use of such devices is rather limited, especially for small and less expensive machines. Data collected with multiple sensors add to those that the operator has been able to detect with his five senses in the configuration and operating situation, consequently his decision-making process does not take place in the absence of information, due for example to "shadow cones" or inattention.

However, the real technological quantum leap occurs when entering the more complex field of the Artificial Intelligence (AI) able to develop learning models on the basis of a proper elaboration of data collected by the sensors to guide the operator's decision-making process, so yielding to even more important results in terms of safety. In other words, data gathered from the sensors on the machine, but also from workers and obstacles present in the operational area can be jointly exploiting with sensor-fusion approaches to provide even more reliable indications for the operator who has to decide.

Of course, the next technological step forward, particularly innovative for the construction and load handling machinery sector, is the possibility of replacing the operator rather than guiding him, in the operation or in the decision-making process or in certain phases of it. This is possible when the control software of the sensor-equipped numerical control machine enables automatic tasks to be performed, or the artificial intelligence system enables "intelligent physical objects", such as robots, or autonomous machines and vehicles, to support autonomous decision-making based on measured data about the state of the object itself or the environment. Available algorithms may be those exploiting Machine Learning, namely systems capable of learning from 'experience' with a supervised approach (classification algorithms, linear regression), an unsupervised method (clustering) or with

reinforcement learning (artificial neural networks). The latter approach represents probably the more flexible solution. Indeed, when exposed to a large amount of data, the system is able to train itself to perform specific tasks even novel ones.

5.1 Some available systems and technologies

Focusing on the case of assisting or replacing the operator in operational and/or decision-making processes, several technologies, mainly used in sectors such as industry, logistics and road vehicles, deserve to be examined with interest and a critical eye. In fact, it is necessary to identify the aspects that can be borrowed quite simply and those that require adaptation to the specific reality of construction and load handling machines. Suitable solutions are Automatic Identification and Data Capture (AIDC), Real Time Locating Systems (RTLS), Advanced Driver Assistance Systems (ADAS) that could provide a technological reference with appropriate contextual differences to develop a greater autonomy in the operational and/or decision-making processes of construction and handling load machines, so reducing the operator's exposure to hazards and the human factor as a source of error or misuse.

The above-mentioned systems can allow for one or more of the following capabilities:

- Detection: observing the presence of objects/subjects within the reference area.
- Identification: determining the identity of objects/subjects and recognition of its safety-relevant characteristics.
- Localization: measuring the absolute/relative position of objects/subjects within the reference area.
- Tracking: determining the trajectory running by moving objects/subjects, possibly predicting the future motion direction and preventing possible interference with other objects/subjects in the reference area.
- Feedback: giving instructions to the operator, e.g., image, alert, or to the machine, e.g., stop, corrective actions, based on the measured data and detected events.

Briefly, these systems aim to identify and localized fixed or moving objects/subjects, e.g., obstacles, machines, people, workers, to be monitored within the working areas in real-time, by providing an active or passive feedback.

It is worth noting that when developing localization and tracking solutions, detection and identification become implicit in them.

5.2 The constituent elements

The main constituent components can be defined as follow.

- A “detection/locating system” capable of detecting the presence/identity/position/tracking of the object/subject to be monitored (the system may be capable of detecting only one or more of these parameters).

- A “management/control system” able of collecting and processing the information coming from the detection system (input) and returning operational indications/control messages (output) to the objects/subjects in the area.
- A “transmission system” to transmit the input and output information to/from the management/control system or, if appropriate, outside the system.

The choice of technologies to be adopted for these constituent elements naturally influence the possibility of supporting, or not, all the functions indicated, the precision of the system and its reliability. To implement all the required functions and to make the performance (accuracy) and reliability of the system acceptable/improved, the integration of various technologies is generally applied.

5.2.1 The detection/locating system

The detection system is relevant for the functions performed, which determine its intended use. It can be implemented using one or more technologies, often used together to combine their different capabilities and potentialities, minimize their limitations and inefficiencies, improve the overall reliability of the system, e.g., by pursuing strategies of redundancy or complementarity of functions, and achieve higher performance and more accurate results.

It is possible to distinguish the following two main infrastructures.

Detection/Locating systems with external infrastructure: the location of all monitored objects/subjects is determined through a fixed infrastructure of sensors with respect to a local reference frame and transmitted to the centralized operational control system.

Detection/Locating systems with internal infrastructure: each monitored object/subject is equipped with sensors able to measure its relative distance (positioning systems) with respect to other monitored objects/subjects in the working area, or to detect the proximity (proximity systems) of such additional objects/subjects.

The technologies used or potentially being considered for detection/localization systems are numerous: ultrasounds, video-cameras, thermos-cameras, optoelectronic devices, laser scanners, radars, radio frequency systems, satellite systems, Ultra-Wide Band (UWB) systems.

They can be grouped essentially into four “categories,” based on the main characteristics.

1) A device (e.g., thermal cameras and video cameras) measures the “parameters naturally emitted” by the obstacle to detect/identify the obstacle or some of its characteristics, and possibly locate and track it.
2) A device integrated within the machine emits a signal and receives its reflection caused by the presence of an obstacle encountered in its path (object/subject), to detect the obstacle and measure the relative distance. This is the case of acoustic waves emitted by ultrasound systems, or electromagnetic waves transmitted by radars or those used by laser scanners in the visible light spectrum.

3) A device emits radio frequency signals to an active/passive transponder and receives reflected/transmitted back signals to detect, identify and typically localize and track the objects/subjects. This is the case of Radio Frequency Identification (RFID) systems [5][6], both active or passive, or UWB systems with active anchors.
4) A satellite system transmits an electromagnetic signal, which is detected and reprocessed by a terrestrial receiver integrated to the object/subject being monitored (e.g., GNSS systems) to determine the geographical location of the monitored object/subject monitored.

A key distinction for machine safety applications is the level of responsibility for implementing and managing the system. While the systems in the first two categories are essentially 'on-board' machine systems - making the manufacturer entirely responsible for the machine - the systems in the third category, although fully implementable by the manufacturer and supplied with the machine, require the user to manage the transponders (tags or anchors) within the specific working area, including their placement on objects and subjects as required; and this is particularly relevant for construction site applications. Likewise, in the fourth category, neither the design/construction nor the management of the signal emitting system (satellite transmitter) fall under the responsibility of the machine manufacturer.

These significant differences necessitate distinct approaches to assess system availability and reliability. Beyond the intrinsic reliability of each system, determined by the specific technology used, there is another key distinction among the four identified categories. In the first case, reliability also depends on the level of confidence that can be placed in the software ability to accurately process the detected information and ensure accurate results in real-time. In the second case, reliability is also influenced by confidence of intercepting the monitored object/subject (e.g., displacement, orientation, etc.) and in its actual ability to reflect the signal (e.g., morphological characteristics, surface conditions, etc.). In the third case, reliability also depends on confidence in the effective presence and correct positioning of the anchors/tags on the object/subject to be monitored. In the fourth case, reliability is also affected by the confidence in the actual availability and quality of the satellite signal. In all cases, it is also essential to ensure that the machine remains in a safe state in the event of signal loss or degradation.

5.2.2 The management/control system

The management/control system collects and processes data from the detection system and returns outputs of various types (alerts or actions) to objects/subjects for the purpose of managing the functions of the system. Machine Learning algorithms may or not be implemented.

5.2.3 The transmission system

Data transmission typically occurs between the detection system and the management/control system or the object/subject, depending on the purpose and

the system architecture. In the applications under discussion, this data transmission takes place almost exclusively via wireless networks based on different communication protocols, e.g., Wi-Fi, Wireless Local Area Network, Bluetooth, LoRA (Long Range), cellular networks, and so on.
The possible exchange of data outside the system, e.g., remote service centers, generally take place through standard connection and communication systems being global or local networks and both wired and wireless.

5.2.4 The system outputs

System outputs may be relayed, as appropriate, to the management system of the area or the specific object/subject in the form of alerts (audible or visible). Alternatively, they may be integrated directly into the management system itself (of the area or the specific object/subject being monitored), enabling automatic corrective actions when the detected situation approach or reaches the predefined risk threshold. To gradually detect approaching dangerous situations, several thresholds can be defined.

5.3 The reliability of the system

In view of the overall benefits that could be obtained, the most effective solution is to integrate the outputs of the systems described so far into the machine control system in order to modify its operation for safety purposes. As already mentioned, this entails greater complexity in estimating the reliability of the safety functions guaranteed by the system because includes all its components and their interface with the machine (especially for predictive rather than self-evolving systems).
Ensuring this reliability, in this specific case, means both defining the parameters that can influence it and having the statistical data to calculate performance levels or other standardized performance indicators. All this is currently not always state of the art for construction and material handling applications.
However, the difficulty of defining, determining and guaranteeing the reliability required for the specific application increases when the machine, so far considered as a “self-referential product”, becomes instead a “product that communicates and interacts” autonomously with its environment; and this difficulty increases with the variability of the environment, as it is for construction and load handling machines. In these cases, not only it is sometimes impossible to clearly distinguish between what constitutes the “machine product” and what lies outside of it – making it difficult to delineate the responsibilities of the manufacturer and the user – but it also becomes highly complex to establish a protocol (i.e., standard) that can guide the manufacturer in identifying and measuring key parameters for assessing the system reliability. This is the case, for example, of technologies which operate not only through devices (e.g., sensors) embedded in the machine but also require the presence of some of them in the infrastructure (smart working environment) or on other objects/subjects present in the work area (e.g., RFID/UWB, which require the

presence/application of tags on people, obstacles or other machines and/or an interface with a management/control system external to the considered machine).
According to the approach established by European machinery regulations (current Directive 2006/42/EC [2]), technological solutions that are not fully 'integrated' into the machine - such as the one just mentioned - are not admissible as an alternative to a guard or a protective device if they do not ensure the same level of safety. Indeed, for the second step of the “principles of safety integration” (set out in EHSR 1.1.2 of the Directive), which requires of implementing the 'necessary protective measures against risks that cannot be eliminated' through the integration of safety in the design (phase 1), the EN 12100 standard [7] lists protective devices as options (enabling devices, travel control devices, two-hand control devices, sensitive protective devices, active opto-electronic protective devices, mechanical restraint devices, limiting devices, limited motion control devices), and none of them are not fully integrated into the machine.
On the contrary, such technological solutions could provide significant benefits in third step of the “principles of safety integration”, where, for the management of residual risk (i.e., the risk that cannot be further eliminated through the solutions identified in step 1 and 2), they could be used to complement solutions provided by the step 2, as well as information/signaling systems or protective devices. This interpretation, although not officially communicated by the European Commission, has been applied in standard proposals where the use of such technologies as an alternative to guards and protective devices was considered by HAS Consultants.
This assumption was therefore taken into account in the initial hypothesis of this paper: to consider some of the described technologies (including RFID tags) as a tool for reducing/managing residual risk, complementing rather than replacing guards and protective devices.
In the new EU Machinery Regulation 1230/2023, which will come into effect on January 20, 2027, there are no changes to the mentioned text of EHSR 1.1.2, and so far, no views have emerged at this stage that would lead to a reinterpretation of the current understanding. However, the new application guide from the European Commission and the upcoming revision of EN 12100 [7] are still awaited by the stakeholders, as they may provide specific guidance on these technologies.

6 Conclusions and perspectives for the future

In the light of the previous points, it IS therefore clear that the use of systems such as those described in this paper implies a paradigm shift in the approach to machine safety (including those in the construction and load handling sectors), where the long-term perspective is to achieve total integration between the "smart object" (smart machine) and the "smart working environment" (smart construction site). In this case, even if it is currently necessary to refer back to the approach of the European products regulations (in particular the Machinery Directive [2], or soon the Machinery Regulation [3], which was created precisely to introduce the regulation of these

innovative issues), the machine will increasingly tend to integrate functionally into the technological environment in which it operates, and its design/construction will be increasingly difficult to extrapolate from it. The more this happens, the more difficult it will be to comply with the EHSR for the machine without considering the knowledge of and interface aspects with the environment.
The smart vehicle sector itself - an outdoor environment in which scientific studies and experimentation are already at advanced levels with respect to "autonomous driving" issues - is following a technological and regulatory development that is based on the integration of the smart vehicle itself with the smart road system in which it moves and with which it needs to dialogue and interact, just as it needs to dialogue and interact with the set of other smart vehicles that move in it.
In other words, the future machine design/construction paradigm should address the "smart machine" object as an integral part of the "smart working environment" infrastructure (or rather its digital infrastructure). That is, specifically for the construction and load handling machines under discussion here, as an integral part of the "smart construction site." In general, therefore, the issue of EHSR of the "smart machine" product should no longer be treated with the classic approach dedicated to "isolated machines," which is achieved by compliance with the EHSR strictly applicable to them. For example, it could be provide for a more complex system of EHSR in which, to the latter, the EHSR concerning the 'digital infrastructure' system (or 'smart working environment') to which the machine is connected could be added as well as EHSR of 'interface,' as well as interoperability requirements, between "smart machine" and "smart working environment."
In the construction site sector, a standardization activity of the "smart working environment" (i.e., the construction site) exists and it is represented by BIM (Building Information Modelling), which was created as a computerized management model of the design activities and, subsequently, of the construction and management of the work, which also includes the creation of a virtual model of the construction site. It stands as a multidisciplinary information model organized on different levels (as defined by the Italian standard series UNI 11337 [8]); the rising level named "8D dimension" is dedicated to the safety of people throughout the life cycle of the work, including the prevention of accidents on the construction site.
But the standardization of the "smart construction site" through BIM, unlike what happens in the smart vehicle and smart road sector, at the moment proceeds in a disjointed manner with respect to the standardization of the machines used on the construction site, and this could lead to delays in the experimentation and full application of the available technologies with respect to their concrete potential.
Within Inail, this issue is being approaching, trying to capture the real needs for intervention; that is, those that are highlighted by the analysis of the accident phenomenon in construction and that coming from the institutional and scientific research activities, in collaboration with Universities and other Research institutes, carried out or currently underway.

The goal is precisely to improve technologies and specialize them to the needs of the specific applications, but also to promote and foster synergies that could speed up the pace of their development and deployment.

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Exploring the future of human-machine interaction with integrated ai systems

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Abstract
In recent decades, the complexity of human-machine interaction (HMI) has significantly increased due to the technological advancements driven by Industry 4.0. This evolution has led to interactions with intelligent and autonomous machines integrated with artificial intelligence (AI). The advent of collaborative robots, for example, allowed new modes of interaction between operator and robot: they cooperate in executing numerous complex and high-precision tasks sharing the same workplace without barriers. As a result, a new Regulation on machinery products has been developed to address the gaps of the current Machinery Directive 2006/42/EC, taking into account the potential risks arising from interaction with machines designed to operate at varying levels of autonomy.
In this scenario, ergonomics has also evolved, shifting its focus to encompass human interaction with robotic, intelligent, and autonomous systems. The new ergonomic requirements in machinery design must not only reduce or eliminate discomfort, fatigue, and physical and psychological stress, but also ensure that machinery and related products, which may exhibit fully or partially self-adaptive behavior or logic, can interact with operators in an appropriate and predictable manner. These systems must also be capable of communicating their intended actions in a comprehensible and timely way. Additionally, machines incorporating high-risk AI systems must be engineered with human-machine interfaces that allow for effective oversight by natural persons. These interfaces must facilitate real-time monitoring, interpretation, and control during the operation of AI systems. The design must ensure transparency, particularly in high-risk scenarios, and provide operators with the means to intervene if necessary to maintain safety and system integrity.
In this paper, a framework will be drawn up in which the new issues of this dynamic highly complex human-machine interaction are showed and by highlighting those already dealt with by standardization and those that have yet to be addressed.

1 Introduction

The rapid advancement of Artificial Intelligence (AI) is revolutionizing human-machine interactions. As AI systems become more integrated into machines, the way humans

interact with and control them is being redefined. Human-machine interaction (HMI) has undergone substantial transformation in recent decades, driven by the advancements of the fourth industrial revolution and technological innovation. Industry 4.0 has brought about a significant shift in how workers interact with machines, primarily due to the emergence of new enabling technologies such as IoT, augmented reality, smart devices, and collaborative robots. As a result, scientific research in HMI has increasingly focused on the design and development of human interaction with intelligent, autonomous and robotic machines. This evolution suggests that humans and machines should no longer be viewed in isolation, but rather as a cohesive team working together toward a common task and goal.
In this scenario, ergonomics has also undergone an evolution: while before it was traditionally interested in physical and cognitive aspects in a physical world, now it turns to robotic, intelligent and autonomous systems and to the digital world [1].
In this article, we want to explore the new aspects that standardization will have to take into account when designing human-machine interaction with embedded AI. Several issues regarding human-intelligent machine interaction will be addressed within the recently regulatory frameworks in the European Union: the AI Act [2] and the new Machinery Regulation [3] that aim to address these concerns while promoting innovation in human-machine interactions. Finally, a framework will be drawn up in which the new issues of human-machine interaction with integrated AI will be showed by highlighting those already dealt with by standardization and those that have yet to be addressed.

2 Regulatory framework based on human centric approach

EU Regulation 2024/1689, called also AI Act, is the European effort to regulate AI, in order to safeguard principles for the health, safety and fundamental rights of humans with ultimate goal the increase of human well-being. AI rules should therefore be human-centric, so that people can trust that the technology is used safely and in compliance with the law.
The key concept in artificial intelligence regulation (AI ACT) is human centricity, as AI systems should ensure that human values are incorporated into the design of algorithms and that humans do not lose control over automated systems. This concept, therefore, places human-beings at the centre of AI development, features and use.
Currently, there is no specific and global standard for AI Human-Centred Design (AI-HCD), but there are several standards and guidelines that address the general principles of human-centred design and ethics that can be used in the design of AI systems. The most significant references in this area are found within the ISO 9241 series.
According to the UNI EN ISO 9241-210 standard [4], Human-Centred Design (HCD) defines an approach aimed at making systems usable and useful, focusing on users, their needs and requirements. This is achieved by applying principles and techniques

from human factors, ergonomics, and usability. HCD is particularly effective in enhancing the physical design of work environments by integrating people into the design process, ultimately promoting both well-being and productivity. The foundation of this approach lies in studying and understanding users, the tasks they perform, and the context in which these tasks occur. Users are actively involved in an iterative design process that spans from the initial phases of conceptualization and development to subsequent refinements. This collaborative process relies on a multidisciplinary team that brings diverse skills and perspectives. The ultimate goal is to evaluate and optimize the design to ensure a comprehensive and satisfying user experience. The Human Centred Design (HCD) will play an important role in guaranteeing the human interaction with intelligent, autonomous and robotic systems, as it focuses on making systems more effective, efficient, and enjoyable to use. At the same time, it prioritizes protecting users from risks, discomfort, and stress, ensuring a safer and more comfortable experience.

In practice, according to ISO 9241-210, designing and developing an interactive system with a human-centered approach involves four key steps, repeated as needed to refine the outcome:

- *Understand and define the context of use*. This means getting to know the people who will use the system, the tasks they will perform and the technical, organizational and physical environment where they will be used.
- *Identify user needs and requirements.* User and other stakeholder needs should be identified, taking account of any constraints imposed by the context of use.
- *Create design solutions.* A design solution is obtained on how users will interact with the system, user interface, taking into account the whole user experience and needs.
- *Evaluate the design.* Users are brought in to test the design, who provides feedback on what user needs improvement.

This process repeats until the final design meets all the users' requirements [5].

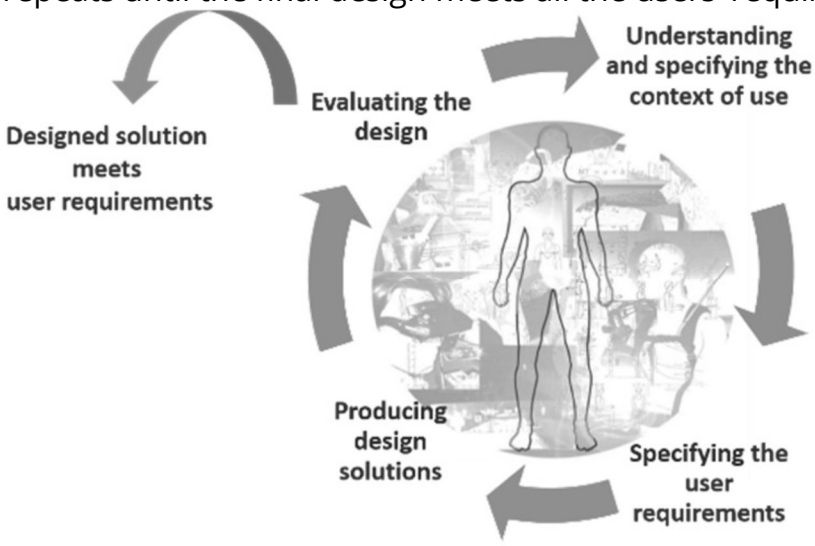

Fig. 1 – Human Centred Design iterative process adopted from ISO 9241-210

Combining the principles of Human-Centred Design (HCD) with the principles of AI development ensures a design that aligns with human capabilities, well-being, and ethical considerations.

3 Human oversight in EU regulation on AI

The European Commission, already in its White Paper on AI, stated that trustworthy, ethical and human-centric AI can only be achieved by ensuring human involvement, which may include human oversight before or after a decision is made [6]. This principle has been taken into account in the AI Regulation [2], in article 14 which defines the design requirements for “high risk” AI systems, requiring that they can be effectively supervised by natural persons during their use. In this perspective, human oversight should be viewed as a type of safeguarding measure according to the type of risks or harms that humans must detect and mitigate.

Human oversight has been much emphasized and discussed as a safeguard to ensure human centricity in AI implementation. However, there is an ongoing debate on human oversight among stakeholders who believe that human oversight can help mitigate the risks associated with AI systems, many others who urge caution and highlight the risks of over-reliance on humans to effectively remedy the negative consequences of AI systems. A key issue is how to ensure meaningful human oversight where and when it is needed. While an obligation to ensure human oversight implies that humans are expected to counterbalance some of the risks associated with AI systems, their ability and suitability to do so will depend on the type of systems they have to oversee, the transparency of those systems, and their mandates and working conditions, including the training humans receive. The requirement for human supervision, provided in Article 14 of the AI Regulation, limited to “high-risk” AI systems, and therefore not to all AI systems, states that such AI systems must be designed and developed in such a way that they can be effectively supervised by natural persons with appropriate human-machine interface tools. Human oversight should aim to prevent or minimize risks to health, safety or fundamental rights that may arise when high-risk AI systems are used in accordance with their intended purpose or under conditions of reasonably foreseeable misuse. The obligation of the provider to ensure oversight capabilities increases where the risk mitigation functions of other main safeguards cannot be expected to be sufficiently effective. Persons assigned to human oversight must be able to fully understand the capabilities and limitations of the high-risk AI system and duly monitor its operation, so that signs of anomalies, malfunctions and unexpected performance can be detected and addressed as early as possible. Human supervisors need to evaluate and synthesize the output of the AI system to be able to detect and respond to potential risks, biases or errors. To do this, the information or output of the system needs to be represented in a way that can be interpreted or understood by the supervisor, so that he or she can intervene in the operation or interrupt the system by pressing a "stop" button or similar procedure.

In practice, the AI regulation to ensure that AI systems operate in a "human-centric" manner has provided for human oversight in Article 14. While designing human-centred AI applications and implementing human oversight measures in AI systems are conceptually related notions, they have different goals, focuses, and manifestations. Human centric design is a *proactive approach*, while human oversight is a procedural and *reactive one*. The goal of human-centred AI design is to attempt to take human values into account in the technical realization of AI systems with the goal of meeting human needs and proactively avoiding harm. Human oversight measures, on the other hand, are more reactive in nature as they involve monitoring and addressing the risks, biases and harms generated by AI systems in operation [7].

4 Towards human-machine interaction with embedded AI

Recently, more advanced, autonomous and intelligent machines have been introduced to the market. These machines are designed to perform specific tasks in controlled environments, but they also have the ability to learn new actions and become increasingly autonomous. Future improvements to these machines, whether already in use or anticipated, will likely include real-time data processing, problem-solving capabilities, enhanced mobility, advanced sensor systems, learning abilities, adaptability, and the capacity to operate in unstructured environments, such as construction sites. So, the European Commission, based on the challenges posed by emerging digital technologies like AI, IoT, and robotics in terms of product safety, highlighted several gaps that current product safety regulations, including Directive 2006/42/EC [8], contained and the need to extend the currently regulation to cover the safety risks associated with new digital technologies [3].

The incorporation of software, including AI, into products can alter the operation of these products and systems throughout their lifecycle. This is especially true for systems that need regular software updates or depend on machine learning. These capabilities can introduce new risks that were not present when the system was placed on the market. Such risks are not sufficiently covered by current legislation, which primarily addresses safety risks at the time of placing on the market. In this context, machine learning, generally refers to a subset of artificial intelligence (AI) where machines learn from historical data and adjust their behaviour accordingly without explicit programming to perform specific tasks. For machinery under Regulation 1230/2023, machine learning technologies must be assessed for their safety implications. Therefore, manufacturers must ensure that all potential risks associated with machine learning systems embedded in machinery are mitigated in line with the Essential Health and Safety Requirements (EHSR) of the Regulation. So, the new EU regulation on machinery products introduces the following innovative general design principle: "*the risk assessment and risk reduction shall include hazards that might arise during the lifecycle of the machinery or related product that are foreseeable at the time of placing the machinery or related product on the market as an*

intended evolution of its fully or partially self-evolving behaviour or logic as a result of the machinery or related product designed to operate with varying levels of autonomy".
Although the new Machinery Regulation was issued to cover the risks emerging from the interaction with new technologies, the text does not explicitly refer to AI systems, but rather to "*machinery that has embedded systems with fully or partially self-evolving behaviour using machine learning approaches".* In fact, as the manufacturer has to evaluate risks before the machinery has been placed to the market, its evolving behaviour does not to perform actions beyond its defined task and movement space. If this was not the case, the risk assessment made a priori by the manufacturer and the related safety measures would not be reliable and consistent with the possible operating modes of the machine. In fact, new risks would arise from the new actions performed by the machine that would have not been evaluated a priori. New research challenge could lead to machines equipped with artificial intelligence systems capable of gradually assessing themselves emerging risks and acting appropriately measures to reduce them; in this case we could think about "*dynamic self-assessment risk".* Even if, this hypothesized development of research, bringing with it an innovative principle, would lead to opportunities but also to potential negative effects [9].

5 Designing regulatory framework of human-machine interaction with AI embedded

The proposed framework identifies the regulatory acts that cover emerging risks posed by AI systems and other digital technologies embedded in machinery in the interaction with humans.
Human-Machine Interaction is viewed in its broader concept, encompassing how humans interact with machines, including cognitive, physical, and emotional aspects, with a focus on how people use and communicate with machines. It also includes the human-machine interface that enables this interaction through tools such as screens, buttons, levers, touch screens and control panels. The framework highlights the current product safety legislation that already covers some of these risks and the issues that yet must be addressed. To ensure an inherently safe design of a machinery with embedded AI that met human needs the regulatory framework is made up of the New Machinery Regulation, the AI Regulation and the ergonomics standards. The most relevant ergonomic standards are the ISO 9241 series, even if recently the ISO/TR 9241-810:2020 has been developed to face new risks deriving from human interaction with intelligent, autonomous and robotic systems [1]. The technical report provides guidelines and recommendations for designing and evaluating these systems, to ensure interface designs that support natural, intuitive and clear interaction between the user and the system.
The human centrality in the design of new technologies ensures that human needs are met and aims to safeguard individual rights and increase human well-being. The autonomous and evolving behaviour of certain machines with AI systems embedded, during its life cycle, may lead to product changes having an impact on safety, in this

perspective, human oversight can be considered as a safeguard. AI system developers must ensure that individuals have the ability to choose not to use high-risk AI systems in specific situations, or to disregard, override or reverse their outputs. They should also allow intervention in the operation of the system, including the option to stop the system using a “stop” button or similar procedure [2]. This means that developers must ensure that their high-risk AI systems are designed to facilitate human intervention by equipping them with an appropriate human interface. The Machinery Regulation, on the other hand, also provides requirements for creating a human-machine interface that is suitable, especially according with (Essential Health and Safety Requirement) EHSR 1.1.6 on ergonomics, under the conditions of use provided, the discomfort, fatigue and physical and psychological stress to which the operator is faced must be reduced to the minimum possible**.** This requirement is reached following ergonomic principles, such as the operator’s physical dimensions, strength and stamina; taking into account work postures and movements, avoiding human stress due to machine work rate and to lengthy concentration for monitoring machinery. Furthermore, the human-machine interface must be adapted to the foreseeable characteristics of operators, especially in the interaction with machinery or related products with fully or partially self-evolving behavior or logic designed to operate with different levels of autonomy. In this case, these products must be designed to respond to people in an adequate and appropriate way (e.g. verbally through words and non-verbally through gestures, facial expressions or body movements) and to communicate the planned actions (e.g. what it will do and why) to operators in an understandable way [3].

Robotic, autonomous and intelligent machines are often designed for collaboration, where the machine complements human capabilities rather than replacing them. In the workplace, you might have robots working alongside human workers in tasks such as assembly line production, maintenance or customer service. To cover this new risk arising from humans and robotic machines sharing the same workspace, the new Machinery Regulation has amended the safety requirement for the protection of moving parts (EHSR 1.3.7 - Risks related to moving parts). This requirement has been extended to cover not only the physical risk arising from contact with them, but also the risk associated with dangerous situations and psychological stress that may be caused by interaction with a machine and/or a robot moving in the surrounding environment. In this regard, the prevention of risks arising from interaction with the machine must be adequate in relation to both human-machine coexistence in a shared space without direct collaboration and human-machine interaction.

However, the Machinery Regulation, although recently developed, is not able to guarantee the safe construction of machines with an evolutionary behavior different from what was foreseen by the manufacturer. To date, in fact, the new Machinery Regulation defines the requirements for machines with incorporated machine learning (ML) applications rather than incorporated AI applications. This is explained by the need for the manufacturer to know all the possible evolutionary modes of the

machine because for each operating mode the manufacturer must carry out a priori risk assessment. Recent developments in AI systems suggest that it will not be long before machines with a high degree of decision-making autonomy are available, so the regulatory framework will have to be easy to modify to adapt to new technological advances. On the other hand, a human-centric design of the interface is achieved only when the following human aspects are adequately taken into account in the legislative and standards framework: behavioral and cognitive models, causes of stress, mental workload, degree of human acceptance of a machine that becomes an intelligent and a social agent. With respect to AI machines, it is also necessary to consider the degree of human trust in the machine. Robotic, intelligent and autonomous systems must be designed ensuring that they are useful, safe and easily understandable for end users, so that they can trust the system's actions.

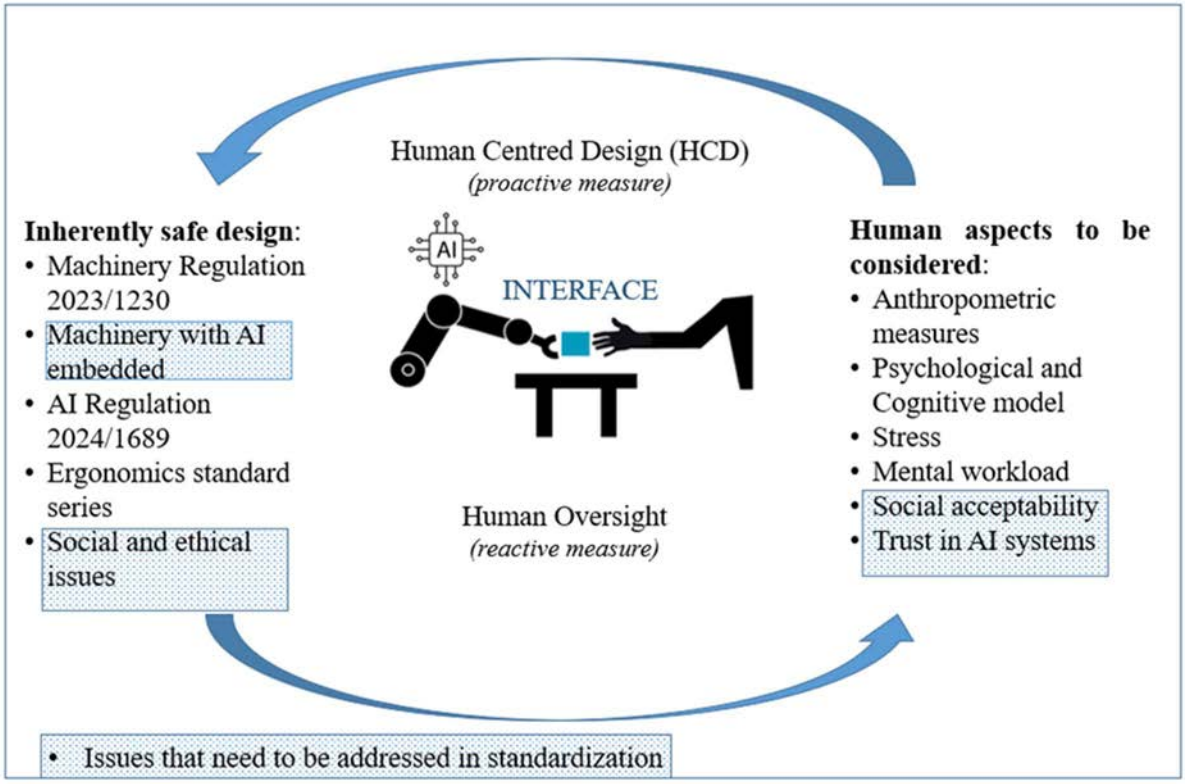

Fig. 2 – Regulatory framework of human-machine interaction with AI embedded

The design of human-intelligent machine collaborative workspace must take into account a multitude of requirements, in order to ensure the protection of human health and safety. Up to now, standardization efforts have focused on safety aspects related to machine design, but human behavior and psychological responses have not yet been sufficiently addressed in standardization. The introduction of intelligent and autonomous machines in work teams, on the one hand, has lightened the tasks of workers, but on the other hand, has increased stress due to the increased attention of human operations monitoring the machines. Ergonomic efforts must also improve

the degree of acceptability of the intelligent machine in the human team in order to reduce the mental workload due to the uncertainty created by its presence.
As AI becomes more integrated into machinery, ethical considerations are paramount. The AI Act emphasizes that AI systems should promote human well-being, prevent harm, and respect fundamental rights. This implies designing systems that safeguard privacy, avoid creating unfair societal divides or discrimination and promote inclusivity and accessibility [2].
Furthermore, as the autonomous and intelligent machinery becomes a member of a human team, it should adapt to the social and cultural norms of the context in which it is performing the tasks. This would require that the machinery, equipped with AI, be able to decode social signals or personal characteristics and respond accordingly. These social aspects that emerge from intelligent human-machine interaction must be addressed and explored in future ergonomic standards. Explicit requirements for manufacturer could be considered also in respect of mental safety risks of users when appropriate (ex. collaboration with humanoid robots). Human-machine collaboration must always respect human autonomy and dignity, avoiding scenarios where AI systems unintentionally exploit or discriminate against human workers (ethical principles). For example, according to de Graaf [9], who explores the ethical implications of relationships between humans and robots, it is essential to develop ethical guidelines for the design and use of robots, in order to ensure that these technologies are used responsibly, protecting the well-being and rights of users. According to the author, a social robot should be able to communicate and interact in a way that the robot allows its users to understand the robot in human social terms and to empathize with it. Recently, researchers in social robotics aim to develop such sociable machines by making use of models and techniques generally used in human–human communication.

6 Conclusion

As the landscape of human-machine interaction evolves with the integration of AI systems, it is crucial for regulatory frameworks like the New Machinery Regulation and AI Act to balance promoting innovation with safeguarding human safety and ethical values. Regulations must be flexible and responsive to the rapid advances in AI and machinery. So, regular updates and reviews will be necessary to ensure these regulations remain timely and effective.
In conclusion, the integration of AI into machinery is revolutionizing human interaction with technology, while this offers immense potential for innovation, on the other hand it poses significant challenges related to safety, accountability, and ethics. The New Machinery Regulation and the AI Act will play a crucial role in ensuring that AI systems operate safely and ethically. The future of human-machine collaboration will be a balance between technological progress and regulatory measures that safeguard the humans.

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Real-time sensing tools for the detection of sudden extreme weather events

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Abstract
Worker safety relies with the ability to monitor working activities performed in a myriad of operating conditions, thus facing a potentially infinite range of risk factors. However, it is well known that, especially in the case of work activities carried out outdoors, one of the most significant risk phenomena is represented by the occurrence of extreme weather events. This type of risk is significantly increasing also due to the global climate change, that is leading to an increase in temperatures and subsequently to a higher frequency of extreme events.
The possibility of predicting events of this type is mainly based on the ability to collect a large amount of heterogeneous data, related to a wide range of phenomena that can jeopardize the operator's safety. This requires advanced heterogeneous sensing technologies, often centered on specific measurement techniques, that face the not-easy integration into portable devices to be used in the field.
The aim of this contribution is to propose a novel architecture integrating off-the-shelf and ad-hoc developed sensing tools, by allowing the real-time acquisition of data that are processed through sensor fusion methods, also adopting the paradigm of artificial intelligence. These algorithms will be trained with datasets acquired by the same sensing structure, with the final purpose of promptly identifying the formation of environmental conditions leading to the occurrence of sudden extreme events like tornados, lightning, or flash floods.
The real time sensing structure will integrate a set of standard sensors (anemometer, anemoscope, thermometer, light radiation sensor, humidity, and atmospheric pressure sensor), together with ad-hoc developed measuring systems, e.g., sensors for measuring the electric field of the atmosphere. The developed system will contribute to enhance worker safety, but also in reducing the stress at the workplace typical of operators exposed to the risk of extreme weather events, fully aligned with the Industry 5.0 vision.

1 Introduction

Safety in the workplace is not only a fundamental requirement from a legislative point of view, but it is essential to protect and safeguard the lives of workers. Besides

standard risks that can occur due to the use of machinery, vehicles and instrumentation at work, there are additional risks in case of severe weather events.
Lots of general studies demonstrated that both extreme heat and extreme cold are related to an increase in mortality of population [1]. However, few manuscripts investigated the effect of extreme temperatures on occupational health and work-related injuries [2]-[4]. As reported at [5], the European Trade Union Confederation (ETUC) by the International Labour Organisation (ILO) estimated that more than 80000 people suffered injuries at work due to heat exposure in 2020 and 67 people died as a result of working in extreme heat, with a 42% increase in heat-related workplace fatalities since 2000 in Europe.
Hurricanes bring very high wind speeds thus presenting a variety of safety risks for workers [6]. From 1992 to 2006, hurricanes caused an estimated 72 fatal occupational injuries in the United States. During Hurricane Ida, in Louisiana in 2001, 4.4% of the 91 fatalities were work-related.
Tropical cyclones, high winds, and heavy rain often lead to flooding, with consequent risks for workers. Between 1992 and 2006, there were 62 fatal occupational injuries due to floods, with nearly half of the deaths occurring to passengers in motor vehicles [6].
Severe weather events are increasingly frequent in this era of climate change. In case of heat waves, sudden thunderstorms, violent hailstorms, water bombs, strong gusts of wind, workers involved in outdoor activities are directly exposed to the risks that such extreme events bring. Consequently, even emergency response workers are in danger together with indoor workers, just think of possible building collapses.
In such a framework, adequate emergency plans must be defined through the cooperation of the employers and the civil and rescue authorities. Moreover, the workers need to be accurately trained on the risks and actions to be taken promptly to safeguard their safety. Hence, timely and effective warning systems are crucial to properly advise workers in case of extreme weather events. However, extreme weather events often occur suddenly, so it is difficult to determine the right time and area in which they develop.
This paper presents a real-time monitoring system for the detection of extreme weather events. The novel architecture proposes to integrate a set of standard sensors, e.g., anemometer, anemoscope, thermometer, light radiation sensor, humidity, and atmospheric pressure sensor, together with ad-hoc sensors developed for measuring the electric field of the atmosphere. Thanks to a sensor-fusion approach, data from all sensors are combined with the final purpose of promptly identifying the formation of environmental conditions leading to the occurrence of sudden extreme events like tornados, lightning, or flash floods. The developed system aims to enhance worker safety, but also to reduce the stress at the workplace typical of operators exposed to the risk of extreme weather events, fully aligned with the Industry 5.0 vision.

2 Standard and ad-hoc sensors

A possible architecture of the real-time monitoring system integrates three different sensing technologies within one platform in charge of collecting the data and transmitting them in real time to a remote data collection centre where further processing will be carried out. In particular, the proposed platform foresees the integration of three subsystems, interfaced with a central processing and transmission unit. The first subsystem consists of a standard weather monitoring tool integrating sensors for the measurement of wind direction and intensity, temperature, humidity, level of precipitation and atmospheric pressure. The second subsystem is a custom-made sensor based on a field-mill structure, in charge of acquiring measurements related to the atmospheric electric field. Indeed, this parameter represents a clear indication of the increased risk of lightning formation. The third sub-system is a radar unit which allows the collection of data related to several parameters, both within the domain of the weather forecasts and related to the safety of the operators.

These data are expected to be acquired at predefined intervals and managed by a central processing and transmission structure in charge of creating data packets and sending them to a remote data centre. The previously described subsystems are integrated in a platform featuring a microcontroller-unit (MCU), the technologies for data transmission and system for long-term operation. For data transmission the system is expected to integrate two different solutions which can be used according to the presence of connectivity on the site where the platform will be used. Indeed, the integrated technologies will be both cellular (4G/5G) and non-cellular (LoRaWAN). The first option will be used when there is an available connection. The second one will be activated only in specific cases and will also require the deployment of an ad-hoc infrastructure thanks to the usage of an associated LoRaWAN gateway.

The powering of the system is expected to be guaranteed by a set of batteries complemented by an energy harvesting solution. In particular, device will also be equipped with a power generation system to allow batteries to be recharged in real time, through the use of solar cells or other systems like thermoelectric generators or small-scale wind turbines. Such an energy provisioning unit will be also equipped with a Battery Management System (BMS), which will be in charge and will integrate on-board algorithms to guarantee data security, also in view of the high level of reliability required due to the critical nature of its task.

A scheme of the proposed platform is shown in Figure 1, while an example of a general-purpose weather station realized with off-the-shelf components for the acquisition of standard parameters is shown in Figure 2.

3 Sensor-fusion method

The possibility of predicting the occurrence of critical events like the ones discussed in this paper is based mainly on the ability to collect a large quantity of

heterogeneous data, relating to a wide range of phenomena that may jeopardise the safety of operators. This of course requires advanced heterogeneous sensing technologies but also the ability to give meaning to these data is of fundamental importance, identifying efficient algorithms capable of processing them in a short time, to generate alerts to warn the worker of the actual risk. These two aspects, the collection of a large quantity of heterogeneous data and their processing in near real-time, clash with crucial factors for the diffusion of these technological solutions, such as the high cost of the instrumentation or the size of the devices, which make them difficult to carry.

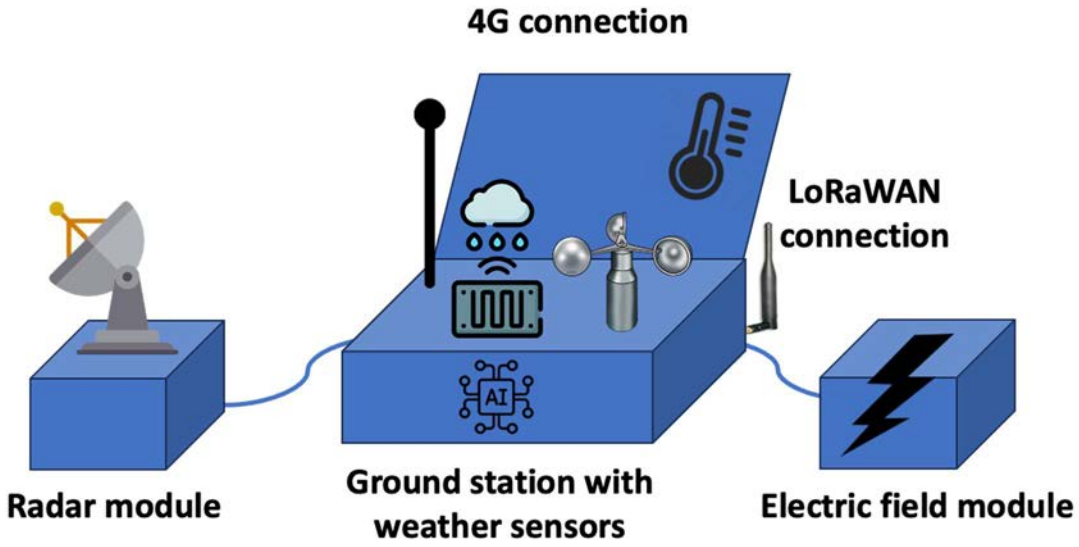

Fig. 1. Architecture of the proposed monitoring platform.

In order to partially overcome these limitations, data collected from the previously described sensors are expected to be combined in a two-layer sensor fusion approach. In particular, to improve the efficiency of the proposed methodology, Artificial Intelligence (AI) is expected to be employed both at the level of the sensing platform, by means of embedded Machine Learning (ML) algorithms and at the level of the data collection centre by means of more complex and structured algorithms. This twofold approach has the main purpose of increasing the overall level of reliability guaranteed by the system.

At the level of the data collection platform, virtual sensing techniques will be employed to exploit the measured quantities with the aim of extracting a risk index. This will involve classification algorithms providing as an output a value indicating the level of the overall risk to which the worker is subject according to the specific meteorological conditions. The final scope will be providing to the workers timely alerts allowing them to seek for protection in case of risk.

In parallel, data transmitted to the data management centre will be exploited both to carry out similar but more accurate predictions, and to improve the accuracy of the ML algorithms. Indeed, the overall structure will rely on a database which will

be enriched day by day, with the aim of providing a solid base for the implementation of more efficiently trained algorithms.
While aiming to develop a system capable of detecting critical environmental conditions of various types that can lead to the occurrence of a wide range of extreme events, the main target scenarios of the system will be two:

- the occurrence of sudden water bombs, which can be extremely dangerous both directly, for workers employed in activities carried out in places at risk (roofs, scaffolding), and indirectly due to the generation of flood phenomena. Consider for example workers employed in riverbed cleaning activities but also simply in construction activities on the roadside or near canals, or in agricultural activities;
- the creation of environmental conditions favorable to the generation of lightning, which can therefore constitute a danger for workers employed in outdoor activities, even in conditions of the presence of metal structures such as scaffolding or canopies. Examples of extremely risky activities in this context are the maintenance and installation of transmission power lines, but also simple agricultural activities in the open field, up to the construction sector again.

Fig. 2. Custom made weather station.

4 Conclusion

The proposed integrated system for real-time monitoring and prediction of extreme weather events represents a significant advancement in safeguarding worker safety, particularly in outdoor environments where the risk of exposure to severe meteorological phenomena is heightened. By leveraging state-of-the-art sensor technologies, innovative ad-hoc measuring tools, and advanced sensor fusion techniques powered by artificial intelligence, the system not only enhances risk detection but also provides timely alerts to mitigate potential hazards.

This approach aligns closely with the vision of Industry 5.0, emphasizing the well-being and safety of workers through the integration of human-centric technologies. The ability to predict and respond effectively to environmental conditions conducive to extreme events, such as lightning or flash floods, holds transformative potential. It empowers organizations to implement proactive safety measures, reducing workplace stress and enhancing overall operational resilience.

While challenges remain—such as the optimization of device portability and cost-effectiveness—the architecture described in this study lays a solid foundation for future advancements in worker protection technologies. By continuously refining data collection and processing algorithms through real-world applications, this system could become a benchmark solution for addressing the evolving risks posed by climate change.

In conclusion, the adoption of such integrated systems is not just an investment in technology but a commitment to preserving lives and fostering safer, more sustainable working environments.

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How can AI reduce fall injuries in the workplace?

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Abstract
Fall-caused injuries are common in all types of work environments, including offices. They are the main cause of absences longer than three days, especially for small and medium-sized businesses (SMEs). However, data, data amount, data heterogeneity, and stringent processing time constraints continue to pose challenges to real-time fall detection. This work proposes a new approach based on a recurrent neural network (RNN) for Fall Detection and a Kolmogorov-Arnold Network (KAN) to estimate the time of impact of the fall. The approach is tested on SisFall, a dataset consisting of 2706 Activities of Daily Living (ADLs) and 1798 falls recorded by three sensors. The results show that the proposed approach achieves an average TPR of 82.6% and TNR of 98.4% for fall sequences and 94.4% in ADL. Besides, the Root Mean Squared Error of the estimated time of impact is approximately $160ms$.

1 Introduction

Every year, 684,000 people lose their lives, as reported by the World Health Organization (WHO). Deaths from falls have increased much faster than any other type of injury in the past two decades. In addition to the number of deaths, 172 million people are disabled by falls each year [1]. This increase is due to many factors, such as aging and urbanization patterns. Although fall-caused injuries are often overlooked, they have a variety of consequences not only for the fall victim and those within their surroundings but also for the entire health/economic system. Specifically, the US spent a total of 50 billion dollars on medical expenses due to falls among senior citizens [2]. Slip and fall injuries are common in all types of work environments, including offices, and are the main cause of absences longer than three days, especially for small and medium-sized businesses (SMEs) [3]. In Italy, falls at the same level cause serious injuries in workers with an average absence duration of 38 days, a duration exceeded only by those due to falls from heights of 47 days. The loss of approximately 2.5 million working days in all sectors

is one of the main causes of unemployment, which has a serious negative economic impact on the entire national production system. Compensation for fall injuries is more than 90 million euros (direct costs) and is one of the primary expenses of the Italian Workers' Compensation Authority (INAIL). Since, as a first approximation, indirect costs can be approximately three times the direct costs, the total cost of fall injuries is more than 370 million euros per year [4]. A key aspect of developing a fall prevention system is to detect and/or predict falls. These technologies can now be found in wearable devices thanks to recent sensors and integrated circuit advances. However, data quality (in the presence of interference and unstructured surroundings), data amount, data heterogeneity, and stringent processing time constraints (fall must be identified within a tight time restriction) continue to pose challenges to real-time fall detection [5]. Most studies focus on the detection of falls after impact [6], [7], [8], [9]; instead, this research aims to find a real-time software solution that can be integrated into a plug-and-play wearable device to mitigate impact. The software solution should be able to adjust to the needs of various users, irrespective of their age, gender, or physical makeup. It should also function well in most environments, protecting workers from injury if they fall to the same or lower level. Unlike previous studies [10], [11], [12], [13], which focus on older people, this work aims to address a more agile group of people, industrial workers. Workers on construction sites are more at risk and are forced to perform repetitive, heavy, and challenging tasks, which have a greater impact on their mental and physical health than in other industries. In addition, most studies ignore the subject's reaction. For example, young and healthy subjects will not fall like older people, but in many cases, they may be fast enough to arrest the fall or catch objects around them. This introduces false positive effects, causing improper activation of the prevention system, and may discourage users from wearing it. The appropriate activation of the prevention mechanism is the main goal; fall detection alone is insufficient for our study. Therefore, this work considers the critical issues and opportunities highlighted above and proposes a new approach based on a recurrent neural network (RNN) for Fall Detection and a Kolmogorov-Arnold Network (KAN) to estimate the time of impact of the fall [14]. Effectively predicting the time of impact (i.e., lead time) during a fall is not yet adequately addressed. Some approaches rely on predicting the trajectory of the fall to estimate the time of impact [15], [16], [17].

2 SisFall

The publicly available SisFall [18] dataset is used to train the proposed approach because it is one of the most comprehensive datasets with many subjects and falls. It contains 15 types of falls and 19 types of Activities of Daily Living (ADLs), listed in Tables 1 and 2.

Code	Activity
F01	Fall forward while walking caused by a slip
F02	Fall backward while walking caused by a slip
F03	Lateral fall while walking caused by a slip
F04	Fall forward while walking caused by a trip
F05	Fall forward while jogging caused by a trip
F06	Vertical fall while walking caused by fainting
F07	Fall while walking, with the use of hands-on a table to dampen fall, caused by fainting
F08	Fall forward when trying to get up
F09	Lateral fall when trying to get up
F10	Fall forward when trying to sit down
F11	Fall backward when trying to sit down
F12	Lateral fall when trying to sit down
F13	Fall forward while sitting, caused by fainting or falling asleep
F14	Fall backward while sitting, caused by fainting or falling asleep
F15	Lateral fall while sitting, caused by fainting or falling asleep

Table 1 - Types of falls selected in SisFall.

Code	Activity
D01	Walking slowly
D02	Walking quickly
D03	Jogging slowly
D04	Jogging quickly
D05	Walking upstairs and downstairs slowly
D06	Walking upstairs and downstairs quickly
D07	Slowly sit in a half-height chair, wait a moment, and up slowly
D08	Quickly sit in a half-height chair, wait a moment, and up quickly
D09	Slowly sit in a low-height chair, wait a moment, and up slowly
D10	Quickly sit in a low-height chair, wait a moment, and up quickly
D11	Sitting a moment, trying to get up, and collapse into a chair
D12	Sitting a moment, lying slowly, wait a moment, and sit again
D13	Sitting a moment, lying quickly, wait a moment, and sit again
D14	Being supine, moving to a lateral position, waiting a moment, and moving back
D15	Standing, slowly bending at knees, and getting up
D16	Standing, slowly bending without bending knees, and getting up
D17	Standing, get into a car, remain seated, and get out of the car
D18	Stumble while walking
D19	Gently jump without falling (trying to reach a high object)

Table 2 - Types of activities of daily living selected in SisFall.

The activities were recorded by 38 volunteers, 23 adults, and 15 elderly (60-75 years old). The elderly simulated only ADLs, except a Judo expert, who also simulated falls. In addition, some elderly did not do some activities due to personal problems

(or medical recommendations). Each task was repeated 5 times for each subject. Overall, the dataset includes 2706 ADLs and 1798 falls recorded by three sensors (two accelerometers: an Analog Devices ADXL345 and a Freescale MMA8451Q, and one gyroscope Texas Instruments ITG3200) worn on the waist at $200Hz$. Accurate labeling of the fall period from the motion sequence is a time-consuming and labor-intensive prerequisite for algorithm development. To annotate the fall period from the SisFall dataset, Musci et al. [19] first defined the standard labeling criteria by consulting experts in the field, then performed the labeling separately and revised it jointly in multiple steps to improve consistency. This process tends to be subjective because SisFall was constructed without video references.

3 Fall Detection Data Processing

A deep recurrent neural network (RNN) was chosen for data-based fall detection, where the data used to train the neural network are obtained from the SisFall dataset [18] labeled in [19] as no-background. Using the two accelerometers and one gyroscope, the orientation of the subject was calculated through a six-axis Kalman filter [20] and expressed as a quaternion. Then, the angle θ and acceleration $\dot{\theta}$ of the body relative to the ground were estimated. A full description of the features used is given in Table 3.

Symbol	Description
y	Age of the subject
h	Height of the subject
w	Weight of the subject
g	Gender of the subject
$a_{x,ADXL345}$	Acceleration data in the X axis measured by the sensor ADXL345
$a_{y,ADXL345}$	Acceleration data in the Y axis measured by the sensor ADXL345
$a_{z,ADXL345}$	Acceleration data in the Z axis measured by the sensor ADXL345
$a_{x,MMA8451Q}$	Acceleration data in the X axis measured by the sensor MMA8451Q
$a_{y,MMA8451Q}$	Acceleration data in the Y axis measured by the sensor MMA8451Q
$a_{z,MMA8451Q}$	Acceleration data in the Z axis measured by the sensor MMA8451Q
$\dot{\alpha}_{x,ITG3200}$	Rotation data in the X axis measured by the sensor ITG3200
$\dot{\alpha}_{y,ITG3200}$	Rotation data in the Y axis measured by the sensor ITG3200
$\dot{\alpha}_{z,ITG3200}$	Rotation data in the Z axis measured by the sensor ITG3200
q_1	Orientation data in Quaternion, the first element
q_2	Orientation data in Quaternion, the second element
q_3	Orientation data in Quaternion, the third element
q_4	Orientation data in Quaternion, the fourth element
θ	Body angle relative to the direction of gravity
$\dot{\theta}$	Body angular acceleration relative to the direction of gravity

Table 3 - List of features

The network has multiple inputs, consisting of 4 inherent characteristics of the subjects: Age, Height, Weight, Gender, and a multivariate time series consisting of the measurements of the two accelerometers and the gyroscope, the orientation of the body (expressed as a quaternion), and the relative angle of the body to the direction of gravity θ. In total, the neural network input has 18 entries. The output is the probability of falling $P(falling)$, and if $P(falling) > 0.5$, the subject is assumed to be falling. The network architecture is chosen similarly to the RNN architecture used in [19] and depicted in Figure 1. The input is processed by the fully connected Layer 1, and a second fully connected layer (Layer 8) collects the output from the LSTM cell of Layer 6. Its output is sent to the final SoftMax classifier (Layer 9), which produces the falling probability of the classification. The core of the network is based on the two LSTM cells stacked in layers (Layers 4 and 6). LSTM cells are popular Deep Learning architectures because of their ability to capture time-dependent relationships in the input data efficiently. The size of the tensors within each LSTM gate, commonly referred to as the inner dimension, is chosen to be 2^4, as well as the neurons in the first fully connected layer. The architecture also includes a batch normalization layer (Layer 2) to regularize the input data and three drop-out layers (Layers 3, 5, and 7). The latter layers are used during training to improve generalization as they are removed from the inference module built into the device. The dropout rate is selected to be 50%.

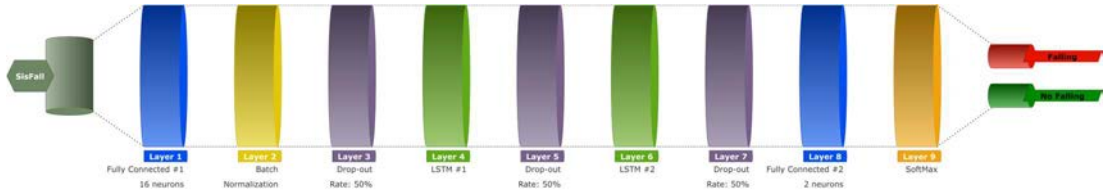

Fig. 1 - The architecture of the Fall Detection Neural Network.

The portion of the dataset used to train, validate, and test the FDNN contains only the sequences with a fall, 1798 fall sequences for 24 subjects, 23 adults, and one elderly. Then, this standardized dataset is shuffled and divided into 3 sub-datasets, one for training, one for validation, and one for testing the FDNN algorithm, in 60%, 20%, and 20%, respectively. The FDNN is trained using the training dataset to train the weight of the FDNN and the validation dataset to choose the optimal weights, that is when the accuracy of the FDNN on the Validation dataset is highest. In the training procedure, the batch size is set to 128 sequences and the number of epochs is set to 64.

4 Time of impact Data Processing

Overall, 19 signals are considered at the beginning of this study. From each 15-second-long experiment, only the part related to the fall was extracted, thus

excluding the initial activity, e.g., walking, jogging, sitting, etc., and the final parts where the subject remains motionless after hitting the ground. This interval was defined from the time the data are labeled by Musci et al. [19] as “FALL'' to the time when the standard deviation of the acceleration is less than a threshold. The time of impact was defined as the time between the moment under investigation and the moment when the subject hits the ground. This value is a multiple of the sampling period, i.e., $5ms$, and decreases during the fall until it reaches zero.

4.1 Feature Selection

A fully data-driven approach is adopted based on the use of two feature selection algorithms to restrict the number of features. Specifically, using correlation analysis and a feature selection algorithm called Minimum Redundancy Maximum Relevance (mRMR) [21]. Correlation analysis is the simplest and, very often, one of the most effective methods for feature reduction. It can be used in a variety of ways, such as when two features have a high correlation, one of them can be eliminated, or if one feature is poorly correlated with the value you want to estimate, that feature can be eliminated. In this study, the second approach was considered and the features below a correlation score were excluded. The mRMR algorithm identifies a set of mutually dissimilar and maximally distinct features, allowing them to effectively represent the response variable. The algorithm seeks to maximize the relevance of the features to the response variable while minimizing redundancy within the feature set. The method makes use of mutual information measures, such as mutual information between a feature and the response variable, as well as mutual information of the variables and features. Through the correlation analysis, four features were found to be the most highly correlated with the time of impact and $a_{y,ADXL345}$, $a_{y,MMA8451Q}$, θ and $\dot{\theta}$ were chosen. Similarly, using the mRMR algorithm, the selected features are $\dot{\alpha}_{y,ITG3200}$ and θ.

4.2 Fine Tuning

The KAN identification problem has been solved by using piecewise linear basis functions as supporting basis functions and the Newton-Kaczmarz method [22] for solving systems of nonlinear equations. However, it is necessary to decide other parameters of the model, such as the number of internal and external piecewise linear basis functions, n and q, respectively, the learning rate or regularization parameter μ of the Newton-Kaczmarz method, and the time window w used to predict the time of impact. All these parameters are calculated through a k-fold cross-validation process. Each subject repeated the task 5 times, so three repetitions are used to train the model and one to validate it. The last repetition was used to test the performance of the proposed approach and compare it with other well-known Machine Learning methods. This approach was used to reduce data overfitting and train with as much varied data as possible. The training processing lasted 10 epochs, and the data were standardized by subtracting from

the mean and dividing by standard deviation to put different variables on the same scale. The best combination of parameters was found to be $n = 4$; $q = 64$; $\mu = 0.0625$; and $w = 50\,ms$.

5 Results

This section describes the results obtained considering our proposed RNN for Fall Detection and KAN for Time of Impact Estimation. The results below relate to the data in SisFall and analyze the performance of the approach both with respect to different activities and for different subjects.

6 Fall Detection

Once the FDNN is trained, it is tested on the Test dataset (~360 sequences). Figures 2 and 3 show the TNR and TPR as a function of the subjects and the activities, respectively. The tables show the average value between the repetitions, and the blank cells mean that there are no samples of those subjects and activities in the Test dataset. In particular, the subjects SE01-SE05 do not simulate the Falling events, as written in the SisFall paper description. Being the annotation a manual procedure, the start and end of the actual fall may not precisely match the time defined in the annotated dataset. The TNR value is, in most cases, more than 95% and, on average, 98.4%. The TPR value is, on average, 82.6%. In many cases, the FDNN succeeds in even perfectly classifying the fall; however, there are some cases in which the TPR is not much higher than 50%. Besides, it is important to consider that since the fall is an event that persists for a very short time, failure to classify even a few samples lowers the TPR significantly. Analyzing the different activities, activity F10 appears to be the most difficult to classify correctly. Then, the FDNN is tested on the sequences of the SisFall dataset without fall (ADLs), 2701 sequences. Figure 4 shows the TNR and TPR, respectively, as a function of subject and activity. The TNR value is, in most cases, 100%; but in some cases, it is also less than 20%. Particularly for activities: D03, D04, D12, D13 and D14. The worst activity for the TNR metric is D04. The average TNR value is 94.4%.

Fig. 2 - TNR as a function of subject and activity for falls.

Fig. 3 - TPR as a function of subject and activity for falls.

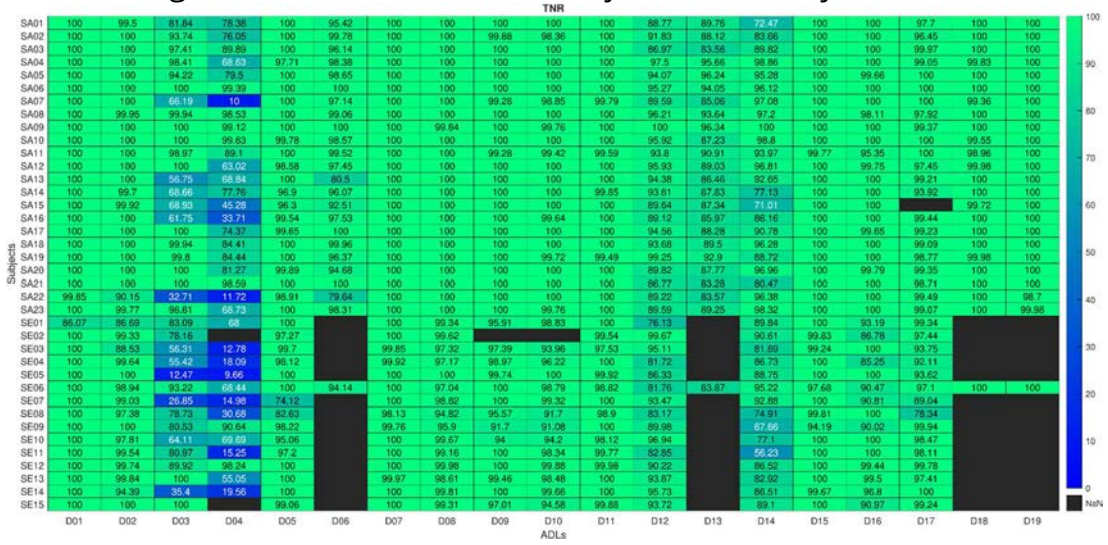

Fig. 4 - TNR as a function of subject and activity for ADLs.

7 Time of Impact Estimation

Figure 5 shows the RMSE for different subjects and falls, considering the best parameters on the test data. The performance obtained is generally positive, on average the RMSE on the 1798 falls is about $160\,ms$. On some subjects, the algorithm obtains worse results, such as for SA10; likewise, some types of falls, such as F13. Particularly in the combinations SA05-F13 and SA21-F11, the RMSE exceeds the mean error by almost 4 times. In contrast on F05 and F15, errors are never found to be too large, demonstrating that the proposed KAN is an excellent method for estimating time of impact and suitable for estimation in the case of falls of different types. With SA03, SA06, and SA12, the proposed approach achieves excellent results for almost all types of falls.

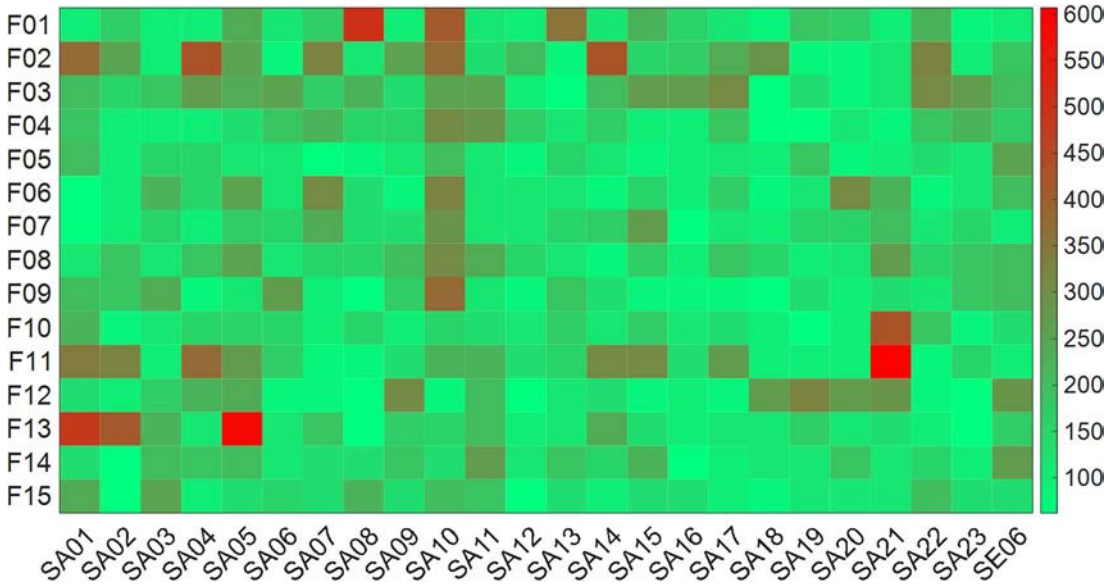

Fig. 5 - Heatmap about RMSE for different subjects and falls [ms].

Finally, the performance obtained by the proposed KAN is evaluated, showing the trend of true time of impact (Ground Truth) and projected time of impact. In each instant, the predicted time of impact is estimated. Figure 6 shows this trend in the case of the 18th subject, who lateral falls while walking caused by a slip (F3). The fall takes about $700\,ms$, and the ground truth is a unit line from this value to 0, which is the moment the subject touches the ground. When the values of time of impact are sufficiently large, the network faithfully follows the trend. On the other hand, when the time of impact is very small, the network estimates a constant value of approximately $140\,ms$.

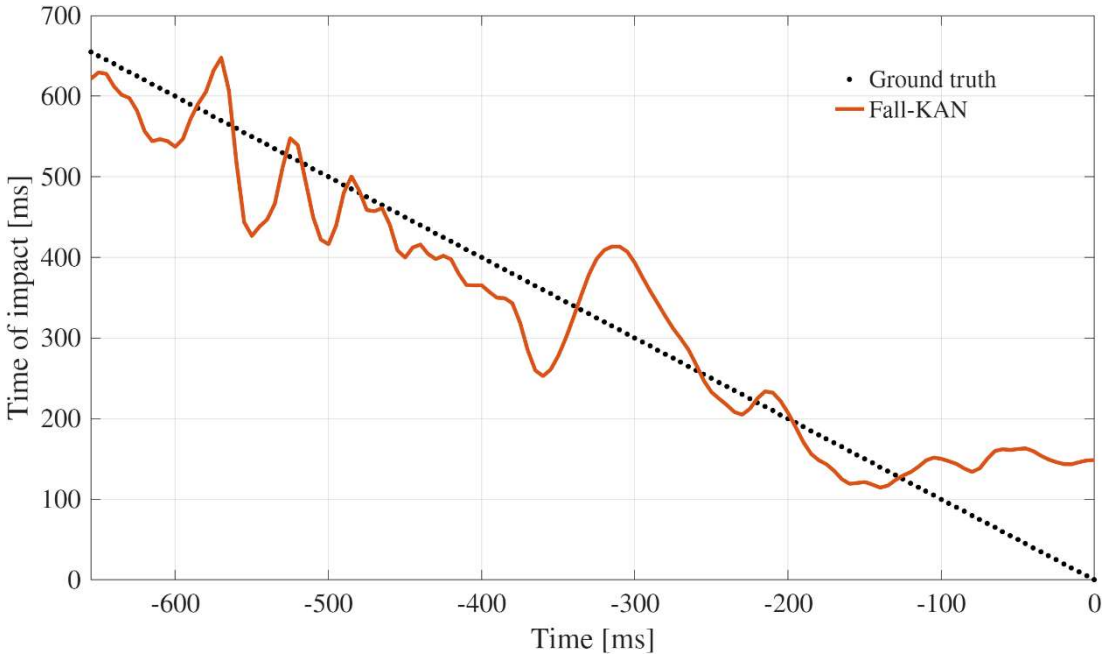

Fig. 6 - Time of impact for the 18th subject during the 3rd fall.

8 Conclusions

The Fall Detection Neural Network performed excellently on SisFall with an average TPR of 82.6% and TNR of 98.4% in fall sequences and 94.4% in ADL sequences. While with the KAN, only five features were found to be useful for time of impact estimation, of which 3 were already in the dataset, and two were calculated using an accelerometer and a gyroscope. The RMSE obtained by the proposed KAN is about $160ms$. However, this value is distorted by estimating very small values of impact time where the error is constant and equal to about $140\ ms$ in the example presented. Future studies will focus on the joint use of the two techniques and performance evaluation.

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How can AI reduce wrist injuries in the workplace?

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Abstract
This paper explores the development of a control and sensor strategy for an industrial wearable wrist exoskeleton by classifying and predicting workers' actions. The study evaluates the correlation between exerted force and effort intensity, along with sensor strategy optimization, for designing purposes. Using data from six healthy subjects in a manufacturing plant, this paper presents EMG-based models for wrist motion classification and force prediction. Wrist motion recognition is achieved through a pattern recognition algorithm developed with surface EMG data from an 8-channel EMG sensor (Myo Armband); while a force regression model uses wrist and hand force measurements from a commercial handheld dynamometer (Vernier GoDirect Hand Dynamometer). This control strategy forms the foundation for a streamlined exoskeleton architecture designed for industrial applications, focusing on simplicity, reduced costs, and minimal sensor use while ensuring reliable and effective assistance.

1 Introduction

Among all types of exoskeletons, in recent decades, very few have focused on the wrist, especially for industrial applications, as reported in many review articles on upper limb exoskeletons [1 - 5], as most are developed for rehabilitation and training post-injury and have limitations in design and control. Control strategies using multi-sensor data—such as position (via encoders, IMUs), force/torque (using load cells, FSRs), and bio-signals (EMG)— have increased over the years and provide critical feedback from the user to drive exoskeleton actuators. Traditional control methods, such as Conventional Trajectory Tracking (CTT) and Assist-As-Needed (AAN), rely on predefined dynamic models, while newer machine learning (ML) and deep learning (DL) approaches bypass complex equations by predicting human movement patterns from measured data [6 - 10]. In wrist exoskeletons, a common ML control strategy involves classifying surface electromyography (sEMG) signals to detect user intention and control actuators accordingly [6 - 10]. However, only a few studies address activity recognition and force estimation together. Leone et al. [11] introduced a hierarchical model based on Non-Linear Logistic Regression (NLR) for gesture and force level classification, while other studies [12] and [13] focus on predicting grip force and wrist

angles using simultaneously sEMG and accelerometers. This research seeks to enhance sEMG-based control for wrist exoskeletons by accurately predicting user actions and efforts while optimizing EMG sensor placement. By identifying the minimal EMG channels required, we aim to balance accuracy with computational efficiency for force prediction across wrist activities. This approach guides the design of an industrial wrist exoskeleton and helps determine if additional sensors are necessary for effective assistance. The paper is organized as follows: Section II covers system architecture and data acquisition; Section III details EMG and force data processing, feature extraction, and reduction; Section IV discusses algorithms for gesture classification and force estimation; and Sections V and VI summarize main achievements and outline future work.

2 Methodology

This chapter briefly describes the aims of this research and focuses on the experimental method of acquiring EMG and force measurements developed from wrist movements.

2.1 System design

This research is intended as a preliminary study for designing and developing a prototype of a soft wrist exoskeleton to assist primary wrist movements, provide sufficient force support, and ensure user acceptance in industrial settings. The exoskeleton will actuate and monitor three degrees of freedom—wrist flexion/extension, radial/ulnar deviation, and grasping—using sEMG sensors to detect muscle activity and predict wrist movement and exerted force. A two-level control strategy will be used, with high-level control interpreting EMG signals to guide movement and provide assistive force, and low-level control ensuring precise tracking at each actuator to guarantee that the user can move freely as intended and experience assistive forces with appropriate timing and intensity. This paper outlines a high-level control strategy using machine learning to classify wrist movements and forces exerted from raw EMG data. The classified movement determines the direction of the force/torque and, thus, which motor to activate based on the expected movement, while EMG signal amplitude determines the output force/torque intensity to be provided by the actuators.

2.2 Experimental setup

To detect and predict wrist movements, forearm muscle activity is recorded with a Myo Armband (Thalmic Labs), an 8-channel, dry-electrode EMG sensor with a 200 Hz sampling rate. While more convenient than gel-based electrodes, it has limitations in signal quality, sensitivity to motion artifacts, and frequency range (recommended EMG sampling is 1000 Hz for EMG signals with a frequency range of 5-500 Hz) [9], [10]. The acquisition system further down-samples the signals to 100 Hz, which may reduce the accuracy of ML classifiers in distinguishing wrist gestures. Despite these

limitations, the Myo Armband is chosen for its ease of use, even in production settings. Additionally, a GoDirect Hand Dynamometer (by Vernier) measures wrist force across various positions. Data is collected on a Raspberry Pi 4, with the Myo Armband streaming wirelessly to a USB dongle on the Pi, and the dynamometer connected via USB. At the same time, the execution and recording program is run from a host computer terminal. Figure 1 shows the setup.

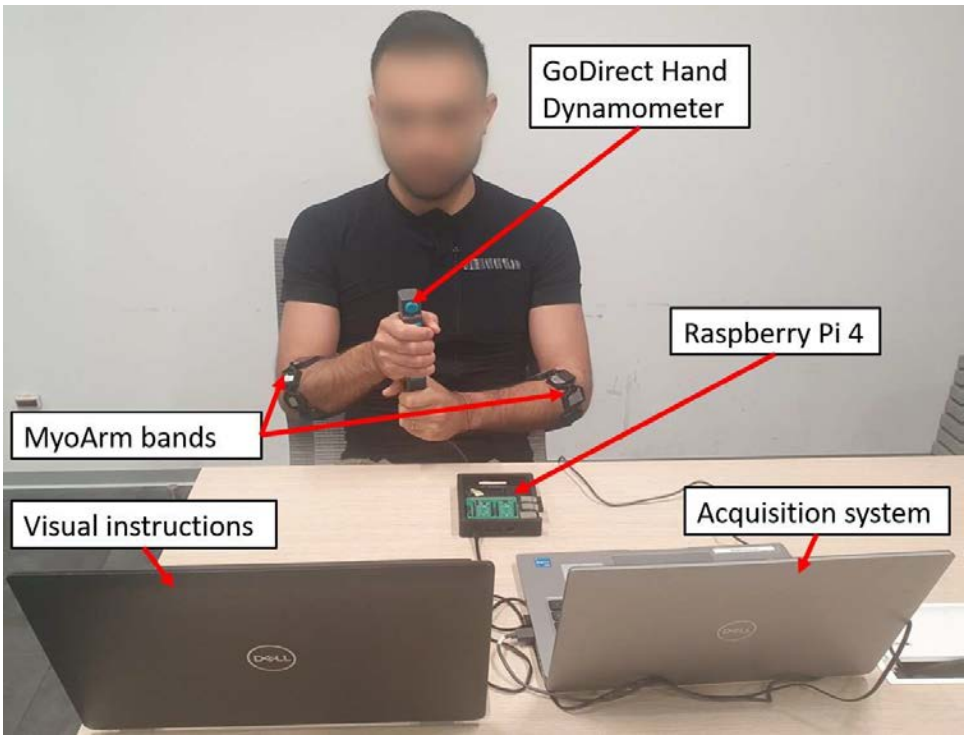

Fig. 1 - Setup of the data acquisition system. Example of measurement during a Hand Close (i.e., grasping) phase.

2.3 Experimental protocol

Participants in this study are artisan workers from Prestige Italia S.p.A., a leading horse saddle manufacturer. Their work is physically demanding, often leading to injuries such as carpal tunnel syndrome. Six healthy male subjects (ages 25–45) were recruited, five right-handed and one left-handed. The Liguria Ethics Committee approved the experiment (CER Liguria 001/2019), adhering to the Helsinki Declaration and GDPR for privacy protection [14]. For each experimental session, participants were seated with elbows and forearms resting on a table, leaving only the wrist free to move, ensuring minimal shoulder and elbow compensation. Visual instructions guided the participants through five wrist gestures, shown in Figure 2, — Wrist Flexion (WF), Wrist Extension (WE), Radial Deviation (WRD), Ulnar Deviation (WUD), and Hand Close (HC, or grasping) — chosen to align with the exoskeleton's degrees of freedom. Each participant wore a Myo Armband on both forearms to capture EMG signals. They are positioned following the arrangement proposed in [9], and about the orientation

of the Myo LED light indicating channel No. 4, the EMG sensors are positioned near the following muscles: *Extensor Carpi Ulnaris* (channel 1), *Extensor Digitorum* (channel 2), *Extensor Carpi Radialis Longus e Brevis* (channel 3), *Brachioradialis* (channel 4), *Flexor Carpi Radialis* (channel 5) *Palmaris longus* (channel 6) *Flexor Digitorum Superficialis* (channel 7), and *Flexor Carpi Ulnaris* (channel 8). To ensure that the same channels read signals from the same left and right muscles, the Myo Armbands are mirrored on the forearms to reflect the anatomical arrangement muscle bundles. Participants performed each movement isometrically to reach the Maximum Voluntary Contraction (MVC) of the forearm muscles while applying maximum force on a digital dynamometer. This helped correlate EMG signal amplitude with exerted force and distinguish muscle activation for each gesture. Data collection for each task followed this sequence: starting with the wrist at rest (5-6s), then moving into the designated position while applying maximum contraction, holding for 5-6s, and finally relaxing for 5-6s. For Hand Close, participants also performed a step-force task, gradually increasing grip from 0N to 100 N by 10N increments every 5-6s. Since grasping is one of the most frequent gestures active during manipulation and is often combined with other wrist movements, this measure evaluates muscle activation across different force levels, especially during sustained activities with force requests far from the maximum (at most 1/3). Participants did not show any signs of physical or mental fatigue.

Fig.2 - Wrist gestures included in the study: from left to right Wrist Flexion (WF), Wrist Extension (WE), Wrist Radial Deviation (WRD), Wrist Ulnar Deviation (WUD), and Hand Close (HC).

3 Data Processing

This chapter presents the processing of EMG data, as schematically illustrated in Figure 3, with a description of the various techniques used to extract features and statistical indices from the dataset for classification.

3.1 EMG Pre-processing

The electromyographic signal is inherently noisy, so it undergoes pre-treatment before use. First, signals are rectified by converting data to absolute values, then passed through a 5 Hz low-pass filter optimized for this dataset. Finally, they are normalized to the 95th percentile of Maximum Voluntary Contraction (MVC) to ensure comparability, smooth out electrical spikes, and produce a cleaner signal.

3.2 Channel selection

For Gesture Recognition (GR) and Force Estimation (FE), a data-driven feature selection approach is used with EMG data. The Minimum Redundancy Maximum Relevance (mRMR) [15] algorithm is applied to select the most informative and distinct channels. Widely used in fields like cancer diagnostics and speech recognition [16], [17], mRMR minimizes redundancy in the feature set while maximizing relevance to the target variable by analyzing mutual information between features and the response variable. or each feature, a score is calculated to assess its importance. Each feature's score is normalized for the total sum, and the most relevant channels are chosen for GR and FE.

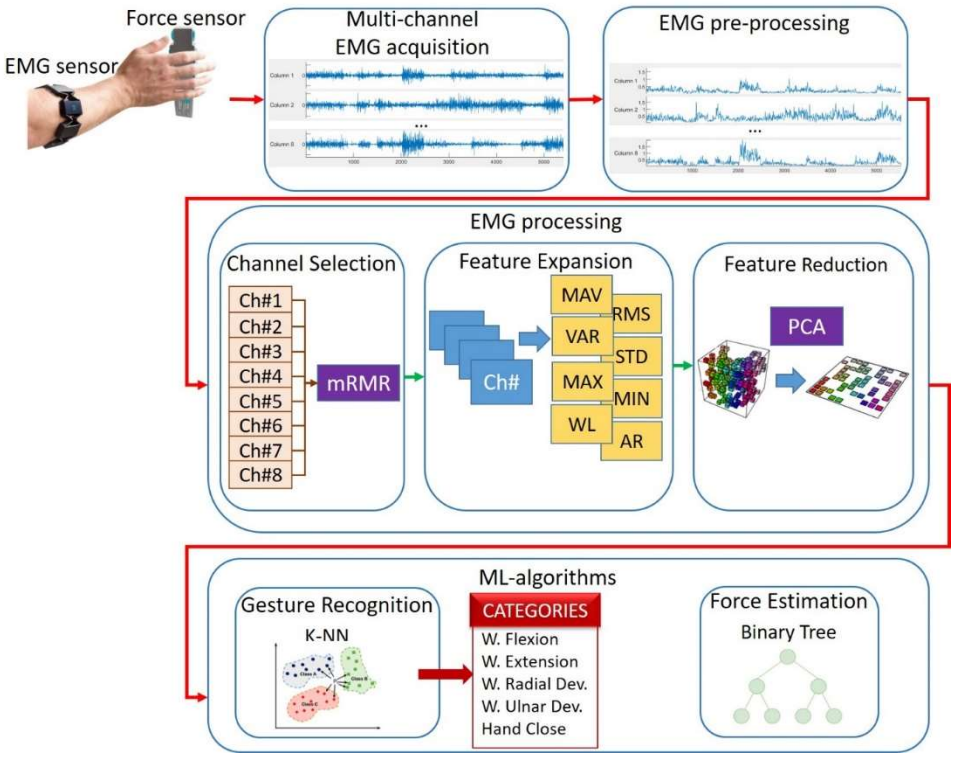

Fig. 3 - Block diagram describing the data acquisition process, the EMG signal classification, and the force prediction scheme.

3.3 Features Expansion

Feature expansion enhances the dataset by generating new features based on the original set, creating a subspace with additional statistical indices from the Time Domain (variation of each EMG signal over a time window) and Spatial Domain (variation across EMG channels at the same sampling time). Time-based features are widely used in EMG recognition due to their ease of calculation [18]. The following features are calculated (summarized in Table I, with N as the time window and K as the number of channels):

- Mean Absolute Value (MAV): Average absolute EMG signal amplitude.
- Root Mean Square (RMS): Average signal power over time.
- Variance (VAR): Mean square deviation of the signal.
- Standard Deviation (STD): Square root of variance, indicating data spread.
- Maximum (MAX) and Minimum (MIN): Highest and lowest signal values.
- Waveform-Length (WL): Cumulative signal length, reflecting its waveform amplitude, frequency, and duration.
- Auto-Regressive (AR) Model: Expresses each sample as a linear combination of previous samples, using AR model coefficients as features.

As the number of channels changes, feature expansion adjusts the feature set accordingly.

3.4 Features Reduction

After feature expansion, Principal Component Analysis (PCA) reduces data dimensions by projecting the dataset onto a lower-dimensional subspace. This technique creates uncorrelated variables that retain the most relevant information and capture maximum variance from the original data. The top transformed features are selected based on cumulative variance. This reduces model complexity, minimizes over-fitting, and enhances computational efficiency and predictive accuracy [19]. The number of components after PCA analysis is shown in Table II. Unlike feature expansion, the number of PCA features can vary depending on explained variance and data distribution, even when the number of channels remains fixed.

4 Results

The control algorithm described is based on state-of-the-art controllers that utilize machine-learning strategies to predict hand/wrist movements according to muscle activation and force [9 - 11], [14], [15]. Instead of more advanced neural networks or deep learning techniques, machine learning has been preferred and considered more efficient due to limited experimental data [19].

4.1 Gesture Recognition (GR)

The Gesture Recognition (GR) part estimates wrist movement using the 8 EMG channels of the Myo Armband. This classification problem is solved with the K-

Nearest Neighbors (KNN) algorithm [20], chosen over Support Vector Machine (SVM) and neural network due to comparable or superior results with less computational demand. Neural networks performed poorly given the need for more subjects and repetitions, so alternative techniques were not further detailed. After data preprocessing, the mRMR algorithm assesses the importance of each channel in the Myo Armband, showing that channels 2, 5, and 8 are the most significant. Selected channels undergo feature expansion, and then reduction with PCA to retain 95% explained variance. Using these features, a KNN model is trained on data from six subjects performing five wrist movements (WF, WE, WUD, WRD, and HC) for a total of 60 sequences and approximately ~45k samples, employing 5-fold cross-validation. Model parameters include 10 neighbors, Euclidean distance, and standardized data. Accuracy increases with the number of channels: averaging 50% with one channel, 70% with two, 85% with three, and over 90% with more. Figure 4 illustrates this accuracy trend. In Figure 5, GR results for the fourth subject compare an 8-channel model (99% accuracy) with a 3-channel model (87% accuracy) against ground truth. While 8 channels provide higher accuracy, the 3-channel model achieves adequate performance with reduced computational load for real-time applications.

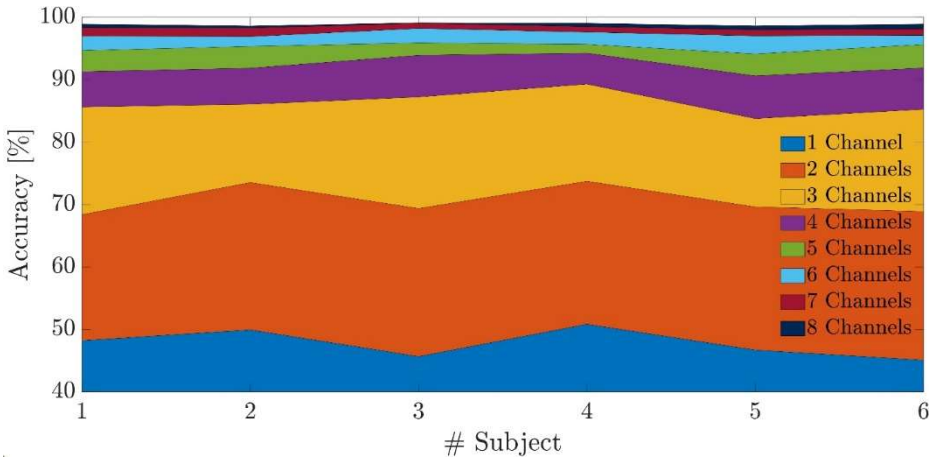

Fig. 4 - Accuracy obtained from KNN models as a function of the number of selected channels (from 1 to 8 channels as displayed in the legend) for different subjects.

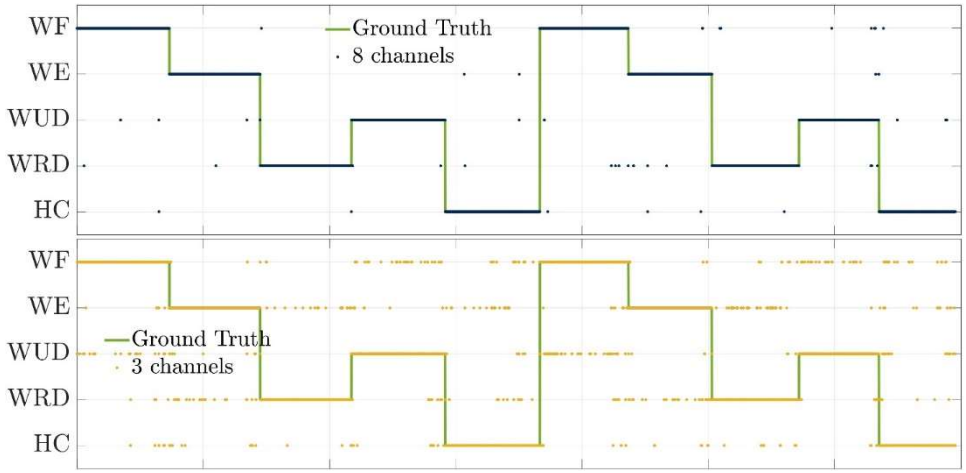

Fig.5 - Comparison of Gesture Classification accuracy for the KNN model with eight channels (top) and three channels (bottom) available for different tasks of the fourth subject. The green line describes the ground truth, while the dark blue/yellow dots represent the expected value of the gesture.

4.2 Force Estimation (FE)

The Force Estimation (FE) process predicts force output using the 8 EMG signals from the Myo Armband. This problem is addressed with a Regression Tree algorithm, chosen over neural networks due to limitations in subject and repetition variety. After data preprocessing, the mRMR algorithm ranks the importance of each EMG channel, with channel 8 rated highest, followed by channels 2 and 5. Selected channels undergo feature expansion and PCA reduction, retaining 95% of the variance. Using these features, a Regression Tree model is trained on data from six subjects performing five wrist activities for both hands, yielding 72 sequences and ~110k samples using a 5-fold cross-validation scheme with the following parameters: a minimum leaf size of 10 and a low-pass filter with a 1Hz cutoff. Force values, ranging from a few to hundreds of Newtons, are normalized by subtracting the minimum value and dividing by the 95% percentile to enhance prediction accuracy, with the regressor output filtered at 1Hz to smooth quantized results. Models trained with different numbers of channels are evaluated using Root-Mean-Square Error (RMSE) and Median Absolute Percentage Error (MdAPE). With one channel, the average MdAPE is around 22%, dropping to 13% with two channels, 9% with three, and below 7% with more. Three channels result effective for FE as well as Gesture Recognition. Moreover, the most effective channels are the same already chosen for GR. Figures 6 and 7 compare FE results for all activities in the fourth subject's left and right hands respectively, using an eight-channel (dark blue lines) and three-channel model (yellow) against the ground truth (green). Although the three-channel model is slightly noisier, it remains accurate, supporting efficient real-time force estimation for wrist exoskeleton control.

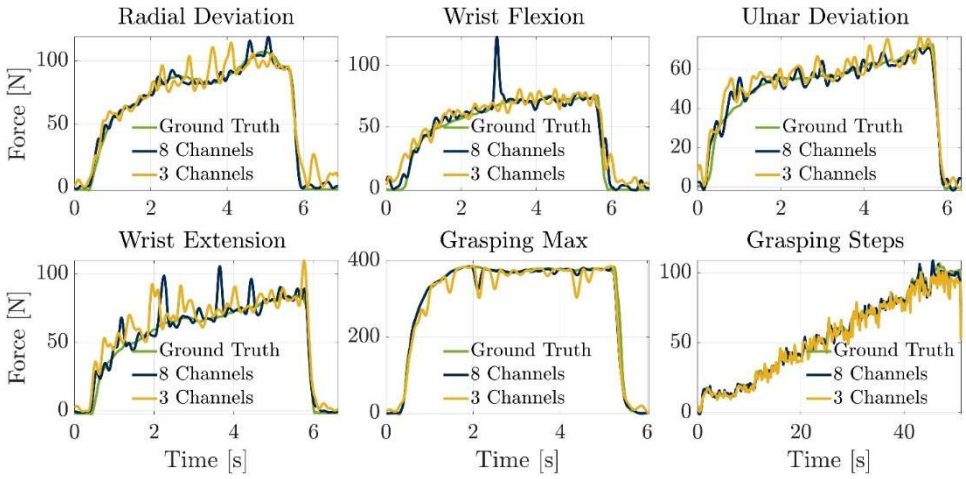

Fig. 6 - Comparison of the Force Estimation for the filtered Regression Tree model with eight channels (dark blue lines) and three channels (yellow lines) for all the activities conducted with the fourth subject's left hand. The green line describes the ground truth.

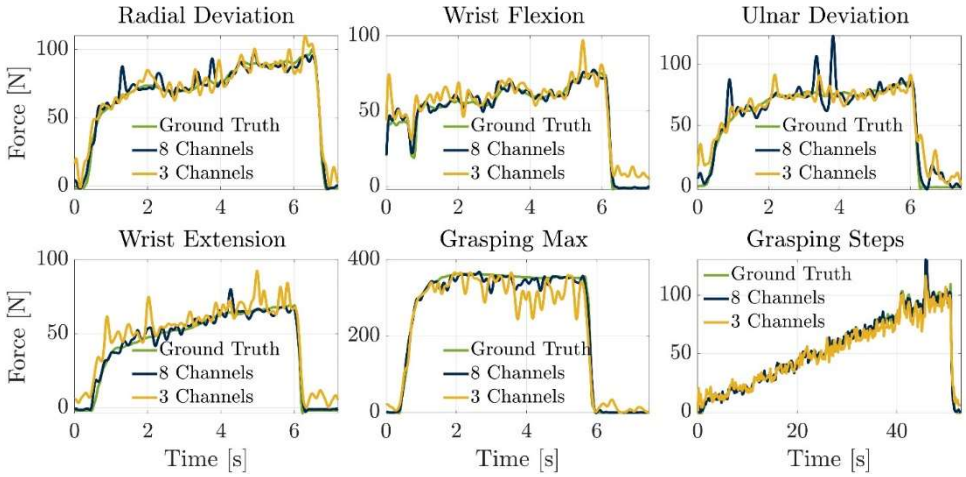

Fig. 7 - Comparison of the Force Estimation for the filtered Regression Tree model with eight channels (dark blue lines) and three channels (yellow lines) for all the activities conducted with the fourth subject's right hand. The green line describes the ground truth.

5 Discussion

Results in Section IV indicate that using eight EMG channels achieves a GR accuracy of 99%, which decreases to 87% when reduced to three channels. For FE, MdAPE is below 7% with eight channels and around 9% with three. Despite these small declines, using three channels is sufficient to get remarkable results, enabling real-time operation with lower computational demand. Notably, the key channels for both GR and FE are channel 2, channel 5, and channel 8 correspond to the *Extensor Digitorum*, *Flexor Carpi Radialis*, and *Flexor Carpi Ulnaris* muscles, respectively. This insight is valuable for wrist exoskeleton design, as positioning three EMG sensors optimally could be sufficient to track wrist motion and estimate force/torque requirements

without needing IMU or force sensors. A limitation of this study is the limited amount of data. While a free dataset [9] is partially helpful, the subjects in these studies are researchers with different muscle activation and joint development compared to field workers. Therefore, integrating data from such sets with that collected at Prestige Italia poses challenges.

6 Conclusion

Wrist exoskeletons require advancements in design and control strategies for improved reliability and precision. Modeling wrist kinematics and dynamics are challenging due to their complexity, making machine learning (ML) valuable for learning, classifying, and predicting user-specific movement patterns without predefined equations. Our research develops a control strategy for an industrial wrist exoskeleton using ML for pattern recognition to identify wrist movements (flexion, extension, radial and ulnar deviations, grasping) and a regression model to estimate the force exerted. An EMG sensor strategy optimization is also considered and evaluated to simplify the design, costs, and data process by adopting as few sensors and electronic components as possible while retaining accuracy and reliability and evaluating whether additional sensors are necessary. The findings show that three EMG electrodes positioned on key forearm muscles (Extensor Digitorum, Flexor Carpi Radialis, Flexor Carpi Ulnaris) can achieve over 85% accuracy in predicting wrist movement and estimating force. Data from six workers are collected using an 8-channel EMG sensor (Myo Armband) and a hand dynamometer (GoDirect by Vernier). After data pre-processing (filtering, normalization), feature selection (mRMR), feature expansion (statistical indices MAV, RMS, VAR, etc.), and PCA-based reduction, significant features are identified for different channels. A Gesture Recognition (GR) algorithm via KNN and a Force Estimation (FE) model via a Regression Tree predict wrist motions and force output. This approach supports both hands and lays a foundation for advanced control in a wrist exoskeleton for industrial assistance. Limitations include the small sample size and repetitions; future work aims to improve accuracy with a larger dataset, training the model to assist users in various tasks and adapt to individual differences.

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Stepps – computer vision solutions for industrial safety

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Abstract

This paper presents a technological solution leveraging Artificial Intelligence, specifically Computer Vision, to address critical challenges in occupational health and safety within industrial environments. Motivated by the high incidence of workplace accidents in Brazil, with over 612,900 incidents reported in 2022 alone, Stepps (a Brazilian Artificial Intelligence startup) and tec.nicum (a division of the Schmersal Group) developed a set of real-time monitoring systems to ensure Personal Protective Equipment (PPE) usage, manage proximity to hazardous areas and detect unsafe behaviors. Using video analytic algorithms, connected to regular CCTV networks, Stepps and tec.nicum achieved fast detection and response capabilities, crucial for preventing accidents and safeguarding workers. Tested in a steel industry setting, our system demonstrated high accuracy even in dusty and low-light conditions. In PPE detection results achieve and average of over 96%, and effective proximity alerts for hazardous objects, with an 83% accuracy for a variety of moving vehicles. By processing data using on-premise servers, latency is minimized, and responses are nearly instantaneous, making our solution feasible with existing CCTV infrastructure. This implementation aligns with United Nations Sustainable Development Goal 8 (SDG 8) to promote safe working conditions and addresses both social and economic challenges by reducing costs associated with workplace accidents. The results emphasize the potential of AI to transform industrial safety, ultimately aiming to reduce accident rates and support sustainable, secure employment practices

2. Introduction

Stepps is a Brazilian startup specialized on the development of artificial intelligence solutions for safety, quality and productivity.Born in the largest urban technology park in Latin America, the company is developing a computer vision ecosystem that operates its algorithms with high performance levels.

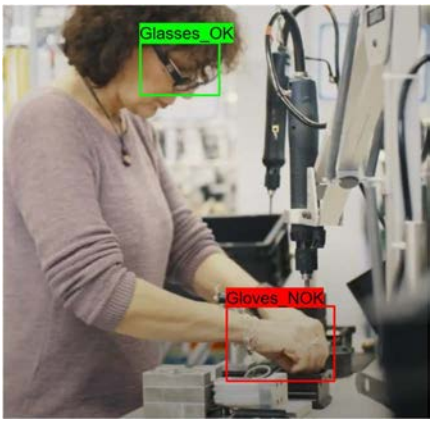

Fig. 1: Computer Vision Demonstration

A partnership between Stepps and tec.nicum was ideal to get this ecosystem to a global level of operation, since tec.nicum is a division of the Schmersal Group that specializes in providing consulting, training, and customized solutions focused on industrial safety. It offers expert services to help companies ensure compliance with safety regulations, such as the NR-12 in Brazil, through risk assessments, machine safety evaluations, and tailored safety solutions. tec.nicum also provides specialized training programs on machine safety, risk analysis, and protective measures, supporting industries in creating safer and more compliant work environments.

The motivation for developing this solution firstly arose from alarming data collected from the Brazil Statistical Yearbooks of Occupational Accidents, published annually by Brazil's Ministry of Social Security through the Social Security Policy Secretariat. The 2023 yearbook revealed that 612,900 Workplace Accident Reports (CATs) were recorded in Brazil in 2022. Additionally, 15,900 people died in Brazil due to workplace accidents from 2016 to 2022. During this period, there was a 25.4% increase in fatalities, rising from 2,265 to 2,842. Even though Brazil has one of the world's most extensive regulations on this subject, according to the Ministry of Labor (MPT), it ranks 3rd globally for workplace accidents, behind only China and the United States.

According to the Smartlab platform, organized by Brazil's Ministry of Labor and the International Labour Organization, the total duration of each benefit granted provides insight into the number of lost workdays. In 2022, 17.9 million days were lost due to sick leave from workplace accidents, and 8.4 million days were lost due to disability retirement from workplace accidents in Brazil.

According to Brazil's 15th Regional Labor Court (TRT), workplace accidents represent an average financial loss of R$13 billion per year. This amount considers the values paid by the National Institute of Social Security (INSS) in accident-related benefits.

In addition to the societal costs described above, numerous direct and indirect costs impact the companies where these accidents occur, such as:

- Medical expenses;
- Worker compensation;
- Repair or replacement of damaged equipment;
- Costs for training and integrating new employees;
- Production interruption;

- Increased absenteeism and turnover among other employees;
- Insurance costs;
- Reputation cost.

Among the primary causes of the high number of records are non-compliance with health and safety regulations, relaxation of rules, and a lack of effective training that demonstrates the importance of adhering to safety standards.

Thus, to reduce social costs and increase the productivity of the national industry, it is essential that workers operate in a safe environment, constantly monitored with tools that can prevent accidents. In this context, Stepps sees great potential for applying solutions based on Artificial Intelligence, particularly Computer Vision.

Technologically-based solutions aimed at promoting a safe working environment bring benefits in multiple spheres. Socially, they contribute to protecting workers, reducing accident risks by ensuring that Personal Protective Equipment (PPE) is used correctly. Additionally, they provide real-time monitoring of operators' access to hazardous areas, as well as proximity detection between operators and moving objects, such as forklifts or suspended objects. This generates consolidated reports with information that allows training employees to reduce potentially risky behaviors, which can lead to lower accident and occupational illness rates, promoting a safer and healthier work environment.

Economically, these solutions can create substantial savings for companies by reducing costs associated with workplace accidents, such as compensation, production interruptions, and workforce losses. Furthermore, by increasing operational efficiency and decreasing downtime, they contribute to increased productivity and competitiveness in Brazilian industries.

Additionally, by managing large data volumes efficiently, technologies developed for this purpose will be able to adapt to various scenarios, establishing new standards of efficiency and precision in safety monitoring systems.

Last but not least, the development of solutions and technologies capable of connecting with industrial equipment will allow actions to prevent accidents to be executed directly by the equipment.

We understand that this type of solution directly aligns with Goal 8 of the United Nations Sustainable Development Goals (SDG): SDG 8. Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all. Specifically concerning the following target: 8.8 Protect labor rights and promote safe and secure working environments for all workers, including migrant workers, particularly women migrants, and those in precarious employment.

Therefore, developing and disseminating technology that helps reduce workplace accidents aligns with the UN's Sustainable Development Goals in general and particularly with the sustainability goal established for Brazil.

3 Theoretical foundation

Artificial Intelligence has proven to be an excellent ally in addressing challenges related to Occupational Safety. One area with a wide range of applications for solving HSE-related challenges is Computer Vision, a field of study that applies AI algorithms to images. The potential of Computer Vision to tackle these challenges is primarily based on the design of a special neural network architecture known as Convolutional Neural Networks (CNNs).

Convolutional Neural Networks, or CNNs, are a type of neural network architecture commonly used in image-related problems, with the primary function of performing convolution operations to extract features of elements in an image, such as edges, shapes, textures, colors, and more. The feature extraction process underpins the development of image processing techniques and algorithms for applications involving pattern recognition, image classification, object detection, pose estimation, and others. The part of a CNN responsible for extracting features from elements within an image consists primarily of a type of layer called a Convolutional Layer. As the input image passes through a CNN, it is, in simple terms, fragmented into its various constituent elements to identify specific patterns and characteristics. These patterns and characteristics are obtained by applying filters, called kernels, to the image. These kernels scan the image, performing convolution operations, which are weighted sums of pixel values within a specific region of the image based on the kernel's weights. The application of kernels to images produces small matrices called feature maps. These feature maps store spatial patterns and characteristics of elements within the images, enabling the CNN to recognize them [1].

For applications specifically involving object detection using Convolutional Neural Networks, one of the most prominent models is YOLO (You Only Look Once) [2]. Unlike other approaches that use classification models for object detection, YOLO was primarily developed for object detection problems. YOLO addresses the object detection problem as a regression problem. Thus, through a single neural network, the YOLO architecture enables real-time image processing, thanks to its straightforward approach.

Approaches using classification models for object detection are slower at identifying and locating objects within an image, as they work by applying the models to different regions and scales of the image. On the other hand, YOLO only needs to "see" the image once, allowing it to consider all elements in the image for detection. In other words, unlike other approaches, YOLO can assess the overall context of the image when detecting objects within it [2].

Additionally, since YOLO can perform real-time detection of objects or specific situations by treating detection problems as regression problems, it becomes particularly useful in applications that require the shortest possible response time. In Occupational Safety, response time to risk events is a key factor in preventing accidents. The ability to identify unsafe behaviors at the exact moment they occur enables the development of solutions and technologies that allow intervention in the situation, thereby preventing accidents in the workplace.

Thus, due to the low latency that YOLO demonstrates in making detections, this model can be directly used in applications that, for example, shut down machines when it detects an operator is not using PPE, trigger sound alerts when excessive proximity is detected between people and moving vehicles, among other uses. In this way, it becomes possible not only to monitor the health and safety of workers but also to prevent accidents in high-risk situations detected by the model.

4. Solutions and Results

Thus, one use of this technology is to identify potential risk situations in factory environments to make the workplace safer for employees. The first application developed using YOLO is a monitoring system for PPE usage by workers. This real-time monitoring allows complete configurability for both the types of PPE that need to be monitored and the areas of interest for PPE detection.

Stepps experts developed an architecture for the solution that uses an on-premise server to run the interface application and the model inferences. The CCTV cameras of the industrial clients are connected to the same network of the server and camera IP numbers were set up to connect everything and transfer the images in real time. Camera specifications were set as FullHD and IP cameras, no further requirements were needed. As shown in Figure 2, the architecture allows users to access the software interface only, keeping all the operational data secured. Stepps users can interact with the solution through scheduled VPN connections for maintenance and update purposes.

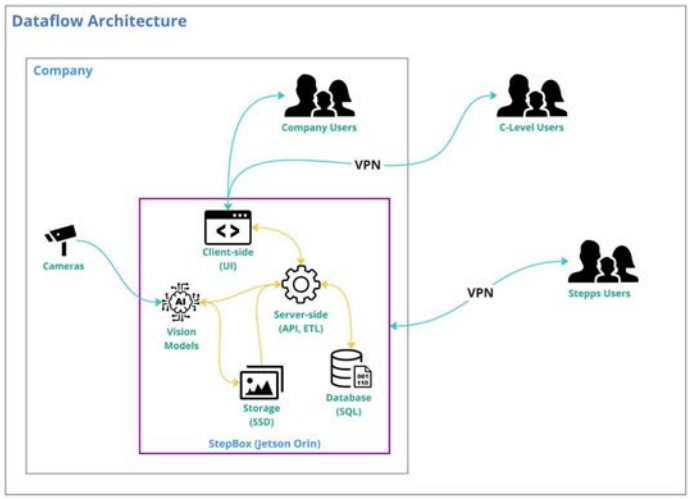

Fig. 2: System architecture

Siemens BX-35A was selected as the ideal server for the solution due to its exceptional processing capabilities. It features a 16GB Nvidia Jetson Orin NX module dedicated to running model inferences. With 100 TOPS of performance, it is housed in an industrial-

grade case, designed to operate reliably in harsh environments. The module is shown in Figure 3.

Fig. 3: Nvidia Jetson Orin NX 16gb

Additionally, the model used for PPE detection has shown satisfactory results in its applications. One application involved PPE usage detection in a steel industry, specifically in the casting stage. The PPE that must be monitored in this application includes: Ear Protection, Face Shield, Aluminum Coat, Gloves, and Safety Boots. Table 1 presents the detection accuracy values for each type of PPE in this application:

Table 1: Accuracy by PPE class detected

PPE	Accuracy
Ear Protection	86%
Face Shield	88%
Aluminum Coat	96%
Gloves	93%
Safety Boots	91%

Another application involves detecting proximity between people and hazardous objects. Hazardous objects may include moving vehicles or suspended loads, for example. Proximity detection between people and hazardous objects can also be performed using the existing CCTV system, without needing additional infrastructure.
In the approach for detecting proximity between people and hazardous objects, in this case involving moving vehicles, an application developed for a steel industry monitors the proximity between people and forklifts. The model used achieved an 83% accuracy in forklift detection, properly generating alerts whenever a person was detected near a moving vehicle.

A system was also developed to detect proximity between people and suspended objects for the same steel manufacturing industry. In this case, the goal is to monitor proximity between people and the following objects: Ladle, Distributor, Lid, and Hook. In this application, the implemented model achieved excellent results in detecting these objects, generating alerts whenever it detected proximity between a person and a moving object. The results are shown in Table 2.

Table 2: Accuracy in detecting hazardous objects.

Objects	Accuracy
Ladle	92%
Distributor	81%
Lid	84%
Hooks	80%
Forklift	83%

5 Conclusion

The solutions developed by Stepps are solutions that assist industrial managers in addressing some of their primary needs concerning Occupational Health and Safety. When discussing Occupational Health and Safety, the primary objective is to create a safer work environment through continuous monitoring of relevant areas to the company. This monitoring involves detecting the correct use of Personal Protective Equipments (PPEs), managing access to restricted areas, monitoring the proximity of individuals to hazardous objects or suspended items, implementing facial recognition for access authorization to spaces or for machinery and equipment handling, among other applications.

Moreover, those solutions are all simple to install and use, once it utilizes the already implemented infrastructure of CCTV at the factories. The only thing necessary is the installation of the required server to run those solutions. Thus, all collected images are processed and stored exclusively on this server, located on the client's manufacturing site, making the latency and response time of the solution close to real time. And once the whole work is performed at the client's site, it's possible to implement the automations required to act directly at the risky situations, avoiding the occurrence of accidents.

Having excellent accuracy results, as 96% for PPE detection, allow us to stay confident about the solution potential. It can be improved much more in further stages of model training, and the results steer the solution toward a bright future.

Finally, as shown by the results above, there is huge potential of applying Computer Vision solutions to address the challenges that industrial managers have to deal with in

the day by day work. These challenges are responsible for the cause of numerous accidents, including those with casualties. For that reason, using AI to help reduce and even eliminate accidents in the work space could save thousands of lives each year around the world.

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Risk Mitigation in Complex Workspaces and Tasks Through AI-enhanced Safety Systems

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Abstract

Complex workspaces that involve workers, machines, and tools often harbour residual risks due to both intended and unintended interactions among these elements. For instance, many incidents arise from operator misuse of machinery, such as working with tampered safeguards or completely removed protections. Additionally, dangerous situations can occur when machines operate without specific auxiliary devices, increasing potential risks within the workspace. The state of the art only provides written warnings in the use and maintenance manual for most of these risks and no more effective technical solutions have been proposed. In this study, a prototypal machine assembly, comprising a robot and a multimodal lathe, is utilized to assess and mitigate risks in a complex workplace. This workspace is divided into different pre-defined zones depending on the task to be completed and the presence of operators. A comprehensive risk assessment is conducted before and after integrating IoT sensors, such as RFID tags and Computer Vision (CV), integrated with an Artificial Intelligence (AI) module with standard safety systems that comply with the upcoming Machinery Regulation. This approach offers promising solutions to mitigate the consequences of operator errors and potential machine malfunctions. The paper explains how well-known hazards in workspaces can be significantly reduced by strategically deploying sensors to monitor specific tasks. Multiple sensors are employed to oversee the case under examination, ensuring a redundant check with sensors based on different technologies to reduce, as an example, Common Cause Failures (CCF) of those innovative systems. By combining traditional safety measures with advanced sensor technologies and AI, it is possible to enhance the overall safety of complex workspaces. The proposed system not only addresses common hazardous situations but also provides a proactive approach to managing risks, ultimately contributing to a safer working environment.

1 Introduction

In January 2027, the new EU Machinery Regulation 2023/1230 (MR) [1] will come into force, replacing the current Machinery Directive [2] (MD). This introduces significant changes regarding machine safety. The relevant provisions of this work are those related with the allowance of technologies based on Artificial Intelligence (AI) algorithms to ensure safety functions, as well as the possibility of human-machine coexistence in a collaborative working environment (the so-called collaborative robots). There are already systems on the market that implement safety functions for human protection based on devices that, at the moment, are not certified according to a specific Type C product standard. For instance, there is significant development in anti-collision systems for industrial robots and autonomous vehicles, as well as in personnel detection using RFID technology.

In the current industrial landscape, the reduction of operator risks due to contact with moving parts is achieved through protection systems and physical separation (such as safety fences or guards). Some tasks linked to the life cycle of the machinery are currently managed only through the step 3 of risk reduction rule [3] for machinery based on warnings signs and/or operating instructions manual. As an example, to prevent incorrect utilization of machinery, tampering such as removal of guards, troubleshooting during malfunctions, maintenance etc.…

Sensors and systems introduced more and more through Industry 4.0 revolution [4] are managed, from a standardization point of view, by the technical specification IEC TS 62998-1, "Safety of machinery - Safety-related sensors used for the protection of persons" [5]. This establishes the requirements for the development and integration of safety-related sensors (SRS) and safety-related sensor systems (SRSS) used for the protection of people, with a particular focus on systematic capabilities. It applies to specific situations where the protection of individuals must be achieved using technologies not covered by specific regulatory standards.

1.1 Complex tasks in complex systems

The above-mentioned technologies such as collaborative robots, are more and more used in recent years [6], for example, to minimize psychological and physical stress on the operator during repetitive work tasks.

In the intended conditions of use, discomfort and fatigue must be eliminated or minimized as much as possible, considering at least the principles of ergonomics. The ergonomic principle was already present in the MD and has been integrated to account for the challenges posed by the human-machine interface due to machines with self-evolving behaviour.

In the next year the demand of new safe machinery system composed by machine tools (such as machining centres lathes …) and collaborative robots working together in a collaborative space among humans with little or without guarding will increase due to the necessity of a real collaborative space of work.

The new requirements and methods aimed at protecting operators will be assured also through:

- the detection of potentially dangerous objects such as tools left unattended over moving part after a maintenance or badly connected/placed parts of the machinery as an example swarf containers;
- the detection of tampered or completely removed guards;
- the detection of entering or leaving dangerous zones during operational times;
- utilization of machine learning and artificial intelligence for safety functions to cover also the new emerging risks.

In the following pages the real possibility of risk mitigation in complex production space will be presented through a real prototype of a small production system currently on test stage.

First the prototype will be presented and the risk analysis useful to highlight the reduction risk possibility for those innovative redundant systems will be presented.

Then a brief discussion of the implemented AI algorithms and signals between the systems useful for real time risk reduction will be shown.

2 Description of the complex workspace and risk analysis

The production system under study consists of a multimodal CNC lathe and a UR3e robot that collaborate to perform the movement and turning of a workpiece. Figure 1 presents the layout of the machines as well as the positioning of the walls in the hypothetical workroom. This preliminary information is essential for defining the workspace, which is divided into three distinct zones based on the operator's position relative to the machines. Zone 1 covers the area near the lathe, Zone 2 surrounds the workpiece holders (before and after the turning process) and encompasses the circular area swept by the robot during its movement. Zone 3 represents the area where the machine assembly can be controlled via the command console.

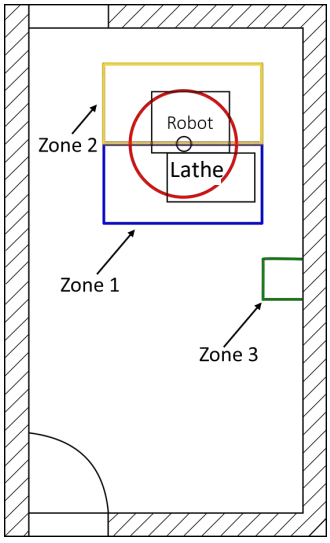

Fig. 1. Prototype disposition into the workspace.

The risk assessment of the described workspace is conducted using the well-known “bottom-up” method [7]. Initially, all operational states that the system can assume are defined, and for each state, the associated risks are identified. In relation to the robot’s activity, two states are considered: full speed and reduced speed. However, since the consequences of impacts at reduced speed have not yet been analysed, the robot will be treated as either stationary or moving in this phase. During the design step, criteria must be established to determine when movement is enabled and when it is not, thus an enable signal has been considered for this purpose. For the lathe, it is essential to define the four operational modes also described in the machine's user manual:

- Manual Mode: allows for manual processing. The door guard could be opened, while other guards remain required. This mode necessitates a simple lathe operator, an experienced operator or a tool technician.
- Automatic Mode: enables automatic processing via CNC programs. The spindle guard could be opened, while other guards are required. Compared to the manual mode, this allows inexperienced operators, provided they are only tasked with part replacement while the machine is stopped.
- Setup Mode: facilitates machine preparation for processing. The carriage guard is necessary, while other guards could be opened/removed to assist with setup. This mode requires a simple lathe operator, experienced operator, tool technician, or maintenance operator.
- Service Mode: used for cleaning and lubricating the machine under safe conditions. Guards are not required, and a maintenance operator is necessary.

This information is crucial for identifying hazards and performing risk assessments. We know that a significant portion of risks is mitigated using traditional safety functions, in accordance with standards such as ISO 13849 [8] and Machinery Directive. However, some hazards are not fully addressed by current state of the art; these hazards, relevant to the case under examination, are presented in table 1 as "Use Cases" (UC). Normally, these situations are classified as residual risks and mere information is provided to the operator. However, the new MR allows for the use of novel technologies for risk mitigation, so, the following section outlines the proposed supervisory system and its key components to perform advanced risk mitigation.

2.1 IoT Sensors Description

This section provides a brief description of the IoT sensors usable in the proposed prototype. The preliminary concept for the experimental supervisory system includes the following elements:

- wearable devices with RFID tags worn by operators, integrated into work overalls or personal protective equipment. A network of antennas placed

around the machine can identify the tags and associated objects, and estimate their position;
- cameras that monitor work areas and, using appropriate image recognition algorithms, detect potential risks for the operator. Similar recognition systems assess the machine's status, including the positioning of safety devices, to detect if any barriers have been bypassed;
- safety related software that processes data from the above systems, enabling a supervisory operator to monitor their proper function and, if necessary, take corrective action, particularly in emergency situations (in compliance with point 1.2.1, Annex III of EU Regulation 2023/1230).

To explore the potential benefits of these new technologies in the workplace, a preliminary design of the system has been developed. Building on insights from previous considerations, this section establishes a basic framework for the prototype, highlighting the critical role of integrating advanced technologies. The integration of autonomous devices equipped with appropriate AI modules and computational capabilities for processing their own information is crucial for calculating the Performance Level (PL) of the safety function. Even though determining the PL of the supervisory system will present challenges, the segregation of the outputs from each sensor provides a solid foundation. The results of each technology inspection are transmitted to the AI module responsible for decision-making. In this context, IoT sensors and AI systems within machines can interpret new operational scenarios, identify potential risk conditions for operators, and issue appropriate stop commands. This integrated smart system, illustrated in figure 2, which shows interactions between the various components, uses a combination of RFID, computer vision (CV), and AI technologies to detect hazardous conditions, such as faults, malfunctions, or improper actions, based on the machine's operational status. Upon identifying a risk, the supervisor system sends commands to the machine control system to ensure operator safety, for instance, by initiating an emergency shutdown.

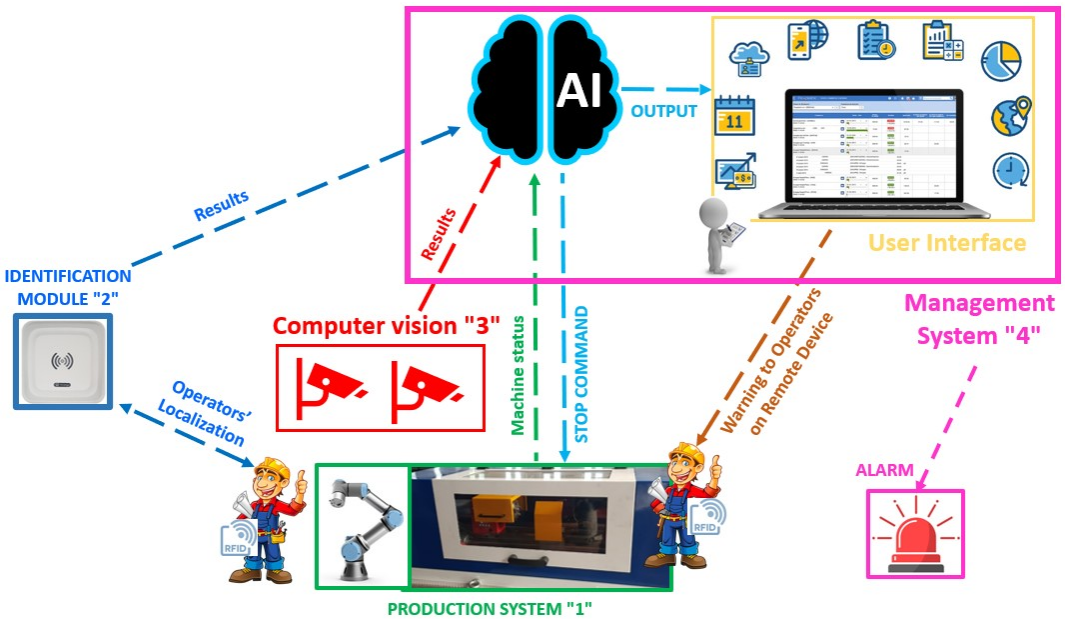

Fig. 2. Prototype scheme components and their relations.

2.2 AI Module Description

The AI module was designed as a Rule-Based Expert System [9]. This system is structured to store knowledge acquired from a domain expert and/or Machinery Regulation and take decisions when specific conditions are met. The architecture of an Expert System, shown in Figure 3, consists of three main components:

- A Knowledge Base (KB), which represents and stores the knowledge using an ontology to model the workspace, along with a set of rules to define relationships and guide decision-making;
- An Inference Engine (IE), which processes input data by applying relevant rules, executing them to generate the appropriate output response.

A System Interface (SI), which facilitates the interaction between a non-expert user (or another application program) and the IE. SI allows users to input new data into the system and retrieve the resulting output.

The initial step in developing the AI module concerns defining a formal representation of the workspace using an ontology, which describes the relevant entities, in the form of classes, with their instances, properties and the relations connecting them. The table 1 shows, as an example, the representation of the lathe according to the defined ontology.

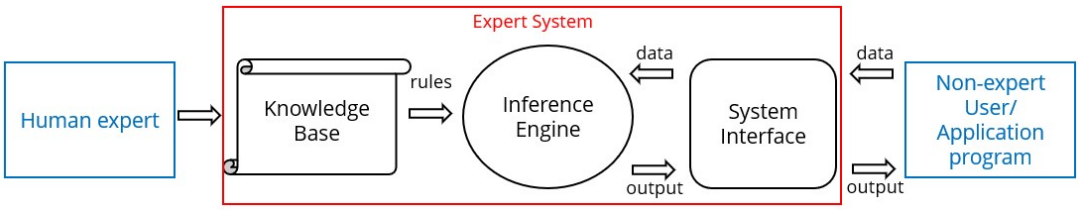

Fig. 3. Expert System architecture.

ENTITY	CLASSES	PROPERTIES	PROPERTY VALUES	INSTANCES
Lathe	Lathe	has_guards	List of Guard instances	lathe
		power	"ON", "OFF"	
		operative_mode	"MANUAL", "AUTO", "SETUP", "SERVICE"	
	Guard	presence	"DETECTED", "UNDETECTED"	-
		position	"MOUNTED", "UNMOUNTED"	
		is_removed	True, False	
	UnmovableGuard	is_subclass_of	Guard	cart_guard tailstock_guard
	MovableGuard	is_subclass_of	Guard	door_guard spindle_guard
		state	"OPEN", "CLOSED"	
		is_tampered	True. False	

Table 1 - Representation of the lathe according to the defined ontology.

Once the ontology is created, the complete set of rules is defined with each rule written in the following format: **IF condition THEN action**. Based on the risk analysis conducted, all reasonably foreseeable hazardous situations were identified and described by distinct rule conditions, each defining a specific combination of property values which can lead to these situations.
For instance, when the lathe is activated (power = "ON") and operates in automatic mode (operative_mode = "AUTO"), the door guard must be closed. The following rule checks whether this condition is met; if it is not, a "door guard tampering" warning is triggered:

IF lathe.power == "ON" AND lathe.operative_mode == "AUTO" AND door_guard.state == "OPEN"
THEN door_guard.is_tampered = True

During runtime, the AI module receives new data from the IoT sensors. The IE evaluates the rules, activating those whose conditions match the incoming data. The module responds by either sending a stop signal to the production systems or by notifying an alarm to the operators.

3 Risk mitigation

First it is crucial to define the specific risk scenarios that will be evaluated, as these will guide the selection and placement of sensors. This study considers some of the most common hazards found in real work environments. For each Use Case (UC), one or more sensors are assigned to monitor specific parameters, with their monitoring frequency determined by the technological capabilities of the sensors. Equally important is defining the type of response triggered when a hazardous situation is identified. Table 2 illustrates the organization of these concepts, showing the role of different sensors in each scenario.

OPERATIVE MODE: **MANUAL**												
		CV		**RFID**			**LATHE**					
USE CASES	**SUBCASE**	PRESENCE	POSITION	PRESENCE	POSITION	ORIENTATION	SPINDLE GUARD	DOOR GUARD	MAN. EN.	AUT. EN.	POWER ON
MOBILE GUARD TAMPERING	SPINDLE GUARD TAMPERING	■	■	■	■		■				
	DOOR GUARD TAMPERING	■	■	■	■	■					
	SPINDLE GUARD REMOVAL	■	■	■	■	■	■				
	DOOR GUARD REMOVAL	■	■	■	■	■					
OPERATOR'S COUNT	PRESENCE	■		■							
INFORMATIC TAMPERING ROBOT	UNEXPECTED MOVEMENT		■		■	■			■		
CV TAMPERING	BLACKOUT	■	■	■							
FIXED GUARD TAMPERING	CART GUARD	■		■							
	TAILSTOCK GUARD	■		■							
TAMPERING RFID	TAMPERING	■		■							
PRESENCE DPI	PRESENCE			■							
	POSITION				■	■					
OPERATOR'S CONDITION	POSITION		■		■						
	ORIENTATION		■			■					
OBJECT POSITION	WORKPIECES STORAGE	■		■					■		
AUXILIARY SYSTEM PRESENCE	CHIPS STORAGE	■	■	■							■

Table 2 - Use Cases for the manual operational state of the lathe.
Note: green indicates the sensor performs the task. White indicates no necessity to do it.

In table 2, each IoT sensor's role is visualized for the specified UC. Given that the Numerical Control (NC) of the lathe provides four operational modes (Manual, Automatic, Setup, and Service), with varying safety conditions, additional matrices similar to the one presented above have been developed.
The definition of these UC and the adopted technologies has allowed the determination of a series of I/O signals required for communication between the AI system and the other prototype components (CV, RFID, and production system). The primary objective is to create a prototype that works as a conventional machine assembly during standard tasks, while offering enhanced safety operations when requested by the responsible operator. This ensures that machines continue to

operate in compliance with the guidelines of the Machinery Directive (MD), while also inhibiting certain operations, such as the robot's collaborative mode, when the supervisory system is inactive.
To initiate the supervisory activity, the responsible operator must use the mode selector placed on the control console to send the “Enable AI” signal to the AI module. The module will then check the IoT sensor statuses to verify whether the supervision task can begin. This enable request must be followed by a return signal labeled “AI-Ready” from the AI module to the Pilz connector of the lathe terminal, using Normally Closed (N.C.) logic. If this return signal is interrupted, or if a discrepancy is detected between the output and the Enable signal, the production system will cease to follow the supervisory system’s safety instructions. In the event of signal fault, it is promptly detected by the safety PLC of the lathe, preventing a potentially dangerous safety issue.
As shown in figure 3(b), the electric circuits of the two systems are isolated via relays to prevent electrical issues, such as short circuits, from affecting both systems. The safety signal is then transmitted from the lathe to the robot's safety terminal, depicted in yellow.

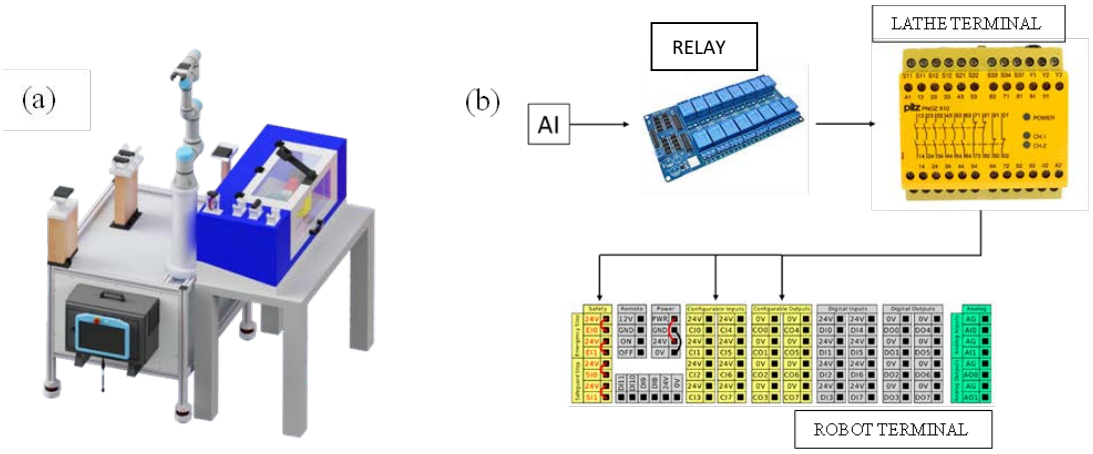

Fig. 3. (a) Rendering of the machine assembly, (b) Safety signal path.

The supervisory system's response to hazardous situations varies depending on the severity of the consequences:

- STOP Cat. 0: Immediate stop of the robot or the entire assembly, with energy removal;
- STOP Cat. 2: Stop of the robot or the entire assembly, but with energy remaining active;
- SOUND ALARM: Audible alarm triggered in the workspace;
- LIGHT ALARM: Visible alarm activated in the workspace;
- COMMUNICATION WITH THE SUPERVISOR: A message is sent to the supervisor’s personal device.

For stop function categories see [10].
When a hazard concerns only the robot, the lathe is not affected, allowing its work cycle to continue. A Category 2 stop is crucial as it halts the machines without losing the current cycle phase. While a Category 0 stop provides a higher safety level, the energy removal may prevent resuming the work process from the last phase, potentially leading to the loss of the workpiece. In some cases, the process can take several hours, and the workpiece itself may hold considerable value. The safety signal shall finally reach the Robot terminal to perform the related reaction. As outlined in the user manual, UR e-Series robots are equipped with a range of integrated safety functions and I/O's, designed for connection to other machines and additional protective devices. Each safety function and I/O is implemented in accordance with the ISO 13849 standard with Performance Level d (PLd) using a Category 3 architecture.
The robot is provided also of three types of stops as defined by the EN 60204-1 standard:

- Emergency Stop → Stop Cat. 1
- Safety Stop → Stop Cat. 2
- Limit Violation → Stop Cat. 0
- Anomaly Detection → Stop Cat. 0

The authors states that this prototypal system can be a base of discussion for implementation of innovative sensors and IA algorithms in machinery as expected by new Machinery Regulation taking place from 2027.

4 Conclusion

The primary aim of this study is the development and evaluation of a prototype designed to assess the system's ability to enhance operator safety, particularly in addressing inadequately managed risks such as the presence of auxiliary devices and intentional tampering. The initial step involved identifying the operational zones that may be occupied by the operator and must therefore be monitored by the supervisory system. Utilizing a machine assembly comprising a lathe and a robot working collaboratively to execute a turning cycle, the system necessitates a well-coordinated and robust architecture to ensure the efficient transfer of safety signals. The mitigation of risks in complex scenarios, beyond the current state of the art, can be achieved through the integration of an AI-driven module capable of processing data from multiple sensors monitoring activity within the operational zones. The system can recognize the severity of the ongoing risk and triggering the appropriate output signal. The authors concur that integrating diverse technologies, each of which autonomously expresses its own outcome for a specific UC, is a fundamental concept for enabling the calculation of the PL for this type of architecture. To validate the system's effectiveness, rigorous testing will be conducted in typical risk scenarios (UC) involving the prototype's turning activities. This testing will provide a comprehensive assessment of the safety mechanisms in place, ensuring the system can reliably protect operators in real-world conditions.

The integration of IoT sensors, AI-driven supervision, and advanced safety protocols promises significant improvements in workplace safety, addressing both traditional hazards and those that remain challenging for current state-of-the-art solutions. Ultimately, this approach paves the way for smarter and safer industrial environments where humans and machines can work together in a shared workspace.

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A Method for Packed (and Unpacked) Malware Detection by means of Convolutional Neural Networks

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Abstract

The current signature-based mechanism implemented by free and commercial antimalware require the presence of the signature of the malicious sample in order to provide protection i.e., to detect the malicious behaviour. This is the reason why malware writers are developing techniques able to change the syntax of the code but leaving the semantic unchanged i.e, the malware business logic. Among these techniques, there is the so-called packed malware i.e., malware with binary code modified by packers, software aimed to pack a software, compress it and package it with a stub. It is a program capable of decompressing it in memory and executing it. In this way a malware detected by antimalware is not even detected in the packed version. In this paper we propose a technique aimed to detect packed malware by exploiting convolutional neural networks. In a nutshell, the proposed method performs a static analysis i.e., it does not require to run the application to detect the malicious samples: we start from the binary code of the application exploited for the generation of an image that represent the input for a set of deep learning classifiers. The aim of the classifiers is to discern an application under analysis between trusted or (packed) malicious. In the experimental analysis we take into account three different packers (i.e., mpress, BEP and gzexe) to generate packed malware, thus demonstrating the ability of the proposed method to detect packed and unpacked malware with interesting performances.

1 Introduction

The main aim of malware, contraction for malicious and software, is to per- pretrate damages on the victim devices (i.e., computer but also smartphones) with particular regard to the information gathering i.e., the ability to retrieve sensitive information and send this information to the attacker.

Malware writers are costantly focused on the developed on new techniques aimed to evade the signature-based detection provided by current free and com- mercial antimalware: one of the last trends is represented by the so-called packed malware. The term packed malware refers to malicious software that has been compressed or obfuscated using a technique known as ”packing.” This process involves

compressing the code of the malware into a smaller, often encrypted format, making it harder for antimalware programs to detect or analyze. Pack- ing can also involve embedding the malware inside other legitimate software or files, disguising its true nature.

Starting from these considerations, in this paper we propose a method aimed to detect packed and unpacked malware. The proposed method relies on convolutional neural network (CNN). We propose a representation of an application as an image and we consider to train a set of CNN with the aim to understand the best one in terms of performance for the classification of (unpacked) malware and trusted samples. In the evaluation, we consider a set of packed malware, with the aim to understand whether the trained model are able to detect packed malware (not exploited in the training phase).

Thus, the paper proceeds as follows: in the section we provide a discussion about the state-of-the-art in malware detection, Section 3 presents the method we designed for the detection of packed and unpacked malware; the experimental analysis is discussed in Section 4 and, finally, in the last section conclusion and future research lines are drawn.

2 Related Work

Authors in [2] proposed a method to identify packed and unpacked malware in the Windows environment. In detail, they created two datasets of 4,075 executable applications, where 2,954 were malicious programs and 1,121 were benign executables. The authors applied the UPX packer to the first dataset, while the second dataset used unpacked malware. Moreover, using Weka, they applied classification algorithms for both datasets. Differently from them, we proposed a methodology to identify packed and unpacked malware leveraging Deep Learning by applying several Convolutional Neural Networks belonging to the state of the art. To do that, we converted all datasets created (one composed of unpacked executable applications and three using different packing methods) into images, reaching accuracy values in most of the cases higher than 0.980. Authors in [1] proposed a method to identify packed malware leveraging three different classification Machine learning algorithms such as Native Bayes, De- cision Tree, and Random Forest Extra Trees. In detail, researchers employed a dataset of 280,000 samples on which they applied two packing techniques (UPX and TheMida), extracting many features. Moreover, they also perform classification using unpacked samples. In our proposed method, we employed a methodology based on Deep Learning. We applied three packing algorithms on each malware sample, obtaining four datasets (one composed of unpacked malware). In the following step, all Windows executable

applications were converted by a script into images and submitted to ten different Convolutional Neural Networks belonging to the literature.
In [3], researchers presented a technique to identify packed and unpacked mal- ware leveraging Machine Learning. In detail, they extracted 13 features from 28,807 Windows Portable Executable files, and in the following steps, they trained several models using different algorithms such as KNN, Logistic Re- gression, Linear SVM, Random Forest, Multilayer Perceptron, Naive Bayes, SVM, and Decision Tree. Distinct from them, we performed a binary classifi- cation (Malware-Trusted), creating four different datasets and leveraging Deep Learning. In the first three datasets, we applied three different packing methods (mpress, BEP and gzexe.) on malware samples, while in the latter dataset, we used unpacked malware.

3 The Method

In this section we present the proposed method for the detection of packed and unpacked malware. Figures 1 and 2 respectively present the training and the testing step related to the proposed method.

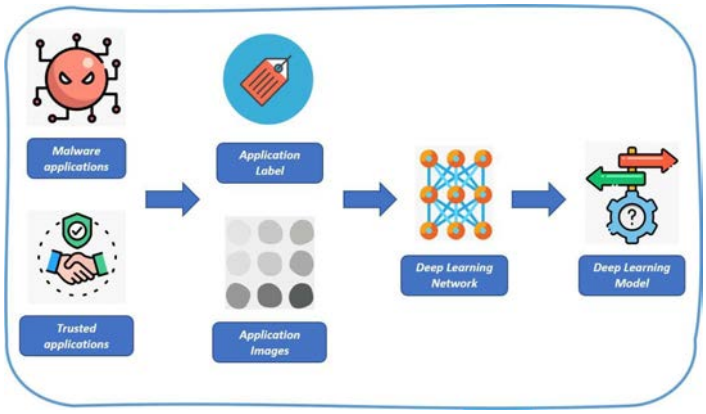

Fig. 1: The training phase of the proposed method.

Figure 1 shows the workflow of the proposed malware detection method consists of the following steps:

a. **Malware applications:** This step involves collecting applications known to be malware. These samples serve as malicious samples during the training process.
b. **Trusted applications:** This step involves gathering applications that are considered safe or trusted. These samples act as legitimate

samples in training

c. **Application Label:** Each application is labeled as either ”Malware” or ”Trusted” based on its nature, which will be used as the target variable in the training process.

d. **Application Images:** The collected applications are converted into images. To convert a binary to an image we treat the sequence of bytes representing the binary as the bytes of a gray-scale PNG image. We consider a predefined width of 256, and a variable length, depending on thesize of the binary. We developed a script to encode any binary file into a lossless PNG [4].

e. **Deep Learning Network:** A deep learning network is then trained on these labeled images to learn features that distinguish malware from trusted applications. We consider several CNNs in this task: ALEX NET, LE NET, STANDARD CNN, MobileNet, DenseNet, EfficientNet, ResNet50,VGG16, VGG19 and Inception.

f. **Deep Learning Model:** After training, the deep learning model can predict whether a new application is malware or trusted based on the learned features. This model can be deployed for real-time malware detection.

Figure 2 shows the testing step of the proposed method.

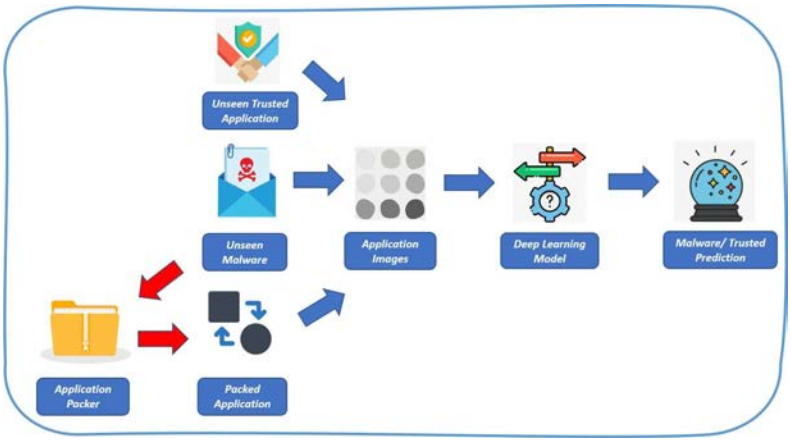

Fig. 2: The testing phase of the proposed method.

As shown from Figure 2, the testing step of proposed malware detection method includes the following steps:

g. **Application Packer:** A tool used to create packed versions of appli-

cations, often by compressing or encrypting their code. This is used to generate packed applications, which can obfuscate the behavior of the software and make detection more challenging.

h. **Packed Application:** Applications processed through the packer. These packed applications are often harder to analyze and detect as malware due to their obfuscation techniques.
i. **Unseen Malware:** This step involves testing the detection method with new malware samples that were not part of the training set, representing real-world malware scenarios.
j. **Unseen Trusted Application:** Similarly, new trusted applications are used during the testing phase to ensure the model's ability to distinguish between malware and safe software.
k. **Application Images:** The unseen malware, trusted applications, and packed applications are transformed into images, which serve as inputs for the deep learning model.
l. **Deep Learning Model:** The trained deep learning model from the train- ing phase is used to analyze the application images and predict their nature as either malware or trusted.
m. **Malware/Trusted Prediction:** The model provides a prediction for each application, determining whether it is malware or trusted. This out- put helps in evaluating the model's performance on unseen and packed samples.

4 Experimental Analysis

In order to collect real-world samples with the aim to evaluate the proposed method,we consider following repositories: the first one is the Dike dataset[1], a freely available collection of trusted and malicious Portable Executable (PE) and Object Linking and Embedding (OLE) files. The malware belonging to this dataset represent the unpacked malware and try a wide spectrum of malware categories i.e., generic trojan, ransomware, worm, backdoor, spyware, rootkit, encrypter and downloader.

Moreover, with the aim to evaluate the robustness of the proposed method with respect to packed malware, we have to generate packed variants, this is the reason why we consider three different packers *i.e., mpress, BEP* and *gzexe*.

With the aim to cover the spectrum of different packers, we experiment with three packers: we consider mpress, as modern and efficient Windows ex- ecutable compressor with added benefits of space saving and making reverse engineering more difficult. From the other side BEP is an older, less commonly used packer that

compresses executables, but has been largely replaced by more modern tools. We take into account also gzexe, a simple Linux-based tool that compresses executables using the gzip algorithm for space savings on Unix-like systems.
Thus, the full dataset is composed by following 5000 applications:
[1]https://github.com/iosifache/DikeDataset

Model	*train loss*	*train acc*	*train prec*	*train rec*		*val loss*	*val acc*	*val prec*	*val rec*
ALEX NET	0.040	0.985	0.985	0.985		0.506	0.879	0.879	0.879
LE NET	0.693	0.508	0.508	0.508		0.693	0.500	0.500	0.500
STANDARD CNN	0.033	0.988	0.988	, 0.988		0.295	0.923	0.923	0.923
MobileNet	0.037	0.991	0.991	0.991		0.413	0.939	0.939	0.939
DenseNet	0.062	0.984	0.984	0.984		0.237	0.945	0.945	0.945
EfficientNet	0.019	0.994	0.994	0.994		2.682	0.498	0.498	0.498
ResNet50	0.021	0.994	0.994	0.994		0.405	0.926	0.926	0.926
VGG16	0.693	0.496	0.496	0.496		0.693	0.499	0.499	0.499
VGG19	0.693	0.491	0.491	0.491		0.693	0.500	0.500	0.500
Inception	0.061	0.988	0.988	0.988		0.197	0.943	0.943	0.943

Table 1: Training and validation performances related to loss, accuracy, preci-sion, recall.

- 1000 (unpacked) malware samples;
- 1000 packed malware samples obtained with the mpress packer:
- 1000 packed malware samples obtained with the BEP packer;
- 1000 packed malware samples obtained with the gzexe packer;
- 1000 trusted samples.

We train the deep learning models with the (unpacked) and trusted samples.
In the evaluation step, we consider following evaluations:

- with the unpacked malware and the trusted samples (i.e., the O dataset);
- with the packed malware (obtained with the mpress packed) and the trusted samples (i.e., the P1 dataset);
- with the packed malware (obtained with the BEP packed) and the trusted samples (i.e., the P2 dataset);
- with the packed malware (obtained with the gzexe packed) and the trusted samples (i.e., the P3 dataset).

For evaluating the model performances, following metrics are computed: loss, accuracy, precision, recall and Area under the Curve (AUC).
Table 1 shows the results related to the training and validation of
the models involved in the experimental analysis.
Table 1 shows the performance results related to the training and validation performance of the model involved in the experimental analysis. The table provides insight into each model's ability to generalize from the training data to the validation set.
First of all, we note that EfficientNet and ResNet50 achieved the highest training accuracy, precision, and recall (0.994), indicating their robustness dur- ing training. However, EfficientNet's validation performance drops significantly (0.498 across accuracy, precision, and recall), suggesting potential overfitting.
The MobileNet, DenseNet, and Inception networks showed strong validation performance (accuracy, precision, and recall values close to or above 0.9), suggesting better generalization compared to models like EfficientNet. ALEX NET and STANDARD CNN both performed well in terms of validation metrics, with STANDARD CNN slightly outperforming ALEX NET (0.923 vs. 0.879). LeNet, VGG16, and VGG19 performed poorly, with validation accuracy, pre- cision, and recall stuck around 0.5, implying these models struggled to learn effectively from the dataset.

- ALEX NET: Shows a moderate drop in validation performance compared to training (validation accuracy of 0.879). This could indicate some over- fitting, though the gap is not extreme.
- LeNet: Both training and validation metrics are around 0.5, indicating that the model failed to learn useful features, likely due to its simpler architecture being insufficient for the task.
- STANDARD CNN: Exhibits strong performance in both training and val-

idation. This model generalizes well and has a low validation loss (0.295).

- MobileNet: Strong validation performance with a high accuracy of 0.939. The model balances good generalization with relatively low training loss.
- DenseNet: Performs very well on both training and validation data, with validation accuracy at 0.945, indicating effective feature extraction and generalization.
- EfficientNet: While this model performs exceptionally well during train- ing, its validation metrics (0.498) suggest significant overfitting, as it fails to generalize.
- ResNet50: Very balanced, achieving excellent results in both training and validation, with validation accuracy at 0.926.
- VGG16 and VGG19: Both models fail to train effectively, as shown bythe high training and validation loss values. Their architecture may notbe well-suited for this dataset.
- Inception: Achieves good performance across all metrics, with particularly low validation loss (0.197) and high accuracy (0.943), indicating good generalization.

Models like ResNet50, DenseNet, MobileNet, and Inception are strong can- didates due to their balance of low loss and high validation metrics, suggesting better generalization. Simpler models like LeNet and the VGG variants strug- gled to capture relevant features, and EfficientNet overfitted despite its high complexity.

Thus, from Table 1 emerges that the models obtaining a validation accuracy greater than 0.90 are Standard CNN, MobileNet, DenseNet, ResNet50, and Inception: for this reason, these models are considered in the testing step.

Model	*Data set*	*Loss*	*Accuracy*	*Precision*	*Recall*	*F-Measure*	*AUC*
STANDARD CNN	O	0.337	0.921	0.921	0.921	0.921	0.963
	P1	0.180	0.954	0.954	0.954	0.954	0.982
	P2	0.156	0.960	0.960	0.960	0.960	0.984
	P3	0.174	0.956	0.956	0.956	0.956	0.983
MobileNet	O	0.3	0.949	0.949	0.94	0.949	0.9

		69			9		70
	P1	0.140	0.974	0.974	0.974	0.974	0.987
	P2	0.167	0.973	0.973	0.973	0.973	0.990
	P3	0.151	0.974	0.974	0.974	0.974	0.988
DenseNet	O	0.214	0.947	0.947	0.947	0.947	0.979
	P1	0.133	0.966	0.966	0.966	0.966	0.988
	P2	0.122	0.968	0.968	0.968	0.968	0.989
	P3	0.120	0.968	0.968	0.968	0.968	0.989
ResNet50	O	0.442	0.920	0.920	0.920	0.920	0.960
	P1	0.248	0.950	0.950	0.950	0.950	0.979
	P2	0.234	0.952	0.952	0.952	0.952	0.980
	P3	0.246	0.950	0.950	0.950	0.950	0.979
Inception	O	0.193	0.941	0.941	0.941	0.941	0.976
	P1	0.175	0.946	0.946	0.946	0.946	0.982
	P2	0.157	0.952	0.952	0.952	0.952	0.987
	P3	0.165	0.950	0.950	0.950	0.950	0.982

Table 2: The results of the experimental analysis.

Table 2 presents the results of the experimental analysis involving four datasets (0, P1, P2, and P3) and five models (i.e., Standard CNN, MobileNet, DenseNet, ResNet50, and Inception).

We note improved performance on P1, P2, and P3 datasets, as a matter of fact all models show better performance on the datasets P1, P2, and P3 com- pared to dataset 0. This suggests that the complexity or size of these datasets helps the models learn more effectively, resulting in higher accuracy, precision, recall, and lower loss. MobileNet and DenseNet consistently outperform the other models in terms of accuracy, precision, recall, and F-measure, particu- larly on datasets P1 through P3. Both models maintain low loss values and high AUC, making them strong candidates for the task. ResNet50, while still performing well in terms of accuracy and AUC, suffers from higher loss values, indicating that it struggles to fit the data as effectively as the other models. In- ception shows balanced performance across all datasets, with competitive met- rics, though slightly behind MobileNet and DenseNet in terms of accuracy and loss.

MobileNet and DenseNet stand out for their ability to generalize and main- tain high performance across all datasets. Both models show minimal fluctua- tion in accuracy and have high AUC, indicating their effectiveness in malware classification. The performance improvements across the datasets suggest that the models benefit from more complex datasets (i.e., P1, P2, P3). While the ResNet50 and Inception models perform adequately, their higher loss values and slightly lower accuracy suggest they may not generalize as well as MobileNetand DenseNet, especially in handling more complex data.

These findings indicate that MobileNet and DenseNet would be the most re- liable models for malware detection, but considering that the MobileNet models obtains slightly higher performances in accuracy if compared with the DenseNet one, we consider the MobileNet model the best model for the detection of packed malware. As a matter of fact, the DenseNet model obtains an accuracy respec-tively equal to 0.949, 0.974, 0.973 and 0,974 while the DenseNet reaches following accuracy i.e., 0.947, 0.966, 0.968 and 0.968.

To better summarize the results obtained from the experimental analysis, we compare the average accuracy obtained for each model, shown in Figure 3.

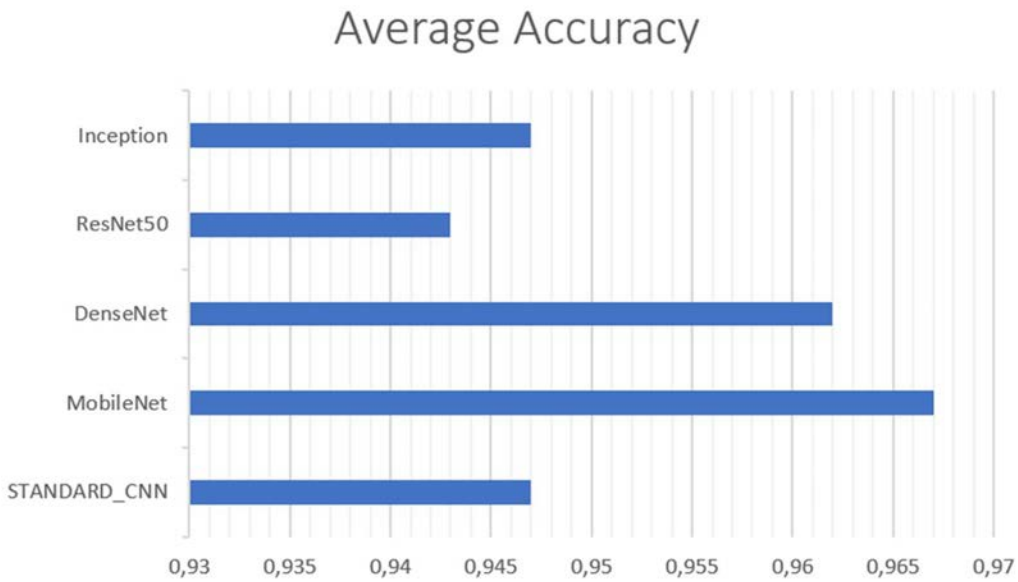

Fig. 3: The average accuracy for each model involved in the experimental analysis.

As shown from Figure 3, the best model in terms of average accuracy is confirmed the MobileNet, with an average accuracy equal to 0,967. The DenseNet model, the STANDARD_CNN and the Inception models obtain, respectively, an average accuracy equal to 0,962 and 0,947 (for the STANDARD_CNN and the Inception models). The worst model in terms of average accuracy is the ResNet50 one, with a value equal to 0,943. Thus, we confirm that the best model is the MobileNet one for discriminating an application between trusted or (packed) malicious.

5 Conclusion and Future Work

In this paper, we introduce a method that utilizes CNNs to detect packed mal- ware. Our approach involves static analysis, meaning it does not require the execution of the application to identify malicious samples. Starting with the bi- nary code of an application, we transform it into an image that serves as inputto a series of deep learning classifiers. The goal of these classifiers is to determine whether the application under analysis is trusted or (packed) malicious.

In our experimental analysis, we consider three different packers i.e., Mpress, BEP, and gzexe, to generate packed malware samples. Our results demonstrate the effectiveness of the proposed method in detecting both packed and un- packed malware, achieving promising performance across the tested scenarios. From the experimental analysis emerges that the MobileNet and the DenseNet models show minimal fluctuation in accuracy and have high AUC, indicatingtheir effectiveness

in malware classification.
As future work, we plan to consider prediction explainability, with the aim to understand which parts of the images related to malware are symptomatic of the model prediction. Moreover, we will consider also the possibility to detect ransomware with the proposed model.

6 References

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Early-warning integrated system for monitoring extreme weather events and enhancing worker safety

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Abstract
Workers operating in outdoor worksites are prone to work-related risks together with additional risks due to natural events that can be sudden and severe, e.g., precipitation (rain or hail), lightning and wind, but also earthquakes or tsunamis. This is particularly pronounced with the climate change that causes an enhancement of extreme weather phenomena, e.g., heatwaves, cold waves, heavy precipitation, drought, tornadoes, and tropical cyclones. In this context, worker exposure combines with both direct risks, e.g., temperature increasing and UV exposure, and indirect ones due to increased pollution, increased use of pesticides, new disease vectors and new pathogens. There are several categories of workers exposed to the above-mentioned risks, e.g., construction-site workers, farmers, foresters, fishermen, miners, but also safe-and-rescue operators. In this framework, it is crucial the risk analysis to which the worker is subjected in case of extreme weather events. Besides, a prompt detection of such phenomena with the development of an early warning system is essential. In this paper, we propose the development of a novel system to accurately monitor the local weather conditions within worksites, in real-time and with high time and space resolution. The solution consists of a set of measurement nodes equipped with several weather/environmental sensors and a SmartLNB. The latter is a commercial-grade device which is both able to receive satellite communications, and to operate as a transceiver, with data-logger modem function, that sends both its own measurements about received signal strength and the data provided by other conventional weather/environmental sensors to a server through an appropriate satellite platform. Collected data is processed through an innovative non-conventional approach, to determine the attenuation of the satellite microwave signal due to precipitation along the signal path and provides an estimate of the rainfall intensity in mm/h and ground accumulation in mm. The system contributes to improving sustainability and work well-being in the context of the Fifth Industrial Revolution (Industry 5.0).

1 Introduction

Workers operating in outdoor workplaces are exposed to standard occupation risks but also to risks related to natural events such as precipitation (rain or hail), lightning and wind, but also earthquakes or tsunamis. The safety of these workers is critically at risk, as such phenomena can lead to severe injuries, fatalities, and long-term health

consequences if not adequately managed. A proactive approach to monitoring and mitigating these risks is essential to safeguard their well-being and ensure compliance with occupational safety standards [1].

Extreme weather events have become more accentuated in this epoch of climate change by causing an increase in the frequency and intensity of extreme climatic phenomena, giving rise, for example, to cloudbursts, the so-called "water bombs", whirlwinds and lightning. In this context, workers' exposure to these events is combined with both direct and indirect risks. Direct risks are mainly due to increased temperatures and exposure to ultraviolet rays, while indirect risks are consequences of increased pollution, increased use of pesticides, new disease vectors and new pathogens [2].

In November 2023, the World Health Organization reported that among documented disasters resulting from natural hazards in the past 10 years, between 80% and 90% were caused by floods, droughts, tropical cyclones, heat waves and severe storms. Floods are the most common natural disasters worldwide, accounting for 43% of events. Also, Italy is increasingly subject to extreme weather events. The “Legambiente's Città Clima Observatory” recorded 684 floods from heavy rains, 166 river floods and 86 landslides due to heavy rains, which represent 49.1% of the total events recorded from 2010 to October 31, 2023 [3]. In the last 25 years (from 2000 to 2024) the number of people who died due to floods and inundations is 289.

Lots of categories of workers are exposed to the above-mentioned risks, e.g., construction employees, agricultural and forestry workers, fishermen, miners, quarry operators, workers involved in search and rescue operations or in transportation. Albeit indirectly, even workers operating indoors can suffer effects due to extreme events.

According to the recent Global Report “Ensuring safety and health at work in a changing climate” by the International Labour Organization, there have been over two million deaths at work due to extreme weather events from 1970 to 2019. In this context, legislation is limited and there are only general emergency plans to be applied for crisis situations without considering physical and mental risks. Therefore, performing certain work activities outdoors increases the risk to workers, as they are more vulnerable to the effects of extreme weather events. For example, a worker operating in construction sites risks serious injury or death in case of infrastructure collapse, a worker carrying out activities at height risks falling with consequent traumas, even fatal.

From a psychological point of view, the greater frequency of such extreme weather events represents a growing threat to the well-being of the worker. Furthermore, these events can often be the cause of one another, such as a heat wave that increases the risk of cyclones or the latter that then induce very heavy rainfall. It is noteworthy that in these extreme situations it is often necessary to deploy numerous rescue teams with a consequent increase in the number of workers exposed to the risks. Of course, training for workers exposed to such emergency situations takes on a priority role. However, this training is often lacking, with obvious gaps both in the phase of recognizing the early alert signals of extreme events and in the actions to be taken in response.

In this context, it becomes essential to analyse the different types of risks the workers are exposed to in case of extreme weather events depending on the work environment, the activities carried out and the type of equipment. Besides, it is crucial to promptly identify such phenomena through Early Warning Systems (EWSs) that accurately and precisely monitor the weather conditions in the working area, e.g., cloudiness, rainfall intensity, wind direction and intensity, together with environmental parameters. The use of innovative systems and technologies that are easily adaptable and scalable to various workplaces represents a turning point in the perspective of reducing work-related risks. These systems become a very useful tool for the worker who is called to an ever-greater resilience in relation to these emerging risks, thus becoming capable of improving his own reaction and the management of the emergency itself. This also contributes to improve sustainability and well-being at work in full view of the Fifth Industrial Revolution (Industry 5.0). Moreover, ensuring worker safety in the face of extreme weather events requires not only the accurate detection of hazardous conditions but also the rapid dissemination of actionable information to prevent accidents and reduce exposure. The proposed EWSs enhance workplace safety by enabling timely responses to weather-related risks, thereby mitigating injuries, fatalities, and associated mental stress. This proactive approach ensures compliance with occupational safety standards and fosters a culture of resilience and knowledge among outdoor workers.

Currently, the forecasting systems are not able to predict rapid-dynamic extreme weather events, especially those of the convective type, and especially to identify the area in which they will occur with high accuracy. Indeed, the latter could be very limited. Although the current forecasting models are still important and useful for planning activities to reduce the risk for workers operating in outdoor environments, it is still essential to support them with reliable and accurate local detection systems, capable of detecting an imminent potentially dangerous weather event.

This paper proposes the implementation of an “early warning” system to improve working conditions and safety of workers in outdoor environments, that are exposed to unpredictable risks associated with extreme weather events. The main idea is based on the deployment of a portable Integrated Weather and Satellite Station (IWSS) within the work area to be monitored or even around. Each station includes a set of conventional weather/environmental sensors and a new-generation commercial satellite terminal, which uses small diameter dishes, called Smart Low Noise Block converter (SmartLNB).

2 The “early warning system” for workers operating outdoor

The proposed system aims to develop a weather monitoring system, based on satellite technology, and supported by specific algorithms capable of providing the status of meteorological events and predicting their evolution in the short term (“nowcasting”) to increase the safety of workers operating outdoors.

Figure 1 illustrates a scheme of the proposed solution that is composed by:

- a system of satellite parabolic antennas equipped with Smart LNB devices capable of performing signal attenuation measurements to determine cloudiness and precipitation;
- a network of portable IWSSs for monitoring weather/environmental parameters such as temperature, humidity, pressure, precipitation, wind speed and direction, solar radiation, UV index, gas and particulate concentrations, air quality index;
- a satellite data transmission link available thanks to the Smart LNB device;
- a data collection and processing centre for the development of "nowcasting" forecasting models with a related web platform;
- an alarm system for the worker via smartphone/smartwatch for the transmission of communications from the supervisor regarding the meteorological situation.

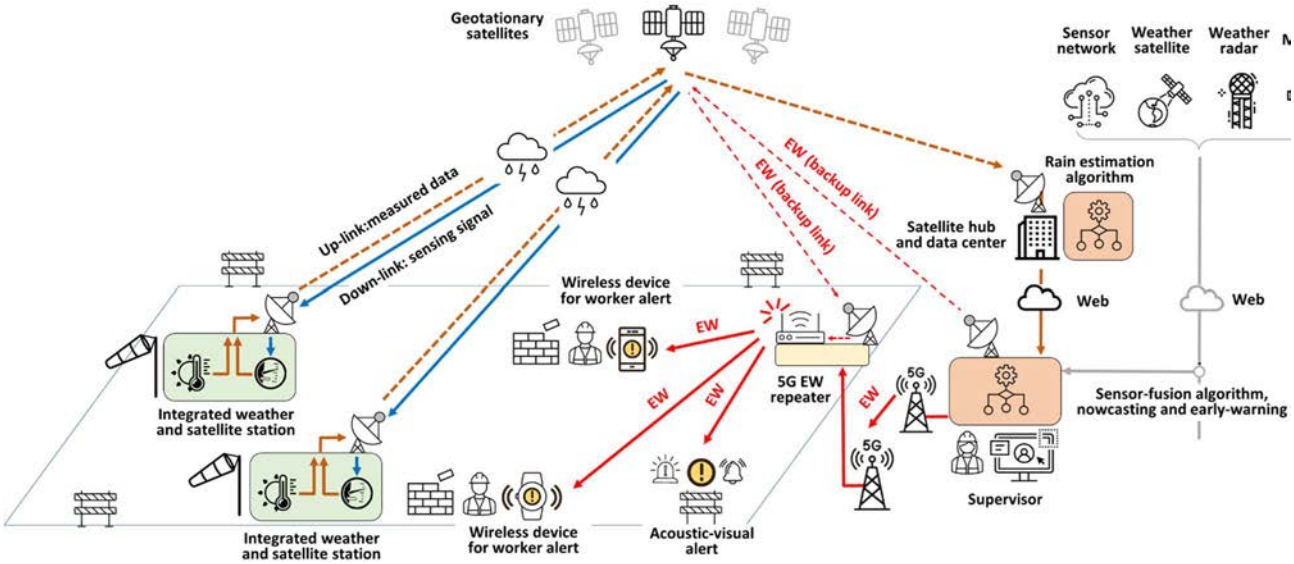

Fig. 1. Schematic diagram of the "early warning" system for workers operating in outdoor environments and exposed to risks related to extreme weather events.

2.1 The SmartLNB

The SmartLNB is an innovative transceiver device that can be used both to measure the intensity of the signal received from the satellite and as a data-logger modem. The SmartLNB monitors the signal received on Earth ("down-link") in the Ku microwave band (10-13 GHz). The same terminal also transmits the measurements on the satellite signal, and those made by the environmental/weather sensors, through a satellite connection ("up-link") to a hub, up to a central server. A suitable satellite platform is described in [4]. In this way, thanks to the bidirectional satellite channel, it is possible to overcome the traditional dependence on terrestrial networks, fixed or mobile, thus releasing from a dedicated connection infrastructure, not always available in construction sites and outdoor working areas.

The measurements of the satellite signal are processed through the method patented by the University of Pisa [5] to determine the attenuation suffered by the microwave signal received on Earth via the down-link connection due to any precipitation present along the route. Such attenuation then provides an estimate of the intensity of the rain

in mm/h and the cumulative on the ground in mm according to an innovative unconventional approach, called "opportunistic" [6]-[12].
Later on, all collected data, both the raw data from the environmental/weather sensors and the satellite rain data processed at the central server, are then made available to a processing system which: i) uses “data fusion” techniques with measurements provided by any ancillary systems (pre-existing sensor networks in areas adjacent to the one of interest, radar and meteorological satellites, models); ii) performs a forecast of the short-term evolution of the weather situation using a specific nowcasting algorithm; iii) signals an alert (Early Warning, EW) if the nowcasting reveals the imminent danger of a critical situation.
The innovative adopted sensor-fusion algorithm is based on Ensemble Kalman Filter (En-KF) [9]. The obtained information is made available to the supervisor of the activities on a local station, or via the web, who decides on the emission of the EW signal for the exposed workers. This can be done via a 5G terrestrial mobile network, with a possible local signal repeater (5G EW) in case of poor coverage of the area concerned. If, however, network coverage is unavailable in the area, a backup satellite bridge can be activated, allowing the processing centre to supply the signal to the 5G EW repeater. In addition to activate specific acoustic-visual alarms, this system sends an alert communication to workers’ smartphone or smartwatch containing also information about environmental parameters, the type of imminent threat, and instructions on how to behave and how to reach a safe place based on the construction site emergency plan.

2.2 Scalability and sustainability

As already said, multiple portable IWSSs can be positioned in different points of the construction site, creating a network for monitoring both local weather/environmental parameters and precipitation intercepted by satellite signals. The density of the devices can be appropriately sized to obtain the desired spatial resolution, ensuring a scalable and easy-to-install architecture in relation to the size of the work area to be monitored. As a guide, a SmartLNB sensor covers an area of at least 2 km in the north/south direction and approximately 2 km in the east/west direction, but the number of satellite dishes and portable weather stations can be increased to cover larger areas without any changes to the data collection and processing system. In fact, the satellite data collection platform covers all of Italy and Western Europe, working even in areas without any terrestrial network coverage.
The proposed solution has several advantages. First, it does not need auxiliary systems for radio coverage, demonstrating high sustainability without increasing workers’ exposure to additional electromagnetic signals. Additionally, compared to solutions that exploit aerial monitoring platforms (e.g., drones, hot air balloons), it is more robust in critical situations typical of extreme weather events characterized by strong winds or even tornadoes. Lastly, it doesn’t require extensive historical data, as is often necessary for training algorithms when using artificial intelligence and deep learning methods.

3 Conclusion

This paper presented the conceptual idea of an “early warning” system to improve safety in outdoor work environments, such as construction sites, quarries, and agricultural land, with respect to the occurrence of extreme and sudden weather phenomena.

It is based on a combination of weather/environmental measurements carried out by conventional sensors of various types and precipitation measurements based on the opportunistic use of signals transmitted by telecommunications satellites. Thanks to the use of commercial and low-cost components, such as small-sized parabolic antennas and SmartLNB terminals, supported by the measurements of various sensors and any other ancillary information, and the use of specific software algorithms for rain estimation and nowcasting, it is possible to monitor the state of precipitation in the working area and its surroundings, follow its evolution and movement and therefore improve the short-term forecast of extreme weather events, often sudden, that can put the health of workers at risk. The data collected by the portable integrated weather and satellite stations in the field are transmitted via satellite link and processed in real time to provide "nowcasting" forecasts. These forecasts are made available to the work supervisors through a web platform, enabling them to quickly inform operators of dangerous conditions with an effective "early warning" tool delivered via smartphone or smartwatch. This solution, in addition to effectively reducing the risk to which workers may be exposed in the event of extreme weather events, contributes to improve the well-being at work.

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An Innovative Intelligent Personal Hearing Protection Device Using Artificial Intelligence Algorithms Integrated in Industrial IoT Architecture

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Abstract
This paper presents the design and development of an intelligent system based on IoT-enabling technologies and Artificial Intelligence (AI) techniques, designed to dynamically filter sounds and noises that could disturb workers and cause permanent damage to their hearing, while allowing the unaltered sound flow of those essential for workplace safety (i.e., voice of colleagues). The system is one of the results of a project funded by the Italian National Institute for Insurance against Accidents at Work (INAIL) that aims to develop a prototype of Personal Protective Equipment (PPE) featuring adaptive electronic filters implemented through AI techniques. The prototypal device, based on IoT-enabling hardware and software technologies, will be integrated in a comprehensive ecosystem that includes a distributed software system that can acquire alerts from machinery and promptly deliver voice messages to workers in proximity, utilizing an indoor localization system based on Bluetooth Low Energy (BLE) technology. The project, therefore, comprises two main components: a smart noise-cancelling headphones and a human-machine feedback system. The smart noise-cancelling headphones, useful as PPE, use pre-trained Machine Learning models to distinguish between harmful noises and safety and task related sounds, such as human voices, allowing the latter to pass while filtering the former. Additionally, they are equipped with a Digital Signal Processor (DSP) for real-time audio filtering and an indoor localization system that uses Bluetooth beacons to monitor the user's position and trigger audio alerts in case of danger. The human-machine feedback system integrates the headphones and the work environment, collecting environmental noise data and monitoring the workers' positions. This information is processed by a cloud-based Machine Learning model to send safety alerts or instructions, enhancing workers'

awareness and protection. In the paper the system will be described in deep and the possible safety reduction due to the utilization of the system will be highlighted.

1 Introduction

Continuous exposure to loud noises can cause hearing damage and increase the risk of workplace accidents. This work aims to develop a system for the smart filtering of sounds and noises that could disturb workers and cause permanent damage to their hearing. The system is composed of 2 main parts, one including an intelligent Personal Protective Equipment (PPE) device and another one acting as a human-machine feedback system. The one including the PPE is designed for dynamic hearing protection and real-time safety management based on IoT [1] technologies and Artificial Intelligence algorithms. The proposed prototype includes smart headphones with adaptive filters based on Machine Learning, capable of identifying the presence of a human voice in a sound and recognize the overall equivalent sound pressure level Leq, and therefore, set a hardware filter to be further integrated into the second part of the system that includes smart machinery and indoor positioning systems. Various existing works already proposed similar solutions based on PPEs, however, to the best of our knowledge, they do not offer dynamic filtering. Moreover, the one based on traditional methods limit communication between workers while filtering the incoming sound. Among the techniques for dynamically filter the sound, the most promising ones are based on the use of Machine Learning algorithms, such as Voice Activity Detection (VAD) and active noise cancellation (ANC) [2], that enables real-time filtering (enhanced by neural networks algorithms specified later in the article), able to isolate human voices from background sounds. Consequently, our solution is based on these ML techniques and, in addition, combines them with indoor positioning techniques and smart machinery. Indoor positioning with Bluetooth BLE beacons allows the monitoring of worker position, thus improving operational safety with contextual alerts. Moreover, the integration of IoT systems [3] enables Machine-to-Machine (M2M) communications, sending automatic alerts in case of danger. A technological scouting did by us highlighted the limitations of commercial PPEs, which this work aims to overcome with a proactive response to changing environmental conditions and integration with cloud-based corporate safety systems. Additionally, the project aligns with international and national safety and hearing protection regulations in industrial environments. In general, the Machinery Directive 2006/42/EC [5] requires machines to include risk prevention devices. Directive 2003/10/EC [4] mandates the use of PPE for exposures above 80 dB(A) and requires their use above 85 dB(A). Furthermore, Italian Decreto Legislativo e no. 81/2008 requires PPE for exposures above 87 dB, with health surveillance and risk updates every four years. Finally, ISO 4869 [6] and EN 352 [7] set standards for noise attenuation and the compatibility of PPE with other systems.

2 System Architecture and Conceptual Design

A conceptual design of the intelligent hearing protection system designed and developed within the present work, is depicted in Figure 1. It was carried out, which includes the filtering logic of the wearable device and the system for hazard localization and notification, defining the main requirements from the state-of-the-art analysis and the contextualization of existing technologies. The high-level components of the system are the smart headphone prototype and the backend system for data collection and management. The overall system architecture can be divided into two main subsystems (see Figure 1).

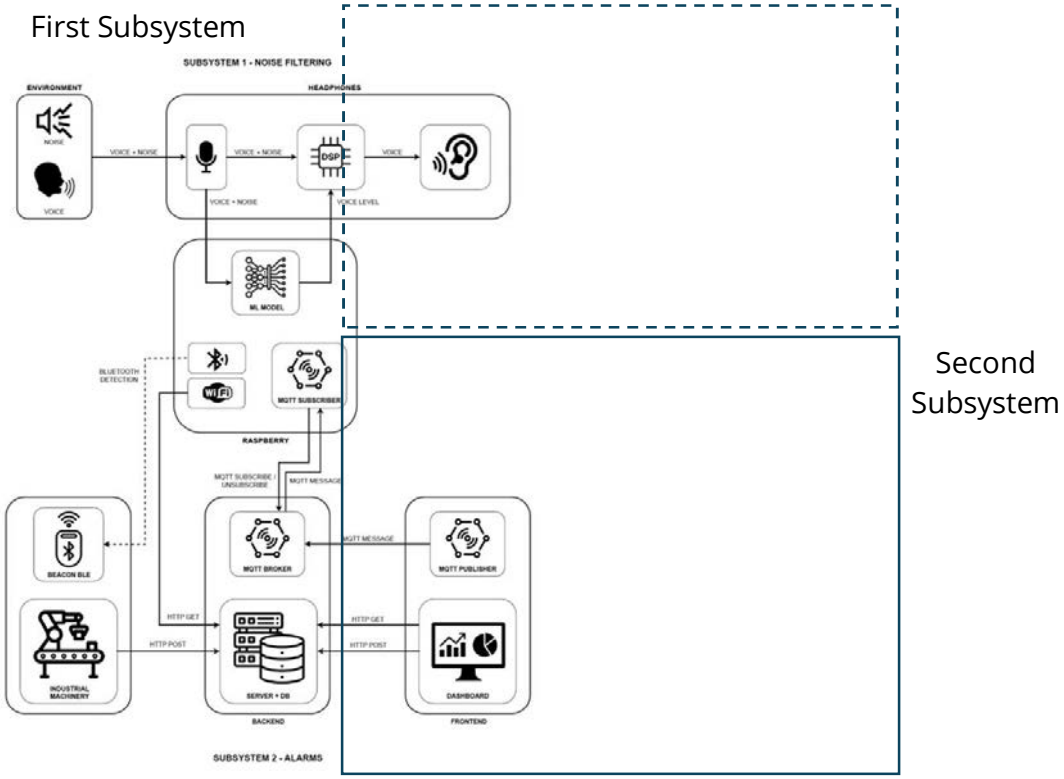

Fig. 1. General System Architecture

The first subsystem is dedicated to filtering environmental noise by recognizing the presence of human voices in the acquired sound and adapting the filter in accordance. The headphones are equipped with a low-cost microphone, previously characterized in terms of frequency and directionality and integrated into them, which captures acoustic signals composed of voices and/or noises. Then, the captured audio is passed to a dedicated algorithm that processes these signals in real-time and exploits a machine learning algorithm, pre-trained on a cloud model and run on a Raspberry Pi, to recognize the presence of voices in the signals (a probability is returned to distinguish a voice easily understandable from a voice that is, instead, immersed in the noise) as well as the equivalent sound pressure level Leq. . The models employ VAD (Voice Activity Detection) [8] techniques based on Gaussian Mixture Model (GMM) and Deep Neural Network (DNN) for real-time identification of

voice in an audio. The worker's environment is characterized by loud and continuous noises. In this same environment, the voices of other workers must remain audible without being “drowned out” by the surrounding machinery noise. Finally, a crucial role is played by the DSP (Digital Signal Processor) filter. This processor, integrated into the headphones, is responsible for real-time adaptive sound filtering using AI algorithms. The DSP receives information about the presence of voice in the real time audio together with Leq, and, by operating with FIR (Finite Impulse Response) and IIR (Infinite Impulse Response) filters, it acts as noise suppression. The Raspberry Pi acts as a key component of the system by running the Machine Learning VAD algorithm.

The second subsystem includes the backend system, which collects and processes data on environmental noise and worker positions. The backend manages a Machine Learning pre-trained model for optimizing the filters in real-time to be used in the PPE to filter the sound. Additionally, the system, based on Bluetooth Low Energy beacons [9-10], monitors the position of workers near machines, alerting them to potential hazards through synthetic audio messages sent to the headphones. The system is activated as soon as the worker puts on the headphones. When potentially harmful noises are detected, the headphones attenuate the noise, allowing relevant acoustic signals such as other workers' voices or alarms can pass through. The Raspberry Pi manages the worker's localization relative to the machinery. Specifically, it continuously performs scan of the nearby environment to identify all the nearby devices that are reachable through a Bluetooth connection. In this way it is able to detect the beacons placed near the machinery. It also manages interaction with the backend software system, making HTTP requests and dynamically subscribing to various MQTT topics associated with the machinery to receive any warning messages for the workers. The data acquired through the microphone is sent to the backend, which processes in real-time information related to noise levels, worker location, and machine status. In case of an alarm, the backend sends targeted notifications via the MQTT protocol, directing messages to workers that are near the danger. Each industrial machine is associated with one or more Bluetooth beacons and an MQTT topic, enabling indoor localization of workers via the Raspberry Pi connected to their smart headphones. When a worker approaches a machine, the Raspberry Pi receives a packet sent by a beacon with an RSSI (signal strength indicator) value. When the RSSI is above a certain threshold, the system automatically subscribes the worker to the MQTT topic related to that specific machine. The smart headphones, knowing the association between the machine, MQTT topic, and Bluetooth beacon thanks to an initialization phase where they obtain this information from the database, query the backend server via HTTP requests. The backend, in addition to managing a database that keeps all system information, including industrial machine statuses, up to date, also implements and manages the MQTT broker, playing a crucial role in communication between the various system actors. In the event of alarms associated with malfunctions or dangerous situations, the backend receives information from

industrial machines via HTTP POST requests and can relay this information to workers through MQTT topics. Finally, the architecture also includes a frontend system accessible to safety managers, who view the status of the machines and send hazard notifications or update system information. This dashboard not only provides a simple visualization of the data but also allows active interaction with the backend. Through HTTP GET requests, the dashboard retrieves information from the database and displays it clearly and structured.

3 Design and Implementation of the System

3.1. Noise filtering subsystem (headphones)

Low-Cost microphones

For the purposes of the project, three low-cost Lavalier microphones [11] were selected, potentially integrable into the headphones (see Figure 2). The choice, aligned with the project's requirements, was guided by their affordable cost, theoretical omnidirectional polar pattern, and operational range corresponding to audible frequencies. The microphones (see Table 1) represent a progression in terms of cost and theoretical performance, which need to be validated through tests conducted in both reverberation and anechoic chambers. The microphone with the best performance in terms of frequency response and directivity will be integrated into the hearing protection device (DPI).

Microphones	Polar pattern (theoretical)	Audio sensitivity (dB re 1 Volt/Pascal +/- 3 dB)	Frequency Range
1	Omnidirectional	-32	50 Hz-20 kHz
2	Omnidirectional	-35	20 Hz-20 kHz
3	Omnidirectional	-38	20 Hz-20 kHz

Table 1. Characteristics of Low-Cost Microphones

a) b) c)

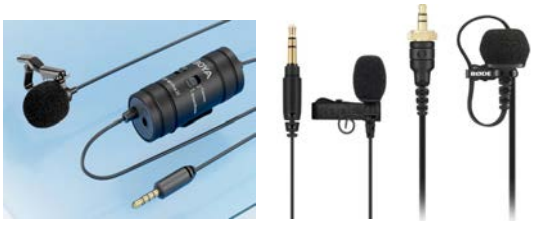

Fig. 2. Selected Lavalier microphones

Specifically, the experimental campaigns conducted in reverberation and anechoic chambers compared these low-cost microphones with a precision sound level meter to analyze their frequency and directional response. In the reverberation chamber, the microphones were tested with pure tones ranging from 125 Hz to 8000 Hz, resulting in equivalent sound pressure levels at the considered frequencies. These levels were compared with those obtained from the sound level meter. Microphone 1 showed increasing discrepancies at high frequencies compared to the sound level

meter values, with a maximum error of 8 dB at 8000 Hz. Microphone 2 recorded a maximum error of only 1 dB, proving to be reliable for non-professional applications. Microphone 3 showed more significant differences beyond 1000 Hz. In the anechoic chamber, tests were conducted to validate the directional response: Microphone 2 demonstrated good sensitivity, with minimal losses, confirming itself as the best performer in terms of both performance and cost, making it the most suitable for the project's objectives.

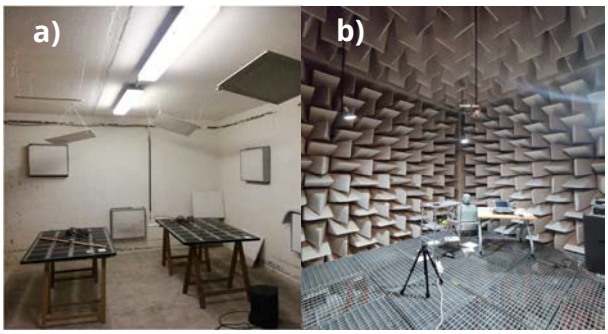

Fig. 3. a) Reverberation chamber b) Anechoic chamber

Real-time Code in Python for Processing Acquired Audio Data

A software has been developed in Python for noise characterization, using libraries for acoustic signal processing, such as the scikit-maad library [12] used for environmental acoustic measurements. The system acquires signals from microphones and processes them in real-time, calculating the equivalent sound pressure level Leq [13], both instantaneous and averaged over the measurement time, as well as the spectra in octave or third-octave bands. Audio acquisition was initially implemented on a computer with a Windows operating system and later transferred to a Raspberry Pi, achieving comparable noise analysis times for each value of Leq and octave/third octave band (1 sec of acquisition) between the two operative systems: specifically, a noise analysis time of 1.3 second on the Windows PC and 3.3 seconds on the Raspberry Pi 5. It is to say that the difference between the two operative systems is on the stream time acquisition because the calculation time is lesser than 0.1 second for every system. In addition to scikit-maad, the software employs libraries such as PyAudio for real-time audio capture, NumPy for numerical processing, SciPy for filtering, and Matplotlib for result visualization. Furthermore, the code has been enhanced with a user interface using Qt Creator [14], providing an intuitive graphical environment to configure parameters related to audio recording, such as the gain of the audio card of the device (PC, Raspberry) and microphone sensitivity. Additional configurable parameters include the bandwidth (octave or third-octave), processing time (with options to start and stop measurement manually or set a default duration), and the weighting (A, C, or Z) of the signal. The interface allows users to choose the data recording mode, either as a "sound level meter" (real-time display and recording to a text file) or as "wave" (recording to a text file and in

.wav format of the acoustic signal). Before the acquisition phase, preliminary calibration procedures for the microphones and the sound level meter [15] were carried out. In particular, calibrations were conducted using reference values of 94 and 114 dB at 1000 Hz. The signal acquired from the microphones, encoded at 16 bits, allowed for the calculation of the microphone's dynamic range, which is 96 dB. Additionally, the algorithm normalizes the output voltage raw signal from the microphone to waveform format, as done for recorded .wav files, and, through scikit-maad, results are obtained, as previously mentioned, in terms of sound pressure levels and spectra in bands. The calculation is performed every second, with slow integration, in line with the settings of the sound level meter to allow for comparison between instruments. The results include both plots of the spectra in octave or third-octave bands and the temporal trend, averaged over the processing time, of the equivalent sound pressure level (see Figure 4).

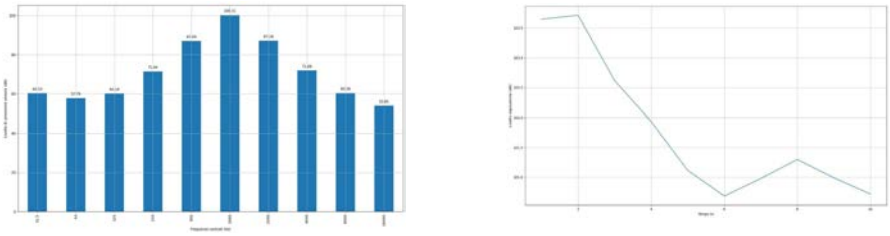

Fig. 4. Spectrum in bands averaged over the duration of the individual test and temporal trend, averaged over the measurement time, of the equivalent level

Additionally, a post-processing program has been developed to process offline the .wav files saved by the real-time algorithm. This program allows users to select the wave file through an interface created with Qt Creator, automatically detecting the recording parameters.

Smart Headphone Hardware Device

The DSP module selected for the smart headset project is the NEDSP-1901-KBD (see Figure 5 and [16]) from BHI-LTD, chosen for its miniaturization and ability to process audio samples in real time, such as those from an electret microphone. The module supports adjustable noise reduction while preserving voice intelligibility. The Attenuation levels range from 8 dB to 40 dB, enabling the selection of the best configuration to significantly improving voice clarity in different noisy environments. The DSP uses bandpass filtering algorithms that allow only the vocal signal components, between 0.2 Hz and 5 Hz, to pass through, while attenuating irrelevant frequencies classified as noise. The module is programmable through external microcontrollers (during the testing campaign a simple Arduino board was used for the scope, but it can be interfaced with much more complex and miniaturized devices), enabling remote control of functions such as power on/off and noise filter levels. During the test performed on the device, a setup including audio file recordings was developed. These audios had the aim to simulate industrial

environments with typical sounds like chainsaws, pneumatic hammers, and engines, to assess the DSP performance in attenuating noise and maintaining vocal clarity. The module was interfaced with a PCB, powered at 12V, and connected to the audio input and output devices, allowing efficient signal processing and application of DSP filters. Additionally, the NEDSP-1901-KBD module features a 7W high-efficiency audio amplifier from Texas Instruments, easily integrable into existing devices. Obviously, the miniaturization of the final circuit would be crucial to allow for the module to fit into the ear cups or belt of the PPE that would be developed, but this could be achieved by developing a final PCB containing all the selected element but organized in a clever and well-designed architecture.

Fig. 5. NEDSP-1901-KBD module

3.2. Human-Machine backend subsystem

This subsystem, as previously mentioned, connects industrial machinery, backend, and frontend. To replicate this scenario, a data transmission layout between the machine and the backend server has been created, integrating a CNC lathe console, the modified Data Collector Manager (DCM) from D.Electron [17], a Python HTTP server (running on PC or Raspberry), and a modem for connection (see Figure 6). The following libraries were used in the server python script: http.server is a library used to quickly create static web servers for development or testing purposes. Socket server allows for easier server development and customization, without having to manually create sockets (virtual software for transmitting and receiving data), listen, and accept connections. Datetime is used to record the current date and time of the computer; socket allows for manipulation of IP addresses and ports. Communication between the machine and server occurs via HTTP POST requests, where the DCM collects, formats, and transmits data (see Figure 7) to the server via a specific IP address and port where the server is running. The system sends information regarding the operational status of the machine, alarms, maintenance, control display status, smart service functionalities, and details regarding the programs executed. As mentioned earlier, data is sent to the server following a specific formatting that includes the machine's serial number, data type, numeric value, value explanation, and date and time. In the tests conducted on the system, no information loss occurred during transmission (zero failure rate).

Fig. 6. Data transmission layout between machine and server: a) lathe console + DCM, b) HTTP POST server in Python environment, c) Connection modem between lathe and server

```
Your Computer Name is: HP-bric
Your Computer IP Address is: 192.168.20.6
Server avviato su 192.168.20.6:4060 con la versione CustomHTTP/20231120
192.168.20.5 - - [20/Nov/2023 11:58:44] "POST / HTTP/1.1" 200 -
Data received in POST request: mserial: 9000, value: 200, timestamp: 2023.11.20+12:14:05
192.168.20.5 - - [20/Nov/2023 11:58:45] "POST / HTTP/1.1" 200 -
Data received in POST request: mserial: 9000, value: 4, timestamp: 2023.11.20+12:14:09
192.168.20.5 - - [20/Nov/2023 11:58:46] "POST / HTTP/1.1" 200 -
Data received in POST request: mserial: 9000, name: DOOR_G, value: 0, timestamp: 2023.11.20+12:15:03
192.168.20.5 - - [20/Nov/2023 11:58:47] "POST / HTTP/1.1" 200 -
Data received in POST request: mserial: 9000, name: SPLN_G, value: 0, timestamp: 2023.11.20+12:15:03
192.168.20.5 - - [20/Nov/2023 11:58:48] "POST / HTTP/1.1" 200 -
Data received in POST request: mserial: 9000, value: 4, timestamp: 2023.11.20+12:15:31
192.168.20.5 - - [20/Nov/2023 11:58:49] "POST / HTTP/1.1" 200 -
Data received in POST request: mserial: 9000, code: CN0000/MU0000, description: "*** NO ALARMS CN***"/"*** NO ALARMS
MU***", timestamp: 2023.11.20+12:16:37
```

Fig. 7. Example of transmitted strings

To simulate a complex industrial environment the layout has been enhanced by digital twins of a typical machine tools through a virtual client developed in Python/Qt Creator reproducing the operations of the DCM via POST requests. Those clients, one for every simulated machine, act as a digital twin of the real machine, simulating operations and complex scenarios in real-time. The digital twin is implemented on a Raspberry Pi (see Figure 8.2). Specifically, the real machine included in the layout is a modified CNC lathe, integrated with a PLC for direct communication with the system supervisor (see Figure 8.1). The PLC sends real-time information on machine downtime and emergency situations, ensuring a continuous data flow to the backend server. The system supports asynchronous transmission of information between the PLC and backend, ensuring quick and accurate responses in emergencies. The architecture is designed to provide continuous control and immediate feedback between machines, the digital twin, and the supervisor, optimizing operational management and improving overall system reliability.

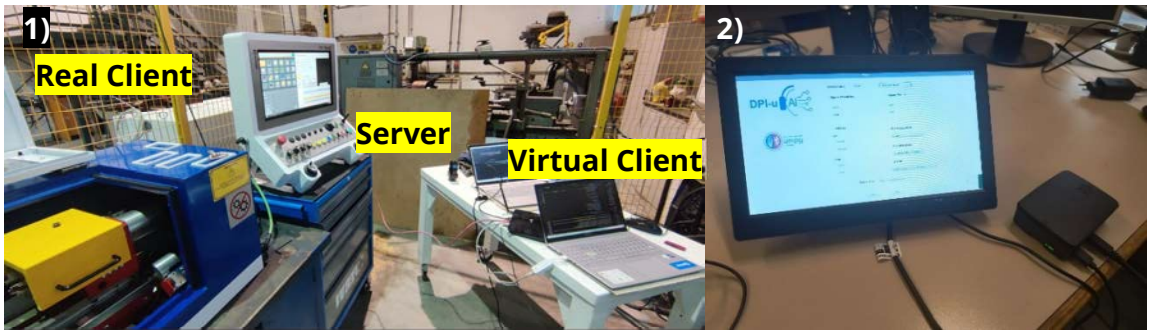

Fig. 8. 1) Data transmission layout between real machine, digital twin, and server; 2) Digital twin of machine on Raspberry Pi

The human-machine feedback system integrates the smart headphones with the work environment, collecting data on ambient noise and monitoring worker positions. This information is processed by a cloud-based Machine Learning model, which analyses the data to send safety alerts or operational instructions, enhancing worker awareness and protection.

4 Conclusions

The work described has demonstrated the feasibility of an advanced intelligent hearing protection system, integrated with IoT technologies and Artificial Intelligence algorithms, capable of operating in real-time. The developed prototype employs a Digital Signal Processor (DSP) for adaptive noise filtering, supported by pre-trained Machine Learning algorithms, capable of distinguishing between sounds critical for safety, such as human voices, and potentially harmful noise. The smart headphones are integrated into a distributed architecture that uses Bluetooth Low Energy (BLE) technology for indoor localization and transmission of alerts to workers in dangerous situations. The backend system, through continuous monitoring of environmental conditions and worker positions, adapts audio filters based on acquired data, ensuring a proactive response to changes in the operational environment. Tests conducted on hardware components, such as MEMS microphones and DSP modules, have confirmed high performance in terms of noise attenuation (up to 40 dB) and low latency (less than 10 ms), essential for applications in high-noise industrial environments. The IoT infrastructure, supported by an MQTT communication system, allows dynamic alarm management and constant interaction between wearable devices and the central system, significantly improving operational safety. These results represent an important advancement in the field of intelligent Personal Protective Equipment (PPE), offering a system capable of optimally responding to complex work scenarios while adhering to regulations such as Directive 2003/10/EC and ISO 4869.

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A new tool for manufacturers of pressure equipment to face the hazards/risks related to the nature and characteristic of the intended contained fluid(s)

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Abstract
According to Pressure Equipment Directive (2014/68/UE or PED) all hazards arising from pressure shall be assessed for the intended use and the intended contained fluid(s). The equipment shall be designed and constructed taking into account this analysis. This requirement can't be addressed by simply classifying the pressure equipment or assembly, but classification is a fundamental step to proportion the regulatory requirements according to the level of hazard. One of the factors to consider for classification is the group of the fluid which refers to the classification of substances and mixture according to the Regulation (EC) No 1272/2008 or CLP, then it correlates with the nature of the fluid or its intrinsic hazards, but its identification does not exhaust the obligation to assess the hazards arising from pressure for the fluid.
The experience acquired evaluating the technical documentation presented by the manufacturer highlights difficulties in performing a complete and exhaustive risks analysis and assessment, sometimes also for the fluid and there are even cases where the equipment/assembly is manufactured to contain more than one hazardous fluid.
The present work, after an introduction showing the impact on the conformity to PED which an incomplete or outdated classification may lead to, introduces a tool structured to associate the hazard foreseeable for a pressure equipment with the hazard classes and, when possible, the physical properties characterising the most common hazardous fluid to be contained.
The tool aims to support both the manufacturer to fulfil his obligation to analyse and assess risks and the notified body to verify the adequacy of the analysis and assessment performed in relation with the fluid.
The work illustrates the basis on which the tool was developed and concludes with an application example showing the flexibility and ease of use of the tool.
Key words: pressure equipment or assembly, fluid nature, hazard/risk analysis

1 Introduction

According to Pressure Equipment Directive (2014/68/UE or PED or, hereafter, "the directive" [1]) all hazards arising from pressure shall be assessed for the intended use and the intended contained fluid(s). The manufacturer shall design and construct a pressure equipment or assembly considering this analysis. PED defines fluids as gases,

liquids and vapours in pure phase as well as mixtures thereof and states that fluids may contain a suspension of solids.

1.1. Hazard and risk analysis and assessment in Pressure Equipment Directive

The first stage of the hazards and risks analysis and assessment laid down in the PED Guideline [2] [3] H-04 is the determination and recording of all the characteristics, extent, surrounding and circumstances of the intended use of the pressure equipment or the assembly. Next, it is necessary to identify hazards and/or hazardous situations that could occur during the life cycle of the pressure equipment or the assembly in reasonably foreseeable conditions.

The manufacturer shall analyse each hazard and/or hazardous situation and evaluate the significance of the risk for each identified applicable hazard and/or hazardous situation and follow the mitigation measures applying the principles of the risk hierarchy reported in Annex I of PED, Essential Safety Requirement or ESR 1.2, that is eliminate or reduce hazards as far as is reasonably practicable, then apply appropriate protection measures against hazards which cannot be eliminated and last, where appropriate, inform users of residual hazards and indicate the need to take appropriate special measures to reduce the risks at the time of installation and/or use.

The goal of the risk assessment is the appropriate application of the relevant ESRs of the PED and the implementation of associated measures. The analysis and assessment of the risk(s) must be documented and included in the technical documentation. In addition, the manufacturer needs to document how he is addressing the risks identified to ensure that the product complies with the applicable essential requirements (for example, by applying harmonised standards) [4] [5].

The analysis of Annex I of the Directive 2014/68/EU results in the classification into 4 hazard groups [6] [7]. The hazard group where the fluid plays a role are the first, “failure of the pressure-bearing wall during intended use as a result of inadequate design”, and the fourth, “hazards resulting from the release of fluids”. In this respect the release of fluids during the operation but also the safe clearance and disposal of the fluids at the end of the equipment’s life cycle must be considered [8].

1.2. Pressure Equipment hazard categories

PED classify pressure equipment in four categories, according to an ascending level of hazard. Classification is a fundamental step to proportion the regulatory requirements according to the level of hazard.

From the second category onwards, the manufacturer is required to submit the pressure equipment or assembly to a third party, usually a notified body, to have the conformity assessment carried out, or to have a quality system approved by a notified body. For each category, the manufacturer can choose the conformity assessment procedure (modules) he considers most appropriate among those provided. He may also choose to apply one of the procedures which apply to a higher category, if available.

The criteria used to identify the risk category of a pressure equipment are the nature of the contained fluid if dangerous according to art. 13 of the directive or not, its physical state, if gas, liquefied gas, gas dissolved under pressure, vapour or liquid and the stored energy that is the product of the maximum allowable pressure per the volume (for vessels) or the nominal diameter (for piping and accessories)
According to the art. 13 of the directive [1] fluids shall be divided into two groups, group 1 and group 2, based on the classification of the fluid according to CLP Regulation.
In synthesis we could say that group 1 includes all substances and mixtures which CLP Regulation classifies in a class and category of hazard implying lethal or acute effects on human health, while group 2 is dedicated to all other substance and mixtures, that is the not hazardous ones or those classified by the CLP Regulation in a class and category of hazard with insignificant effects on human health, at least when referring to a single exposure [9] [10].
CLP classification of the fluid contained in the equipment correlates with the nature or the intrinsic hazards of the fluid itself, but its identification does not exhaust the obligation to assess the hazards arising from pressure for the fluid [9] [10].
The experience acquired as notified body in conformity assessment and particularly evaluating the technical documentation presented by the manufacturer highlights difficulties in performing a complete and exhaustive risks analysis and assessment, sometimes also for the fluid and there are even cases where the equipment/assembly is manufactured to contain more than one hazardous fluid.
This may result in the manufacturer classifying the fluid in group 1 according to a restrictive interpretation of the precautionary principle, thus overestimating the risk category of the pressure equipment containing that fluid, without this corresponding to an actual excess of precaution [11].
Then a tool was implemented aiming to support both the manufacturer to avoid a classification overly cautious and, above all, to fulfil his obligation to analyse and assess risks and the notified body to verify the adequacy of the analysis and assessment performed in relation with the fluid [12] [13].

2 Description of the tool

The tool is structured as a data file composed by work sheets elaborated in consideration of:

- indications given by the art. 13 of PED about classification of pressure equipment [1];
- CLP Regulation and its Adaption to Technical Progress (ATP), particularly Annex VI to CLP ATP18 (Regulation (EU) 2022/692) [14] which applies from 1 December 2023 and represents the harmonised classification and labelling of hazardous substance to date, but also the subsequent ones with the date of entry into force established for specific classifications;
- Guideline PED B-41 [2] about additional information on classification of fluids, but adapted to the technical progress with particular reference to flammable gas classification (CLP ATP 19) [15];

- other Guidelines PED [2] [3] providing some indications about specific classification of a fluid, as illustrated below;
- ESRs directly linked to the nature and/or characteristics of the fluid.

3 Classification and grouping of fluids in pressure equipment as tool basis

The application of the CLP regulation allows for the determination of which properties of a substance or mixture classify it as hazardous, so that the dangers it poses can be adequately identified and communicated. Under the CLP regulation, two types of classification are referenced: harmonized classification and self-classification [8] [9].

Regarding harmonized classification, which is included in Table 3.1 of Annex VI of the CLP regulation, it generally applies only to carcinogenic, mutagenic, or reprotoxic substances (CMRs) and respiratory sensitizers. If a substance does not have a harmonized classification in Annex VI of the CLP regulation and has hazardous properties the substance must be self-classified. Anyway the harmonised classification does not refers only to health hazards.

In contrast, the classification of mixtures is always done through self-classification, applying the criteria set out in the CLP regulation [9] [12].

The full classification of a substance or a mixture is contained in the Safety Data Sheet (SDS) being the most important technical documents for informational purposes concerning chemicals and their mixtures. which the supplier is required to provide to the recipient if a substance or mixture meets the criteria for classification as hazardous and update if new information becomes available that could affect risk management measures or provide new information on hazards, when an authorization has been granted or refused, or when a restriction has been imposed under REACH regulation (EC 1907/2006) [8]. Therefore, the main reference for fluid classification is the SDS in the last edition provided by the supplier and the information contained in its section 2 must be used.

The first sheet of the tool is Table 1 synthesizing PED criterion for fluid grouping and specifying all the hazard classes and categories with their characteristic abbreviation and related hazard statement and also precautionary statement according to CLP regulation for fluid group 1.

To use the tool the information element about classification should be enough.

Beyond the art.13 of PED and the Guideline PED B-41, whose content is included in Table 1, the other guidelines considered are the following ones [2]:

- Guideline B-21 is related to Annex I sections 2.2.1 and 2.3, ESRs about design for adequate strength and provisions to ensure safe handling and operation, which both impose to consider decomposition of unstable fluids and also to Annex II Table 1 and Table 6, where it's specified that, exceptionally, respectively vessels and piping intended to contain an unstable gas and falling within categories I or II shall be classified in category III.
- Guideline E-10 specifies that considering the decomposition of unstable fluids for adequate strength, is aiming at the slow decomposition of unstable fluids occurring

without ignition source and resulting in a slow increase in pressure (e.g. Diborane CAS No. 19287-45-7, UN No. 1911 and Germane CAS No. 7782-65-2, UN No. 2192). Such gases also have specific requirements about the test pressure according to the dangerous goods regulations.

CLP hazard classes and categories (as listed in art.13 of PED)				Standard abbreviation	Hazard statement according to CLP	Code
art.13 PED	Classes		Categories (or divisions or type)			
(i)	Unstable explosives		-	Unst. Expl.	H200	P201 - P250 - P280 - (P370+P372+P380+P373) - P503
(i)	Explosives of Divisions		1.1	Expl. 1.1	H201	P210 - P230 - P234 - P240 - P250 - P280 - P373 - (P370+P372+P380+P373) - P503 - P372
(i)	Explosives of Divisions		1.2	Expl. 1.2	H202	
(i)	Explosives of Divisions		1.3	Expl. 1.3	H203	
(i)	Explosives of Divisions		1.4	Expl. 1.4	H 204	P234 - P240 - P250 - P280 - P373 - (P370+P372+P380+P373) - P503 - P372 - P375
(i)	Explosives of Divisions		1.5	Expl. 1.5	H 205	P210 - P230 - P234 - P240 - P250 - P280 - P373 - (P370+P372+P380+P373) - P503 - P372
(ii)	Flammable gases	.	*1A*	Flam. Gas 1	H220	P210 - P222 - P280 - P377 - P381 - P403
(ii)	Flammable gases	*Pyrophoric gas*	*1A*	Flam. Gas 1	H220, H232	P210 - P222 - P280 - P377 - P381 - P403
(ii)	Flammable gases	*Chemically unstable gas*	*A*	Flam. Gas 1, Chem. Unst. Gas A	H220, H230	P202
(ii)	Flammable gases	*Chemically unstable gas*	*B*	Flam. Gas 1, Chem. Unst. Gas B	H220, H231	P202
(ii)	Flammable gases	.	*1B*	Flam. Gas 1	H221	P210 - P377 - P381 - P403
(ii)	Flammable gases	.	2	Flam. Gas 2	H221	P210 - P377 - P381 - P403
(iii)	Oxidising gases		1	Ox. Gas 1	H270	P220 - P244 - (P370+P376) - P403
(iv)	Flammable liquids		1	Flam. Liq. 1	H224	P210 - P233 - P235 - P240 - P241 - P242 - P243 - P280 - (P370+ P378) - (P303+ P361+P353) - P403 - (P403+P235)
(iv)	Flammable liquids		2	Flam. Liq. 2	H225	P210 - P233 - P235 - P240 - P241 - P242 - P243 - P280 - (P370+ P378) - (P303+ P361+P353) - P403 - (P403+P235)
(v)	Flammable liquids where the maximum allowable temperature is above the flashpoint;		3	Flam. Liq. 3	H226	P210 - P233 - P235 - P240 - P241 - P242 - P243 - P280 - (P370+ P378) - (P303+ P361+P353) - P403 - (P403+P235)
(vi)	Flammable solids		1	Flam. Sol. 1	H228	P210 - P240 - P241 - P280 - (P370+P378)
(vi)	Flammable solids		2	Flam. Sol. 2	H228	P210 - P240 - P241 - P280 - (P370+P378)
(vii)	Self-reactive substances and mixtures		A	Self-react. A	H240	P210 - P234- P235 - P240 - P280 - P373 - (P370+P372+P380+P373) - P403 - P420
(vii)	Self-reactive substances and mixtures		B	Self-react. B	H241	P210 - P234 - P235 - P240 - P280 - P375 - (P370+P380+P375+P378) - P403 - P420
(vii)	Self-reactive substances and mixtures		C	Self-react. C	H242	P210 - P234 - P235 - P240 - P280 - (P370+P378) - P403 - P420
(vii)	Self-reactive substances and mixtures		D	Self-react. D	H242	P210 - P234 - P235 - P240 - P280 - (P370+P378) - P403 - P420
(vii)	Self-reactive substances and mixtures		E	Self-react. E	H242	P210 - P234 - P235 - P240 - P280 - (P370+P378) - P403 - P420
(vii)	Self-reactive substances and mixtures		F	Self-react. F	H242	P210 - P234 - P235 - P240 - P280 - (P370+P378) - P403 - P420
(viii)	Pyrophoric liquids		1	Pyr. Liq. 1	H250	P210 - P222 - P231 - P233 - P280 - (P231+P232) - (P370+P378)
(ix)	Pyrophoric solids		1	Pyr. Sol. 1	H250	P210 - P222 - P231 - P233 - P280 - (P231+P232) - (P370+P378) - (P302 + P335 + P334)
(x)	Substances and mixtures which in contact with water emit flammable gases		1	Water-react. 1	H260	P223 - P231 - P232 - P280 - (P231+P232) - (P370+P378) - (P302+P335+P334) - P402 - P404
(x)	Substances and mixtures which in contact with water emit flammable gases		2	Water-react. 2	H261	P223 - P231 - P232 - P280 - (P231+P232) - (P370+P378) - (P302+P335+P334) - P402 - P404
(x)	Substances and mixtures which in contact with water emit flammable gases		3	Water-react. 3	H261	P231 - P232 - P280 - (P231+P232) - (P370+P378) - P402 - P404
(xi)	Oxidising liquids		1	Ox. Liq. 1	H271	P210 - P220 - P280 - P283 - P375 - (P306+P360) - (P370+P378) - (P371+P380+P375) - P420
(xi)	Oxidising liquids		2	Ox. Liq. 2	H272	P210 - P220 - P280 - (P370+P378)
(xi)	Oxidising liquids		3	Ox. Liq. 3	H272	P210 - P220 - P280 - (P370+P378)
(xii)	Oxidising solids		1	Ox. Sol. 1	H271	P210 - P220 - P280 - P283 - P375 - (P306+P360) - (P370+P378) - (P371+P380+P375) - P420
(xii)	Oxidising solids		2	Ox. Sol. 2	H272	P210 - P220 - P280 - (P370+P378)
(xii)	Oxidising solids		3	Ox. Sol. 3	H272	P210 - P220 - P280 - (P370+P378)
(xiii)	Organic peroxides		A	Org. Perox. A	H240	P210 - P234- P235 - P240 - P280 - P373 - (P370+P372+P380+P373) - P403 - P410 - P420
(xiii)	Organic peroxides		B	Org. Perox. B	H241	P210 - P234- P235 - P240 - P280 - P375 - (P370+P380+P375+P378) - P403 - P410 - P420
(xiii)	Organic peroxides		C	Org. Perox. C	H242	P210 - P234- P235 - P240 - P280 - (P370+P378) - P403 - P410 - P420
(xiii)	Organic peroxides		D	Org. Perox. D	H242	P210 - P234- P235 - P240 - P280 - (P370+P378) - P403 - P410 - P420
(xiii)	Organic peroxides		E	Org. Perox. E	H242	P210 - P234- P235 - P240 - P280 - (P370+P378) - P403 - P410 - P420
(xiii)	Organic peroxides		F	Org. Perox. F	H242	P210 - P234- P235 - P240 - P280 - (P370+P378) - P403 - P410 - P420
(xiv)	Acute oral toxicity		1	Acute Tox. 1	H300	P264 - P270 - P405
(xiv)	Acute oral toxicity		2	Acute Tox. 2	H300	P264 - P270 - P405
(xv)	Acute dermal toxicity		1	Acute Tox. 1	H310	P262 - P264 - P270 - P280 - (P362+P364) - P405
(xv)	Acute dermal toxicity		2	Acute Tox. 2	H310	P262 - P264 - P270 - P280 - (P362+P364) - P405
(xvi)	Acute inhalation toxicity		1	Acute Tox. 1	H330	P233 - P260 - P271 - P284 - P403 - P405 - (P403+P233)
(xvi)	Acute inhalation toxicity		2	Acute Tox. 2	H330	P233 - P260 - P271 - P284 - P403 - P405 - (P403+P233)
(xvi)	Acute inhalation toxicity		3	Acute Tox. 3	H331	P233 - P261 - P271 - P403 - P405 - (P403+P233)
(xvii)	Specific target organ toxicity – single exposure		1	STOT SE 1	H370	P260 - P264 - P270 - (P308+P311) - P405
.	substances and mixtures contained in pressure equipment with a maximum allowable temperature TS which exceeds the flashpoint of the fluid					

Table 1 - PED criterion for fluid in group 1 completed with the related hazard and precautionary statement

Then there are guidelines providing indication about classification not directly related with the fluid classification, but with other characteristics of it such as [2] [3] [6]:

- Guideline B-27, related to Article 13, states that the classification of a pressure equipment containing one or more fluids when a chemical or physical reaction takes place therein shall be determined by the fluid which gives the highest category considering the starting, intermediate and final fluids, which could arise from all reasonably foreseeable conditions;
- Guidelines B-26 and B-30 are related to the definition of fluids and treat the case of a fluid containing a solid, respectively a "non-suspended" solid group 1 in a block blanketed by a group 2 gas and in a suspension. In the first case the characteristics of the solid should be considered as part of the hazard analysis and do not influence the classification of the equipment, while in the second case the classification shall take account of the group of the fluid and of the group of the solid and of the group of the mixture if available. When the group of the mixture can be determined based on its classification in the CLP Regulation, this group is used for the classification, but if not, the classification is based on the higher group of the fluid and the solid.
- Guideline I-24, related to various article of the directive, is also important in relation to the nature of the fluid. It confirms that all technical (design, manufacturing, conformity assessment) requirements addressing hazards related to pressure are covered by the PED, shall have been considered by the manufacturer as part of the hazard analysis and any additional national requirements related to pressure such as specific requirements for protection against the release of the fluid or for materials due to the nature of the fluid or to avoid explosions/fires triggered by pressure, would constitute an impediment of the free movement of products falling into the scope of the PED and are not permissible.

3.1 Characteristics of the tool

Beyond Table 1, the tool describes each hazard and precautionary statements put in relation to each hazard class and category, not only for group 1, but also for those afferents to the group 2. It also recalls the ESRs related to hazard referred to a specific classification of the fluid and link each of them to some examples with indications about the prevention and/or protection measures against those of the cited hazard which can be eliminated or reduced and about the appropriate information to provide in the operating instruction for the users, as required in the already cited ESR 1.2 [16]. An example of the relation referred above is represented in figure 1 where the precautionary statement constitutes a residual risk management measure mainly aimed at workers operating to run and/or to check and maintain the equipment.

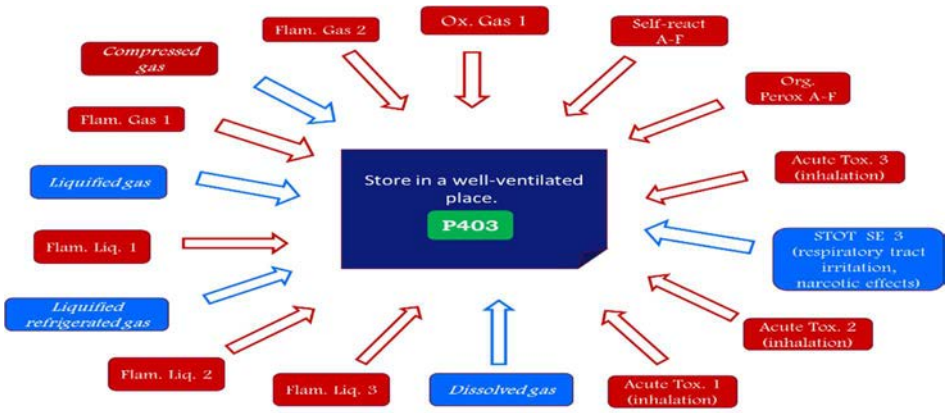


Fig. 1. An example of the relation among precautionary statements and hazard class and category (in red for the ones afferent to group 1 and in blue for the other).

Other ESRs directly linked to the characteristics of the fluid are:

- point 4.1 lett. b), in Annex 1 of the directive: "Materials for pressurised parts shall: (b) be sufficiently chemically resistant to the fluid contained in the pressure equipment; the chemical and physical properties necessary for operational safety shall not be significantly affected within the scheduled lifetime of the equipment";
- point 2.6, Corrosion or other chemical attack: "Where necessary, adequate allowance or protection against corrosion or other chemical attack shall be provided, taking due account of the intended and reasonably foreseeable use".

In the light of these two ESRs and also of the ESR 2.2 about design for adequate strength imposing to consider corrosion (erosion, fatigue, etc.), another class of hazard of the fluid has to be warned by the manufacturer in the hazard and risk analysis: Corrosive to metals, referred by CLP Regulation to a substance or a mixture which by chemical action will materially damage, or even destroy, metals. According to the CLP Regulation, regarding their corrosive properties only those substances are given consideration that attack qualities of steel and aluminium relevant in transport legislation, because these metals can most frequently have contact in the transport of chemicals [17]. This hazard class (only one category) does not belong to group 1 and then does not influence the fluid group, but could affect design and particularly, calculation, drawing, materials (e.g. Particular Material Appraisal or PMA) and operative instructions. On the ECHA database C&L inventory [9] [12] 1.889 record of substances characterized by this harmonised and/or notified classification are present to date. An example are mixtures containing sodium hypochlorite with concentration above 5% of active chlorine. The tool allows to be alerted to this hazard.

4 A case of application and discussion

If the hazard statements can help the manufacturer to identify the hazard related to the fluid, the precautionary ones, giving indication about general preventive and/or protective measures, can be helpful for the management of an eventual residual risk and then to include the correspondent suggestions in the operative instructions. These statements are also included in the section 2 of the SDS, but the tool allows to immediately link them with the element in PED to which they are relevant.

The note 3 of the Guideline PED B-41 [2] just warns about the CLP regulation is subject to adaptations to technical progress (ATP) and therefore the information given should be checked with the version of the CLP regulation in force at the time the equipment is placed on the market.

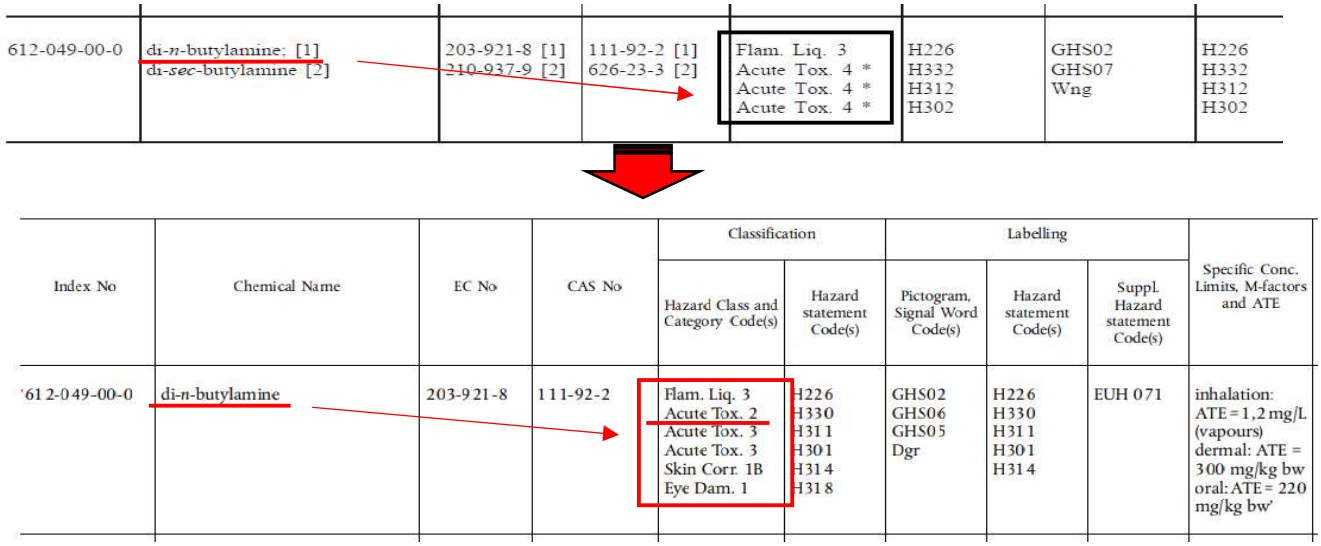
The tool is then conceived to be periodically updated thus being able to prove useful for classification and also for notified bodies when assessing the conformity to PED according to a module B (EU type examination) or H1 (conformity based on full quality assurance plus design examination). For this type of module, according to both the points 3.1 and 3.2, subpoints 7 and to the point 12, subpoint 4.4 of the Annex III of the directive, notified bodies shall monitor the state of the art generally recognized and where this suggests that the approved type may no longer comply with the applicable requirements of this Directive, determine whether further examination is necessary. This can be the case when the classification of the fluid according to CLP changes due to adaptations to technical progress.

An update of the fluid classification may result in a change from group 2 to group 1, with the following consequences:

- change in the category of equipment/system, with potential impact on the module used e.g., in the case of modules for II or III category that is B design type or production type combined with E or C2;
- need to update the risk assessment with reference to the ESRs 2.3, provisions to ensure operations and functioning under safe conditions, 2.12, external fire which, according to Guideline PED E-02 [2] specifically refers to damage limitation and 5 equipment with overheating risk, point e), in the case of flammable materials;
- variation in the joining coefficient and the type/extent of the NDT (Non-Destructive Testing), e.g. according to EN 13445-5 [18], note b) to table 6.6.1.1 or to the national (Italy) PdR (reference practice) UNI 55/2019 [19], point S.2.3;
- need to update the operating instructions accompanying the equipment in relation to residual risks and periodic verifications.

The tool is being tested by some real cases. A significant case selected in this first phase is that occurred during the checks for a module C2 for an assembly referred to a module B (EU type examination) production type which was issued before the national PdR UNI 55/2019 [19] came into use and provided a testing group associated to a joining coefficient equal to 0,7. The PdR UNI 55/2019, according to the harmonised standard EN 13345-5 [18] provides the limitation of that testing group only to fluids of group 2. We

verified the classification of the fluid contained in the vessel to be sure about its updated classification according to CLP and then to confirm the adequacy of the module B. The fluid was n-butylamine and the SDS provided by the manufacturer in its section 2 listed the following classification, corresponding to the harmonized classification now in force. Afterwards, with the release of the 22nd ATP of the CLP regulation [8] becoming mandatory from September 1, 2025, new hazard classes were implemented, and some of the existing ones have had their severity increased. The new classification has already been implemented in the tool. Figure 2 illustrates how the classification is going to be modified.



612-049-00-0	di-*n*-butylamine; [1] di-*sec*-butylamine [2]	203-921-8 [1] 210-937-9 [2]	111-92-2 [1] 626-23-3 [2]	Flam. Liq. 3 Acute Tox. 4 * Acute Tox. 4 * Acute Tox. 4 *	H226 H332 H312 H302	GHS02 GHS07 Wng	H226 H332 H312 H302

Index No	Chemical Name	EC No	CAS No	Classification		Labelling			Specific Conc. Limits, M-factors and ATE
				Hazard Class and Category Code(s)	Hazard statement Code(s)	Pictogram, Signal Word Code(s)	Hazard statement Code(s)	Suppl. Hazard statement Code(s)	
'612-049-00-0	di-*n*-butylamine	203-921-8	111-92-2	Flam. Liq. 3 Acute Tox. 2 Acute Tox. 3 Acute Tox. 3 Skin Corr. 1B Eye Dam. 1	H226 H330 H311 H301 H314 H318	GHS02 GHS06 GHS05 Dgr	H226 H330 H311 H301 H314	EUH 071	inhalation: ATE = 1,2 mg/L (vapours) dermal: ATE = 300 mg/kg bw oral: ATE = 220 mg/kg bw'

Fig. 2. The change of the classification of di-n-butylamine in the Annex VI of the CLP regulation, according to the 22nd ATP of the same regulation [20]

Therefore, di-n-butylamine and its mixtures, even below the flash point, could move from Group 2 to Group 1. The maximum temperature declared by the manufacturer for the assembly was actually below the flash point (45°C versus 47°C) but the verification made utilizing the tool confirmed the obligation to inform the manufacturer of the need to revise the module B, just in time for the entry into force of the updated classification.
The tool has proven to be particularly useful to verify the revision of the following sections of the technical dossier: risk analysis, checklist for the conformity to the ESRs and operating instructions.
On the other hand, the tool cannot cover a priori all the aspects to be defined by the manufacturer who, anyway, shall define and document in the risk and hazard analysis the limit enabling him to identify the ESR of Annex I of the PED which are applicable to the equipment, considering the amount of information known or reasonably achievable [20]. The tool can help in “reasonably achieve” information.

5 Conclusions

The manufacturer shall design and construct a pressure equipment or assembly considering the analysis of all hazards arising from pressure for the intended use and the intended contained fluid(s) [22]. A tool was implemented aiming to support both the manufacturer to fulfil this obligation with particular reference to the fluid and the notified body to verify the adequacy of such analysis and assessment.

To understand the value that the tool adds to the indication already present in the directive and its Guidelines, it is essential considering the details, the comprehensiveness, the link with specific ESR of the directive and the indication from or about the most up-to-date and authoritative source of information used. The tool is being optimised and it must be then further tested. Anyway the first cases for which it was applied and an example of which has been given above, showed its flexibility and ease of use. It seems to offer interesting potentiality to reduce the margin of uncertainty characterising hazard and risk analysis, at least in relation to the nature of the fluid, supporting both the manufacturer to avoid a classification uselessly cautious and, above all, to fulfil his obligations and the notified body, but also other actors involved, such as competent authorities, to verify the adequacy of the analysis and assessment performed. After its validation the intention is to make the tool available to the stakeholders.

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Improving safety of earth moving machinery

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Abstract
The Earth moving sector is characterized by a multiform presence of machines. At least twelve different families of machines are identified which perform different specific tasks. Considering this manifold situation and the changes in the legislative and normative references introduced by the new Machinery Regulation 2023/1230, which will soon be applicable throughout the European Union, it is worthwhile to investigate how new technologies may improve safety for this specific sector. In fact, innovative technologies may enhance workplace safety, offering solutions that support workers and proactively eliminate or reduce risks by design and training. Moreover, they could be also exploited for machines already in use to check and to improve their safety level. The use of sensors and control units based on artificial intelligence (AI) may reduce the risk of interference with worksite (e.g. overhead power lines), workers in the nearby of the machine and other machines. If correctly trained, AI-based technologies may also be useful for supervising the correct coupling of interchangeable equipment on the base machine. In the same way, AI and immersive systems, like augmented reality or virtual reality, may be a useful tool also for the training of earth moving machinery operators based even on the feedback coming from them.
In this connection, AI-based technologies could be applied for evaluating the safety level of old earth moving machinery, which often lack proper technical specifications or guidelines.
In particular, starting from the safety requirements set for each family of earth moving machines by the applicable harmonized standard, and considering the changes of their requirements over time, AI techniques could help develop risk analysis on old and in use machines by providing specific check lists and technical solutions for their most relevant risks.

1 Introduction

Tools that may facilitate the task of safety and prevention experts, including inspectors, in the risk assessment of machines in service, are increasingly helpful: they play a crucial role in verifying safety compliance, whether for CE-marked or non-CE-marked machinery. Currently, in some Member States, machines in service are analysed with the help of checklists. For example, for non-CE marked machines, in several Member States there are guides to perform or evaluate the technical solution

necessary to conform the machine to safety requirements. There are very useful tools for inspectors who should verify the presence of features and devices necessary to meet the applicable legislative provisions. However, such resources are limited to only a few machine families.
The authors believe that an assessment supporting device which may allow an inspector to verify if the machine is in line with safety requirements through a visual examination is particularly useful. In fact, without performing functional tests or having to see how the machine works in the field, such a device could be able to establish whether a certain machine is in line with the state of the art or not. This is much more relevant for those macroscopic aspects that have an impact on accidents. The supporting device may also discriminate if machine should be compliant with the relevant type C technical standard, if it exists, when CE marked, or compliant with the minimum requirements established by Annex I of Directive 2009/104, when not CE marked.
In addition, this tool would also be useful for evaluating the suitability to the state of the art of the machines exhibited at trade fair, a place where the machines are often stationary, turned off, without documentation (user manual, declaration of conformity, etc.). This could have a powerful impact in terms of prevention. In fact, it could be possible to activate market surveillance even before the machine is put into service, avoiding potential accidents.
With respect to what aforementioned, in this paper some examples of potential application in earth moving sector are proposed. In this sector, two most widespread issues are faced:

1. the assessment of compliance of earth moving machinery with respect to specific requirements set by harmonized standards, if any, according to the year of their manufacturing;
2. the safe coupling of the basic machine with interchangeable equipment.

At present, the above issues could be solved only acquiring information from:

- operator's manual, identification plates and information physically present both on the machine and on the interchangeable equipment (for example, load and stability diagrams);
- relevant harmonized standards for machinery and equipment;
- applicable legislative provisions (Directive 2006/42/EC, Regulation (EU) 2023/1230, national decrees implementing EU provisions, associated circulars, etc.);
- official guides for the interpretation of the legal provisions (for example, the Guide to the implementation of Directive 2006/42/EC and its section on ergonomic requirements).

A machine learning system, based on artificial neural networks (ANN) can represent a solution to the two problems raised above. With reference to Figure 1, for the sake of simplicity, we will refer to an input-output system designed to process, through

computational statistics operations, data provided as input, and to give desired output information.

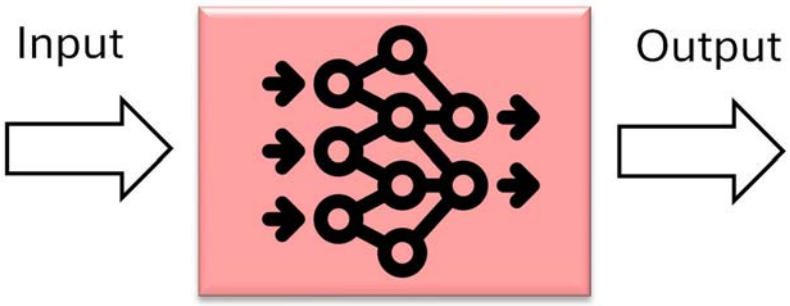

Fig. 1. Example of computational flow for ANN system

In other words, an ANN system well trained could allow to recognize the characteristics of a machine by means of simple photos taken with a smartphone. Then an app would generate, starting from those photos, the answers that, nowadays, could be obtained only manually by checking the presence or absence of devices, the main dimensions, the construction characteristics in operator's handbook, the information on the CE plate, safety requirements in harmonized standards, if any, with a significant consumption of resources.

2 The use of ANN system for improving safety of machinery

According to what aforementioned, a ANN based system could be applied to three main areas:

- the compliance of earth moving machines already in use with respect to the state of the art;
- the safe combination of basic machine with interchangeable equipment;
- Enhancing the usability of operator manuals for training and specific safety-related information.
-

2.1 Compliance of earth moving machines already in use

It is worth differentiating the approach for CE-marked and non-CE-marked machines. For CE marked machine, a possible analysis process may be summarized as follow. The ANN system may receive as input a series of photos of the machine including a photo of the identification plate. One can suppose that the machine, an hydraulic excavator for instance, was placed on the market in 2008. Then, the ANN system establishes the type, year, manufacturer, and ideally verifies the machine's compliance with the essential requirements of the legislation applicable in 2008 (e.g. Directive 98/37/EC). If the machine was covered by a harmonized type C standard, then it could verify that the machine complies with specific safety requirements. If not, the ANN system could generate an alert of this type: "*Attention, from the photos provided at the input it emerges that the machine is not equipped with neither FOPS nor TOPS, while the C standard applicable at the time the machine was placed on the market*

required both TOPS and ROPS for the application provided". This is the added value. Starting from a data base of all the necessary safety information according to the state of the art, it is possible to refer to the proper safety requirements in force at the time of machine fabrication. As an example, the employer who uses a CE marked excavator placed on the market, for example, in the year 1997, is not obliged to equip it with devices that were not required by the harmonised standard in force in that timeframe. The only obligation to be respected is to maintain that excavator over time at the safety levels associated with the design requirements in force in 1997. Of course, the employer is free to 'do more' and install devices present on more recent excavators, but it would be incorrect to make a requirement for the absence of a radar sensor for detecting people on an excavator built in a year in which the harmonised standard in force did not require such a device. Hence the importance of an ANN system that can communicate in output specific statement like "*from the photos provided at the input it emerges that that machine is fine because the current configuration complies with the safety level established by the standards of the time*", or "*Your excavator is not compliant with safety requirements, because the standard in force when it was placed on the market required the presence of a Tip Over Protective Structure (TOPS) which is not installed on it*".

For what concerns not CE marked machine, the ANN system receives as input always the information provided as in the case of CE marked machines. However, in this situation the employer has a certain margin of maneuver in choosing the technical solutions to ensure the suitability, or at least the approach, for ensuring the necessary safety level for the machine according to the state of the art. In fact in this case, a part from special mandatory situations, the employer has not the need to reach the safety level of “new” machines. He can choose the technical solutions appropriate to the age of the machine. Currently, there are certainly not many application guides dedicated to the adaptation of not CE marked machines to the state of the art. Nonetheless, employers are required to meet the technical requirements of Annex I of Directive 2009/104/EC. For example, in relation to the risk of overturning, in Annex I point 3.1.4, there are provisions that must be applied. How to act technically is still an open field, because guidelines have only been developed for a few families of machines. In this situation, the ANN system could provide some technical suggestions, even derived from harmonized standards published since the 2000s. Thus, it could generate an output list of “mediated” technical solutions that, even if not optimal, would represent a starting point for appropriate in-depth analysis to be done by the employer.

2.2 Interchangeable equipment

For many applications earth moving machineries are used in combination with interchangeable equipment (see Figure 2).

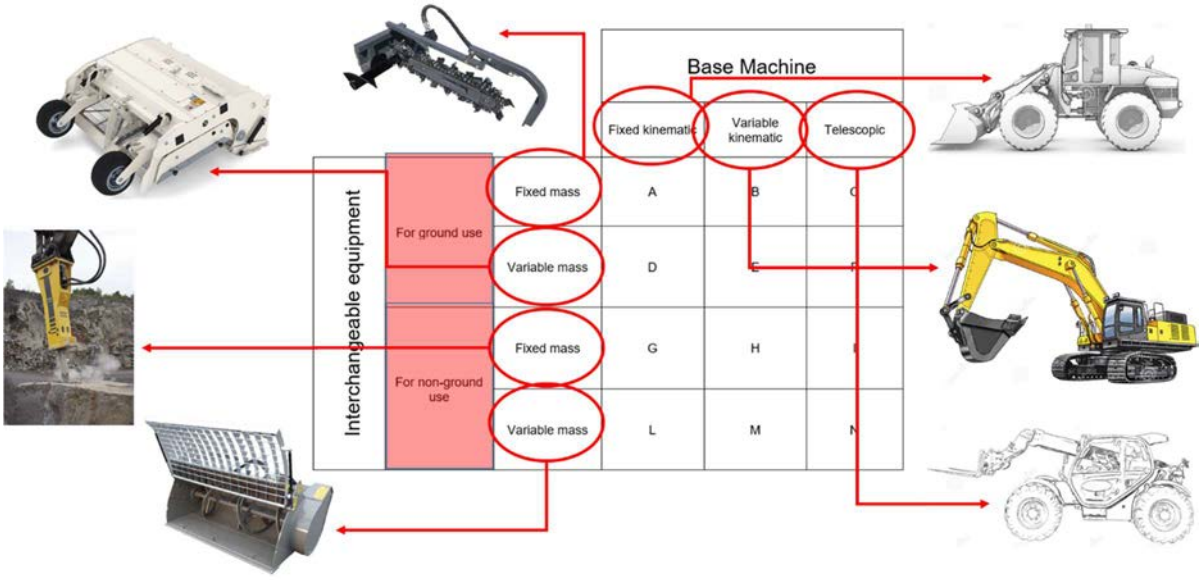

Fig. 2. Example of possible combinations between basic machine and interchangeable equipment

It is just worthwhile to recall that an interchangeable equipment is an equipment that is designed and constructed to be assembled with machinery by the operator himself, after the basic machine has been put into service. The fact that interchangeable equipment is intended to be assembled with the machine implies that the combination of the basic machine and the interchangeable equipment functions as an integral whole. Moreover, interchangeable equipment may be placed on the market by the manufacturer of the basic machine or by another manufacturer. In either case, the manufacturer of the interchangeable equipment must specify in his instructions the machine with which it can be safely assembled and used, either by reference to the technical characteristics of the machine or, where necessary, by reference to specific models of machinery.

This is necessary to ensure that the combination of the interchangeable equipment and the basic machinery with which it is intended to be assembled fulfils all the relevant essential health and safety requirements of Directive 2006/42/EC (Machinery directive). As a consequence, the operator as a crucial role even for safety when combining basic machine and interchangeable equipment. Nowadays the operator has to carefully read both instruction handbooks, the one of basic machine and the one of interchangeable equipment, to check all the relevant information for a proper and safe combination. Sometime this is an even harder task, considering that not all the information are provided or they are not easy to gain when considering also old machines.

In order to support the operator, the use of ANN system could be very useful. First of all, it is necessary to perform a specific training for the ANN system by means of a database of operator's manual for basic machine and for interchangeable equipment, pictures of single machines and combinations of basic machine and interchangeable

equipment, technical data (e.g. gross mass, rated capacity, electric and hydraulic inlet/outlet, etc.), specific risk assessment (e.g. stability, visibility, access to driving position, etc.) based even on standards and technical specifications, where available. Once the ANN system is trained, the next step is to provide as input data, pictures of basic machine, interchangeable equipment and their information plates. As output AI should give all the necessary information to the operator for the right choose and the proper combination of the interchangeable equipment with the basic machine. A valuable add-on could be the possibility to give some safety hints in terms of procedure and operative limitations with respect to the task the operator will perform. Considering self-evolving behavior machines, it will be possible even to improve and develop specific safety measures according also to the attitude of a single operator.

2.3 Operator's manual

The instructions provided by the manufacturer with the machinery are an essential tool for employers to apply the implementing provisions of Directive 2009/104/EC. To this scope The Machinery Directive 2006/42/CE comprises specific requirements at point 1.7.4 defining the minimum contents of the instruction handbook. The standard ISO 12100:2010 *Safety of machinery — General principles for design — Risk assessment and risk reduction*, defines the Instruction Handbook as an accompanying document and gives requirements for the production of the instruction handbook, but just in the print format and without references to any digital format.

On the other hand, the standard EN ISO 20607:2019 *Safety of machinery — Instruction handbook — General drafting principles*, allows the use of a digital format. The new "machinery" regulation 2023/1230 wants to allow and favour the use of, not only digital formats for the manual but also the development of videos that are a better format to explain aspects of the machinery than text or pictures. The first reason is related to the monetary and environmental costs due to extensive paper-based documentation, but there are advantages also in the training activities.

New trends in training and instruction for personnel operating earthmoving machinery, such as loaders, excavators, and backhoes, are undergoing significant evolution due to the integration of digital technologies, particularly augmented reality (AR) and virtual reality (VR). These technologies not only enhance operational efficiency but also comply with the requirements set forth by the EN ISO 20607 standard, which addresses the design and implementation of training systems. It emphasizes the importance of providing clear and accessible information to operators, ensuring that training techniques are effective and safe. The integration of AR and VR into training practices not only meets these requirements but also exceeds them by offering immersive experiences that significantly enhance learning and workplace safety.

Moreover, how to handle information provided by operator's manual when coupling basic machine and interchangeable equipment is another challenge.

One of the main issues is that operator's manuals in this case are often poorly conceived and structured, and difficult to read. Finding answers to specific queries is often laborious. An ANN system could offer the possibility of querying the manual and having precise answers, perhaps enriched by contents external to the manual but linked to it (for example coming from the results of relevant feedback[i] projects). For example, it is possible to make a query on the stability of the assembly starting from the information provided in operator's manuals, before making the physical connection between machines. In short, it would be the ANN system that "reads" the manual together with other relevant documentation, to then produce accurate and precise answers to the queries posed by the user. A project on this topic would combine:

- the technological evolution towards increasingly complex machines to operate;
- the regulatory evolution with a harmonized standard dedicated to instructions for operators;
- the evolution towards intelligent systems capable of absorbing data and producing summaries, diagrams, resources that are easier to understand and apply.

In this regard, at European (CEN) level a Technical Specifications (TS) on interchangeable equipment is currently been developed. Once completed, the TS will provide the set of information that must be contained in the user manuals of earthmoving machines. In the next future, the operator will have to combine the information from the TS and the machine operator's manual. An ANN system could help lighten the user's task in this sense, always exploiting the interpolative, associative and interpretative capabilities of neural networks.

3 Conclusions

The study of an ANN system, like the one described here, allows various stakeholders to connect with a horizontal prevention strategy that also involves the national supervisory and surveillance bodies. Ideally, one should start from simple projects with an indisputable preventive impact, dedicating oneself, for example, to the study of widely used machines with a recognized criticality, such as earth-moving machines. On these machines, the relevant harmonized standards and their evolutions in the last two decades could be exploited, to identify the critical characteristics (for example, the presence of a windshield, three-point seat belts, an actuator disconnection lever, protection of a moving part, an emergency exit, etc.) that could be visually detected. To this end, one cannot ignore the need to have all the standards in all their editions, otherwise one will never be able to ascertain whether the technical solutions valid today were also valid ten years ago or not.

In a further refinement, the ANN system could be trained on the Essential Health and Safety Requirements (EHSR) applicable to earthmoving machines and on the historical periods in which they have changed as a consequence of the evolution of

the relevant harmonized standards. As an output, the ANN system could transmit an alert such as "*pay attention to this aspect, because it has changed over time in this way*". Once the year of construction of a machine in use has been identified, the ANN system offers for that machine the list of critical EHSR that have undergone an evolution over time. This application, provided just as a possible one, suggests exploiting the ANN use in this direction. This approach has the potential to significantly reduce workplace accidents in the earth-moving sector, fostering a safer and more efficient work environment.

[i] ISO/TS 16710-1:2024 Ergonomics methods Part 1: Feedback method — A method to understand how end users perform their work with machines.

Augmented & Interactive tool for Occupational safety

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Abstract
This paper presents a software framework developed by the University of Naples Federico II – DII and INAIL DR Campania, leveraging Augmented Reality (AR) technologies and tracking systems integrated into common tablets and smartphones. The system is designed to streamline and enhance the flow of information between safety managers and workers regarding workplace safety. The application, which is called *DVR plus*, is available for both Android and iOS mobile devices and assists safety officers and safety managers in conducting workplace inspections and provides guidance for identifying and accurately classifying risks. Data is securely stored on a remote server and can be accessed and edited via a web application (DVR plus web-app). Additionally, workers can use our app to view safety information displayed in AR, contextualized to their specific work environment. The results of the usability tests carried out to improve the user experience with the app are briefly discussed.

1 Introduction

Most occupational health and safety laws and regulations worldwide suggest or require periodic workplace inspections to identify possible hazards and to assess the related risk. Then, the necessary policies and procedures to mitigate each risk shall be clearly established and documented and kept updated. However, as it is very well-known, documented information is not a solution in itself; it is merely the starting point for preventing injuries and improving workplace ergonomics and quality. To be truly effective, that information must be generated using clear and standardized methodologies, kept up to date, and properly communicated to the relevant recipients—ideally at the moment it is needed. This gives rise to two key challenges: the first is the inspection and identification of all potential risks, and the second is the development of methods and policies for transferring this information to workers (through education, training, surveillance, hazard signage, periodic inspections, etc.). There are several software applications that help in risk assessment, such as the ones in [1], [2], [3]. In addition, the published literature reports methodologies for structuring and keeping the risks documentation promptly updated [4].

In recent years, mobile devices such as smartphones and tablets have opened up the possibility of generating, processing, receiving and sending information in real time quickly and easily. From this point of view, many apps have also been developed aimed at improving safety in the workplace. Some of them focus on specific risks [5] and others, such as iAuditor [6], are addressed to safety managers and help in risk assessment. Both types are essentially based on interactive checklists.

AR has also been proposed in the field of industrial safety. In [7] the authors present an AR system tailored to a specific task that provides workers with step-by-step instructions, tips and safety checklists. AR has also been proposed to show escape routes in real time [8]. Hazard Scout [9] and Tap into Safety [10] help users in creating QR code-based safety reports. In addition, workers can be trained online, and the safety manager can check the training of workers. Safety Compass [11] is another application that assists the user with contextual augmented safety information based on GPS tracking. The main limitation of such software is related to tracking systems. GPS is not suitable for indoor use, and QR codes are not always viable in real-world industrial settings.

Furthermore, from the analysis of the applications already developed and those proposed in the scientific literature, no solutions for mobile devices have emerged capable of addressing the safety problem in a more complete way: from the moment of the first inspection, to the drafting of the risk assessment documentation, up to the timely information of workers.

The University of Naples Federico II and INAIL have therefore explored the use of mobile technologies and augmented reality in the field of industrial safety as part of the IDEE (*Interactive Design for Ergonomics*) project funded by the Fraunhofer Joint Lab IDEAS and INAIL – Campania Regional Directorate. In particular, the authors focused on developing a marker-free solution that would offer the user the ability to create augmented content, not anchored to physical "markers" or GPS data. In addition, the app had to be suitable for any work environment where the use of a common smartphone connected to the Internet were allowed.

The solution developed, called DVR+, is based on a multi-user architecture, in which users with administrative rights (e.g. safety officers) can create content and non-privileged users (e.g. workers or occasional users) can consult the previously saved information and actively report any safety-related issue.

Safety officers can use the app as a useful tool for inspection and risk assessment through the module called augmented inspection. Photographs captured with their smartphone are automatically linked to the position and orientation of the camera at the time of shooting. This frees the safety officer from the need to make annotations on paper plans, speeding up their activities. In addition, thanks to its extensible risks list, the app guides the user in identifying possible dangers in the work environment and creating content. The locations of the hazards and the information entered are saved on a remote server and associated with a specific

workplace. Places, in turn, are associated with companies. Through the DVR+ web application, the same user can consult the hazard plan, print or modify the results of the inspection and any information stored therein. On the other hand, workers can use the same application as an information tool that provides safety-related content when and where necessary through augmented reality technologies: by framing a possible hazard with their smartphone, they receive the information previously prepared by the safety manager (e.g. textual and graphic indications, safety prescriptions, etc.). Our application enriches the work environment with safety-related information depending on the context and the person using it; therefore, it can also be used to prepare exercises, for continuous training on the job and as a tool for verifying learning.

1.1 DVR+ architecture

As mentioned, the DVR+ architecture (Figure 1) is made of a front-end, which is an app for smartphones/tablets developed with Unity (*DVR plus*), and a back-end, which is a web-app based on PHP and SQL (DVR plus web application server).

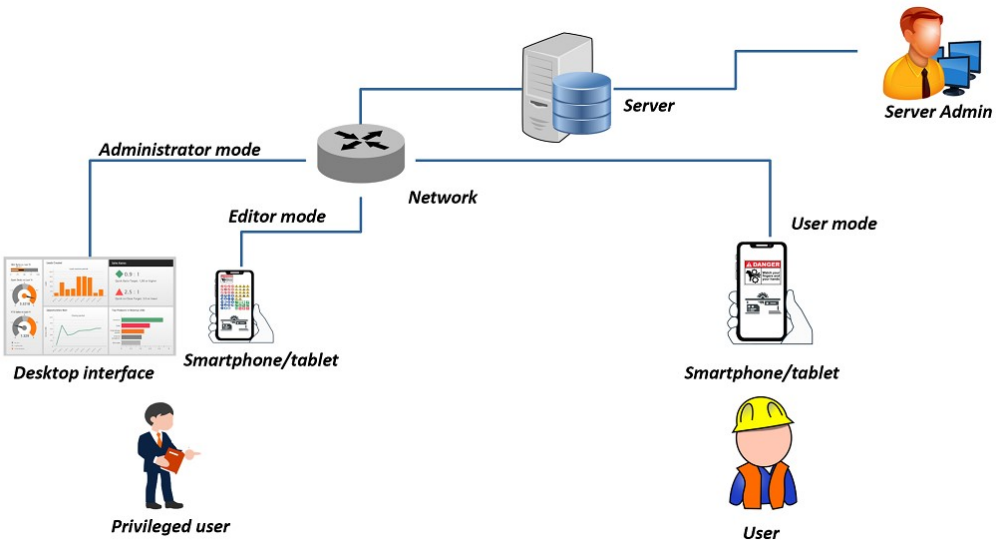

Fig.1: DVR+ architecture.

DVR+ architecture provides three different user profiles (or roles), each allowing for different levels of privilege on information management and, therefore, for different workflows:

- **Privileged user (e.g. safety officer):** is allowed to create augmented content in the inspection phase
- **Non-privileged user (e.g. worker):** will just read and see the information created by the safety manager.
- **Server Administrator:** All security information is saved on a remote database; therefore, each user will have their own account on the server. The

server administrator has full powers to manage users, data, and company records.

DVR plus web-app basically allows a privileged user to edit all the information stored in DVR+ database. One can create and delete users, browse and edit content stored on MySQL databases. Through the web-app it is also possible to access features not available via the mobile-app, such as creating new users or exporting risks to an excel spreadsheet.

Safety officers can self-apply for an account by specifying their company and business email address. Pending requests are sent to the server administrator for approval.

1.2 DVR plus app

DVR plus app uses Google's ARCore to create and manage augmented reality content. ARCore is based on SLAM (simultaneous localization and mapping) technology to infer the position of the smartphone in relation to the world around it. However, by default, the reference system is created “on the fly” based on the position and orientation of the device when the ARCore framework is activated; therefore, there is no guarantee that the position data will be relative to the same reference system in the next sessions. It is clear that, in order to achieve the persistence of the positioning data, which will be stored in a remote database, a unique "fiducial point" must be set. The problem has been solved by requiring a picture (Marker) to be attached in the workplace. Before using the DVR plus for inspection, the system shall be calibrated by framing the marker with the device camera: this operation will connect the marker to that place (Figure 2). Several predefined markers are provided that can be edited and then printed to be fixed at the entrance to a work environment. All positional data will be referenced to this marker.

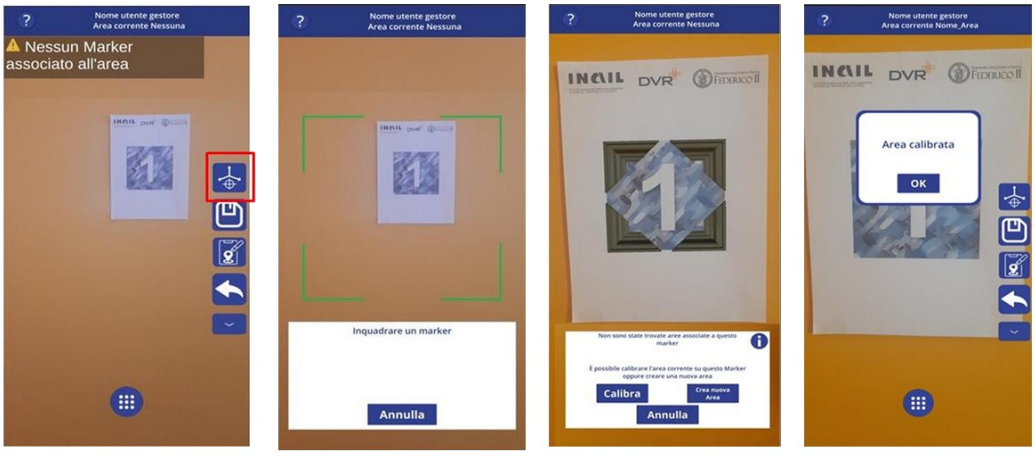

Fig. 2: Calibration procedure.

As mentioned, during the inspection phase, DVR plus supports the safety officer in risk assessment through special menu items that refer to distinct risk categories (modules). The safety officer frames the source of the risk and presses on a point in the space to bring up the information panel to be customized. It is also possible to prescribe the *Personal Protective Equipment* (PPE) to be used and attach web documentation (Figure 3). Moreover, any other information can be linked to a certain marker (e.g.: checklist, list of rules to follow, reminders, etc.).

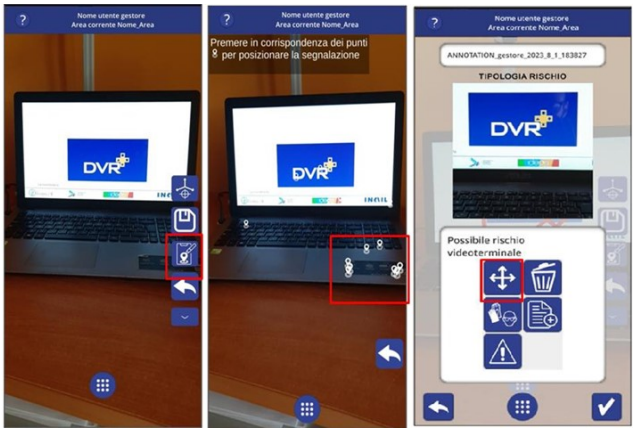

Fig. 3: Augmented content creation with DVR plus.

Experimental Design and Statistical Analysis

Usability is particularly important to ensure a good user experience and thus is crucial to the success of any software solution or device [12]. Therefore, the graphical user interface (GUI) has been developed according to ISO 9241 reference standard and, more generally, to the most common interface design best practices [13]. In addition, the interface layout meets Google's app design guidelines, and the visual language matches the principles of "good design" [14]. Then, we used a systematic approach to objectively measure the usability of our app [15]. According to the ISO 9241 definition, usability has been considered as the combination of three factors: ***Effectiveness***, ***Efficiency*** and ***Satisfaction*** in use. The Analytic Hierarchical Process (AHP) methodology, which is based on user opinions [16], was used to relate these factors to the following measurable indices.

Eventually, an experimental campaign was conducted to compare our application with the traditional paper-based procedure in terms of usability.

Participants.

The experimental campaign was carried out at the four IDEAS Laboratories (Astro, Cogito, Creami, Soft Prototyping) of the University of Naples Federico II and involved 10 students aged between 20 and 30 years old (3 women and 7 men), all of whom

had no prior experience in industrial safety. The participants were divided into two equal groups to compare the effectiveness of two different inspection tools: *Traditional paper-based procedure* and *DVR plus augmented inspection*.

Fig. 4: Users carrying out the inspection with the two risks assessment tools. Left: Paper-based approach; Right: DVR plus app.

Data Analysis.
The participants were briefly introduced to the purpose of the experiment and the type of risks that they would have possibly encountered in the laboratories. Then, they were asked to inspect the four IDEAS laboratories to identify selected hazards in each of them. During the experimentation, both Subjective and Objective Measures were collected. More specifically, the effectiveness of the application and satisfaction of the users were evaluated through two different questionnaires. The effectiveness questionnaire is a list of 15 questions about the risks inside the labs [1 Suppl. Mat.]. The satisfaction was extrapolated from a standard SUS questionnaire [2 Suppl. Mat.]. On the other hand, the efficiency of the app was measured based on the time needed to accomplish each task.
Eventually, *Effectiveness* (E_1), *Satisfaction in use* (S) and *Efficiency* (E_2) indices were calculated based on the answers and on the questionnaires and the accomplishment time.

Results and Discussion.
The results of the experiments are shown in figure 5.

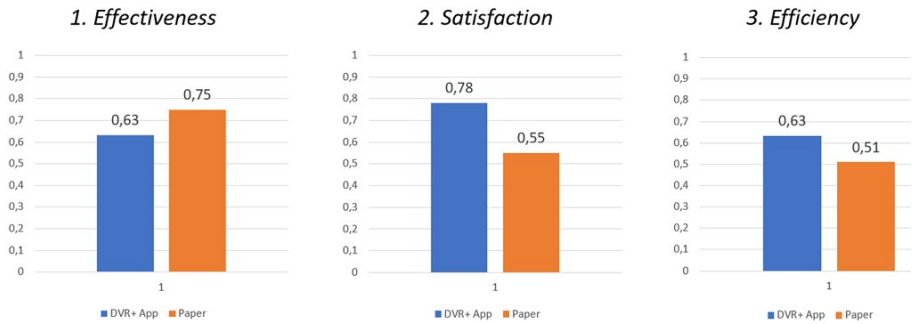

Fig. 5: results for each usability factor: Effectiveness, Satisfaction in use and Efficiency.

Surprisingly, the paper-based procedure demonstrated slightly greater effectiveness than the augmented reality tool. However, the satisfaction and efficiency ratings were higher for the DVR+ Application tool. A synthetic usability index was finally computed as the weighted sum of each factor (Figure 6).

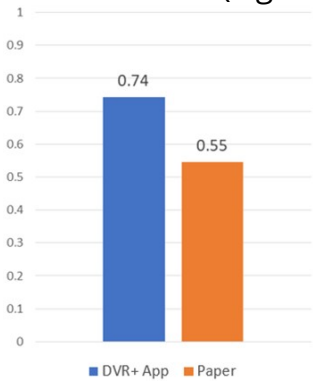

Fig. 6: Synthetic usability index.

2 Conclusions

DVR+ is a mobile app that enhances the work environment by providing three-dimensional safety notes linked to specific locations, accessible through AR technologies. To the best of the authors' knowledge, it is the only industrial safety app that enables users to locate digital content in AR without the need for markers, and to store this location persistently on a remote server. During its development, particular attention was paid to the platform's usability. To evaluate usability objectively, the authors employed the AHP methodology, ensuring reliable and repeatable experimental results. Despite some limitations, primarily related to technological factors, the usability analysis yielded encouraging results. Moreover, the developed application has shown significant potential. On one hand, it can serve as a valuable inspection tool, allowing users to easily locate hazards by simply framing them with their device's camera, and to manage room floor plans. On the other hand, it acts as an effective communication tool, enabling real-time dissemination of safety information to workers. It can also be used for on-the-job

continuing education or other relevant applications.
For usability testing, the app includes timed assessments. For example, a user can begin training for an evacuation procedure by pressing a start button that activates a timer. The user must then follow the path displayed in AR via their smartphone or tablet's camera. Once the user reaches the designated goal (e.g., a predetermined meeting point), they stop the timer by pointing the camera at a predefined marker. The execution time for each user is saved in the remote database, accessible by authorized personnel. Similarly, the date and time of each annotation created are stored, allowing the app to be used for training purposes, such as in serious safety games.
As noted, there are some technological limitations. The primary issue concerns the accuracy of the ARCore framework. Localization accuracy decreases as the user moves farther from the reference point, limiting the app's use to enclosed spaces. Another constraint is the graphic and computational resources required by the app. Some devices, after extended use, exhibit signs of overheating that can compromise the app's performance. Ongoing experiments are being conducted at the Fraunhofer Joint Lab IDEAS and the INAIL Campania Regional Directorate to address these challenges.

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4 Supplementary Materials

[1 Suppl. Mat.] - https://docs.google.com/forms/d/e/1FAIpQLSdo-plCtqgoo2-3ndSLR5YptRX-jXfqSR33WrJ1Uo0lbmSh4w/viewform?usp=sf_link
[2 Suppl. Mat] - https://docs.google.com/forms/d/e/1FAIpQLSf-xZeCrrm9seTnX9fnzGE6-0YixHFO2wLShOdSMKANTWiGFQ/viewform?usp=sf_link

5 Acknowledgements

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Integration of inspections in major-accident hazards establishments also under directive 2010/75/ue (ippc): operational modalities in Arpa Piemonte

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Abstract
The Regional Agency for Environmental Protection in Piedmont (Arpa Piemonte) among its institutional activities for Regional Law no. 18/2016, carries out inspections on installations regulated by Directive 2010/75/UE (IED-Industrial Emission Directive) and Directive 2012/18/UE (so-called Seveso III Directive): the first is the main EU instrument regulating pollutant emissions from industrial sities (IPPC-Integrated Pollution Prevention and Control) and the second is about the control of major-accident hazards involving dangerous substances.
The project is aimed to integrate the skills of the personnel assigned to the two topics, in order to optimize and make the Agency's activities more effective, coordinating operational methods for carrying out such activities within the Agency will be set up, both during the preparatory phase of the controls and during the joint inspections in the establishments.

1 Introduction

After the serious accident occurred in 1976 in Seveso (a small city in Italy), involving dioxin emission, the process of regulating major-accident hazards associated with dangerous substances began with Directive 82/501/EEC (so-called Seveso I Directive), implemented in Italy with the Presidential Decree n°175/1988, followed by Directives 96/82/EC (Seveso II Directive) and 2003/105/EC (Seveso IIbis Directive), implemented respectively by Legislative Decree n°334/99 and Legislative Decree n°238/2005.
Currently, Directive 2012/18/EU [1] (Seveso III Directive) on the control of major-accident hazards involving dangerous substances, is in force, as transposed into Italian law through Legislative Decree n°105 of 26 June 2015 (in Italian D.Lgs. n°105/2015) [2].
One of the most important innovations of Directive 96/82/EC, followed by Directive 2012/18/EU, is that operators should draw up a Safety Management System (SMS) for controlling major-accident hazards and the competent authority should inspect it; this SMS is aimed to adopt criteria for the correct management of several aspects related to process safety (ex. personnel training, maintenance, emergency plan).
In parallel, since the mid-1990s, a strategy common to the entire European Union has been adopted, aimed at the prevention and integrated control of pollution (so-called

IPPC Integrated Pollution Prevention and Control), to increase the environmental performance of industrial complexes subject to authorization.
The initial IPPC standards (Directive 1996/61/EC and Directive 2008/1/EC) were ultimately replaced by Directive 2010/75/EU (so-called IED Industrial Emission Directive) [3], transposed in Italy with Legislative Decree n°46/2014, which amended the second part of Legislative Decree n°152/2006 (in Italian D.Lgs.152/2006), the main Italian law on environmental matter, regarding procedures for Integrated Environmental Authorization (IEA). Recently, Directive 2010/75/EU was updated by EU/2024/1785, published on July 2024, and its Italian transposition is expected by 2026.
As in Seveso context, also with Directive 2010/75/EU the approach to integrated control has evolved towards greater responsibility for managers of installations, in terms of preventing the impact environmental, pursuant to management procedures approved during the preliminary investigation phase.
The two European Directives (Seveso and IPPC Directives), regarding respectively major-accident prevention and integrated pollution prevention and control, have distinct objectives but refer to each other and the aim of this project is to highlight the common aspects.
Arpa Piemonte, among its institutional activities due to the Regional Law n°18/2016 [5], carries out inspections on installations regulated by both Directives and the staff dedicated to these inspections belong to different Agency structures; the further aim of the project is to optimize and enhance the efficiency of these activities, integrating the knowledge of the inspectors. In this context, the project aims to bring the experience gained over more than twenty years of inspections on SMS in major-accident hazards establishments (so-called Seveso establishments), sharing common aspects with the inspectors of IPPC Directive, who are encountering this new approach within the scope of their respective competences.

2 The situation in Piedmont region

In Piedmont region there are about 80 establishments covered by Seveso Directive, which belong to different production sectors; in particular on December 2024 there are 44 upper-tier establishments and 37 lower-tier, according to threshold values of Annex 1 of D.Lgs. n° 105/2015.

The IPPC installations in Piedmont are about 600 (exactly 609 on December 2024): 11 are under State responsibility (e.g. big chemical and combustion plants) and the remaining are under regional competence.

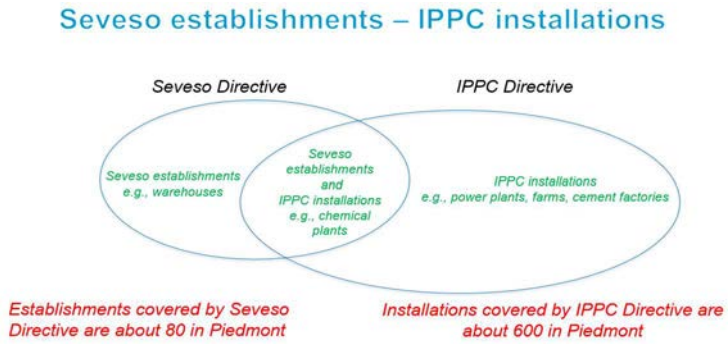

Fig. 1. Seveso establishments and IPPC installations in Piedmont.

As showed in Figure 1, the Seveso establishments covered also by IPPC Directive are only a few: in particular there are twenty-nine chemical plants (IPPC code no. 4) and one refinery (IPPC code 1.2 "Petroleum and gas refineries") at the end of 2024.

a. The activities of Arpa Piemonte connected to D.Lgs. n°105/2015

For Seveso establishments, according to the Italian law D.Lgs. n°105/2015, there are two types of control activities: inspections on Safety Management System (SMS), for both lower and upper tier establishments, and investigations of Safety Reports for upper tier only, according to regional plans. These procedures involve several public authorities (in particular Arpa with other State and regional organizations, e.g. the Fire Department) and last several days, both for on-site inspections and study of documentation in order to verify the consistency of documents with the plant configuration.
In this paper we refer only to inspections on Safety Management System (SMS), whose aim is a planned and systematic examination of the SMS adopted by operators whether of a technical, organisational or managerial nature. In particular they aim to ensure that the operator can demonstrate that he has taken appropriate measures, in connection with the various activities of the establishment, to prevent major accidents and he has provided appropriate means for limiting the consequences of major accidents, on-site and off-site. Moreover, the inspections aim to verify that the data and information contained in the safety report and in technical and procedural documentation, adequately reflect the conditions in the establishments. The final report of the inspection includes findings and recommendations for improving SMS, to which the operator must respond with corrective actions.

b. The activities of Arpa Piemonte connected to D.Lgs. n°152/2006

For IPPC installations, according to the Italian law D.Lgs. n°152/2006, Arpa Piemonte provides its support to the Competent Authority for the Integrated Environmental Authorization (IEA) in case of new installations or substantial changes of existing ones.
Another important activity of Arpa Piemonte is to carry out inspections on IPPC installations under regional jurisdiction, according to a specific inspection plan which evaluates the risk associated with each company, using the “SSPC system” (Control Planning Support System) approved by the Federal Council N. 63/CF of 15/03/2016.
For IPPC installations under state jurisdiction, an agreement with the national Institute for environmental protection and research (so-called ISPRA in Italian) ensures that Arpa Piemonte participates in control activities together with ISPRA.
These activities include the verification of the regularity of the checks conducted by the manager as part of the checks scheduled in the inspection plan carried out during on-site visits. Additionally, the compliance with the conditions of the Authorization is ensured through on-site visits, according to the frequency set in the regional environmental inspection plan, with particular reference to pollution prevention devices and compliance with emission limit values, along with the verification that the operator has complied with its communication and information obligations.
The activities during on-site visits include sampling, emission analysis, and measurement of the effects of emissions on the environment, as outlined in the Monitoring and Control Plan.
In the case of the issuance, review, or amendments, both substantial and non-substantial, to the IPPC authorization, Arpa Piemonte is required to assess the Monitoring and Control Plan (PMC) and provide its opinion to the Competent Authority. In this context, the National System for Environmental Protection (SNPA) published the Guideline no. 39/2022 "Controls on IPPC installations of regional competence" [7].
The controls conducted provide the Competent Authority with a complete reference framework on compliance with the IPPC and the necessary information for taking appropriate measures against the controlled entities or for renewing expiring acts.
The control process also verifies the consistency with respective authorizations, technical requirements from the Best Available Techniques Conclusions (BATcs), BAT Reference documents (BREF), guidelines and/or sector analyses, and the identification of indicators that assess the environmental performance of the controlled parties. In this regard, SNPA Guideline no. 48/2023 "Guidelines for the development of the monitoring and control plan" [6] is to be applied, specifically for BATc Reviews stemming from European BREFs.
The activities may require verification of compliance with predefined legislative requirements and the IPPC, the implementation of the adjustment plan, documentation of the operator's annual reports and self-checks as per the Monitoring and Control Plan, the management procedures of plants and production

phases, and the environmental impacts, including by controlling the instruments used to analyse those impacts.

3 Common aspects between Seveso and IPPC inspections

As mentioned in the previous chapter, the two European Directives concerning Seveso and IPPC inspections have distinct objectives, but they also have several common aspects which are illustrated below.

The first part of the project, which was developed in 2023, led to the elaboration of the "Proposal for operational procedures for integrating the activities of Arpa Piemonte regarding prevention of major accidents (Seveso Directive) and integrated environmental authorization (IPPC Directive 2010/75/UE)".

In 2024, the project continued with a pilot inspection conducted in a Seveso establishment covered also by IPPC Directive; this activity was structured in two phases, a preparatory one mainly of document analysis and an on-site inspection.

The preparatory phase took place between the two Arpa Piemonte structures involved and concerned the sharing of available information, including the description of the establishment and its plans (e.g. sewerage network), the results of the previous inspections carried out and prescriptions on aspects of common interest.

During the on-site inspection, carried out by two structures together, the common environmental aspects were examined, including the procedures relating to the management of accidental spills and emissions into the atmosphere, and to verify the implementation of the prescriptions /recommendations of common interest (e.g. emergency management plans, critical equipment maintenance management plans, incoming raw material acceptance procedures).

This pilot activity resulted in a checklist (shown in Table 1), that collects the common aspects between Seveso and IPPC inspections, giving inspectors an operational tool.

Table 1 - Checklist of common aspects of Seveso and IPPC

Acquire and examine the following documentation for issues of common interest	***Feedback***
○ Safety Management System (SMS) and Environmental Management System (EMS)	
○ Major-Accident Prevention Policy (MAPP)/Environmental Policy and relative implementation and improvement programs	
○ Organization and personnel	
○ Management of dangerous substances/mixtures and related Safety Data Sheets (SDS) and raw material acceptance procedures	
○ Identification and maintenance of critical establishment elements for safety and environment	
○ Procedures for process control and definition of operating parameters in normal, anomalous and emergency conditions ○ Management plan for operating states in non-normal operating conditions (OTNOC Other Than Normal Operating Conditions)	
○ Management of change	
○ Emergency management procedure (e.g. accidental spills and gas leakage)	
○ Management of incidental events	
○ Monitoring performance	
○ Internal audit of SMS/EMS	
○ Review of SMS/EMS	
○ Technical establishment documentation (e.g. plans of storage and production areas, plan with authorized emission points, sewer and fire plan)	

a. Adoption of a SMS/EMS

The main common requirement of both regulations is the adoption of a Management System, which for Seveso Directive concerns the prevention of major accidents (SMS) and for the IPPC Directive concerns Environmental Management (EMS). The general requirements and structure of the Safety Management System (SMS) are established in Annex B of D.Lgs. n°105/2015 which defines the constituent elements of the SMS: organization and personnel, identification and evaluation of major hazards, operational control, management of change, planning for emergencies, monitoring performance and audit and review.

The operator of a Seveso establishment must define its own Major-accident prevention policy (MAPP), which could be integrated with environmental policy. In any case, it is appropriate that the implementation and improvement programs that derive from these policies are integrated, as some improvement actions could be transversal to both systems (SMS/EMS).

Regarding the IPPC regulation, BAT n°1, which is common to all IPPC categories, involves the establishment and implementation of an Environmental Management System (EMS) aimed to improve overall environmental performance. This includes, among other characteristics, elements that are also common to the SMS. The system requires commitment from management, including senior executives, who must define an environmental policy focused on the continuous improvement of the installation's environmental performance. Additionally, management must plan and adopt necessary procedures, objectives, and targets, ensuring alignment with financial planning and investments. The implementation of procedures must pay particular attention to several aspects: the structure and responsibility within the organization, recruitment, training, awareness, and competence of staff, communication, involvement of staff, documentation, effective control of processes, maintenance programs, emergency preparedness and response, and compliance with environmental legislation. The system also emphasizes the need for performance control and the adoption of corrective measures, specifically concerning monitoring and measurement, corrective and preventive actions, record-keeping,

and independent verification (where practicable), either internal or external, to ensure the environmental management system is compliant and properly implemented and updated. Furthermore, top management must periodically review the environmental management system to ensure its continued suitability, adequacy, and effectiveness. The system also highlights the importance of developing cleaner technologies and includes the requirement for an incident management plan.

b. Organisation and personnel

For the implementation of an SMS/EMS management system within the company organization, the responsible personnel involved in the management of major hazards and environment at all levels in the organisation are identified and their roles and responsibilities are defined, together with the measures taken to raise awareness of the need for continuous improvement. Normally a manager of the SMS is identified who may coincide with the Prevention and Protection Service Manager referred to Legislative Decree n°81/2008, as well as with the Health, Safety and Environment manager (HSE manager); similarly, workers' Representatives for Safety, Health and Environment can be appointed. All these figures are represented in an organizational chart which should be integrated for a greater overall vision.

c. Dangerous substances and Safety Data Sheets (SDS)

For a Seveso establishment, it is necessary to have a list of the dangerous substances/mixtures held, with the relevant Safety Data Sheets (SDS) which indicate the classification pursuant to "Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures" (so-called CLP Regulation) [8]; in fact, if these substances are covered by the hazard categories listed in Part 1 or are listed in Part 2 of Annex 1 of D.Lgs. n°105/2015, the maximum quantities that can potentially be held must be estimated for the purpose of verifying whether the establishment is subject to the D.Lgs. n°105/2015. The management of the dangerous substances used in the establishment is formalized in a specific procedure which should provide a periodic updating of safety data sheets, also to take care about any changes in the CLP classification; this aspect also has repercussions on the management of substantial/non-substantial changes for IPPC Directive and increase/non-increase changes for Seveso Directive (see specific paragraph).

For environmental aspects, during the reporting phase it is requested to send to Competent Control Authority the list of raw materials/substances entering the plant/held with the relative quantities and storage methods.

d. Maintenance of critical equipment for safety and environment

In the context of the major accidents hazard, the operator must systematically identify critical establishment elements for safety, which must include all equipment from which incidental releases may occur, as well as the components and devices for

control, protection, and safety, considering risk analysis and the establishment's reality.
The EMS requires the operator to identify equipment and plant parts that are critical for the environment, as well as pollution prevention devices and all the instrumentation necessary for the control of critical phases, taking into account the characteristics of the substance contained (e.g. toxic, corrosive, flammable), the probability of leakage of the substance and the operating conditions (temperature and pressure).
For the Seveso establishment, strategy and methodology for monitoring and control of the condition of critical equipment is required, established on their reliability, as assumed in the risk assessment, or their lifetime or failure frequencies, specified by the supplier or established based on operating experience, and the results of previous controls. Similarly, for critical equipment for the environment, the operator is required to define an annual maintenance plan that contains the description of each intervention, the frequency and the methods of recording.

e. Operational control

D.Lgs. 105/2015 indicates that the SMS must provide the adoption and implementation of procedures and instructions for the operational control of the process and of all plant activities relevant to the safety purposes, which contain information of operating in normal, abnormal and emergency conditions, the maximum operating limits and the consequences, alarm management and temporary stoppages.
In the IPPC context, some BATcs by category of activity (e.g. waste incineration plants, combustion plants, chemical plants, paper mills) provide for the management of operating states in non-normal operating conditions (OTNOC: Other Than Normal Operating Conditions) by adequately monitoring them for the purposes of their minimization; this monitoring is implemented with direct and/or indirect measures on process control parameters specifically identified in the OTNOC Management Plan.

f. Management of change

For Seveso establishments, according to the Italian law D.Lgs. n°105/2015, operators should adopt and implement procedures for planning changes, regarding different types modifications (permanent or temporary, to the plants and related systems or components, to the process parameters, to the organization); the law distinguishes the modifications constituting an increase in the pre-existing level of risk of major accidents, defining the criteria and the authorization process in a specific annex.
Regarding the IPPC aspects, the changes are divided into substantial and non-substantial, based on their significant impact on the environment. According to law, a distinction is made between a change/modification and a substantial change. A change/modification refers to the variation of an approved plan, programme, plant,

or project, including changes in their characteristics or operation, or their enhancement, that may produce effects on the environment. A substantial change, on the other hand, refers to a change in the characteristics or operation, or an enhancement of the plant, work, infrastructure, or project, which, in the opinion of the competent authority, produces negative and significant effects on the environment or human health.
Specifically, with reference to the discipline of integrated environmental authorization, for each activity for which Annex VIII of D.Lgs. n°152/2006 indicates threshold values, any modification to the installation that results in an increase in the value of one of the quantities subject to the threshold, equal to or greater than the threshold value itself, is considered substantial.

g. Emergency plan

For Seveso establishments, the Italian law D.Lgs. n°105/2015 requires the adoption and implementation of procedures for managing both internal emergencies within the establishments and external emergencies under the responsibility of the Prefectures.
A specific Annex of Seveso Directive outlines the minimum contents of internal emergencies plans, which specifically include the management of potential incident scenarios identified in the risk analysis, in terms of emergency actions to be taken, alert, alarm, evacuation and end of emergency procedures, as well as the acute effects on personnel involved in any activity in the establishment, the environmental damages and consequences outside the establishment.
The Environmental Management System provides for the preparation of a "Management Plan in the event of an accident" which identifies the dangers present in the plant and the related risks and defines the measures to deal with these risks, takes into account the inventory of pollutants that are present or presumed to be present and could have environmental effects in the event of leaks.

h. Management of incidental events

The operator of a Seveso establishment needs to adopt and implement procedures to define incidental events that may occur (major accidents, near misses, etc.), particularly those involving failure of protective measures, and the accidents operator’s system for reporting incidental events, their investigation with particular attention to identifying the causes that determined the events and the measures adopted (corrective and preventive actions), both managerial and technical, and follow-up on the basis of lessons learnt.
The IPPC legislation provides that, in the event of accidents or unforeseen events that significantly affect the environment (uncontrolled releases of polluting substances), the Manager informs the Competent Authority, the Municipality, SNPA, immediately adopting measures to limit the environmental consequences and prevent any further accidents or unexpected events. The information on the events that occurred must

concern, among other things, the data available to evaluate the consequences of the accident for the environment, the analysis of the causes, the emergency measures adopted, the measures envisaged to limit the effects of the accident in the medium and long term and prevent it from happening again. In this regard, in order to prevent environmental impacts, the operator must prepare the Environmental Emergency Plan pursuant to BAT 1.

i. Monitoring performance

For Seveso establishments, the Italian law D.Lgs. n°105/2015 requires the adoption and implementation of procedures for the ongoing assessment of compliance with the objectives set by the operator's MAPP, which also include performance indicators such as safety performance indicators (SPIs).
Performance indicators (BAT-AEPL) are also provided for the IPPC in the BATconclusions documents deriving from the sectoral BREFs. A BAT-AEPL is an environmental performance levels associated with the best available techniques.
Performance indicators for the SMS/EMS could be common, in some cases; for example, the number of incidental events that occurred in the establishment with environmental repercussions, as well as those related to the prevention of major accidents. These indicators serve as input tools for the review of the systems (see next section), with the methods for their enhancement and the frequency of their monitoring. During the review of performance of the policy and safety management system target values for each performance indicator are established, against which the values monitored throughout the year are compared.

j. Internal audit and review of SMS/EMS

The SMS/EMS provides the adoption and implementation of procedures for planning and carrying out periodic internal safety audit activities for the evaluation of the efficiency and effectiveness of the SMS/EMS in the pursuit of the objectives indicated in the major-accident prevention policy (MAPP)/Environmental Policy.
The manager of a Seveso establishment has to carry out a periodic review of the adopted SMS which takes into account all the activities carried out within the System, such as the analysis of the incidental events, the trend of the performance indicators, the results of emergency simulations and audits (internal and external, including those of the supervisory authority), in order to identify the critical issues of the System and the related corrective actions which must be included in the major-accident prevention policy (MAPP) and in the relative implementation/improvement program.
In the IPPC, both these aspects must be provided for as required by BAT 1 by the company and/or external EMS in the case of ISO 14001 certification or EMAS Registration (Eco-Management and Audit Scheme), according to the principles of ISO 9001 of the Deming cycle (or PDCA cycle, that stand for Plan-Do-Check-Act), a four-step iterative management method used for the control and continuous improvement of processes and products.

4 Conclusions

This project, started in 2023, is aimed to integrate the activities of Arpa Piemonte regarding Seveso and IPPC inspections, in order to optimize and enhance the efficiency of our Agency. Following a first proposal of operational procedures, during 2024 a pilot inspection was conducted in a Seveso establishment covered also by IPPC Directive; this activity led to the elaboration of a specific checklist with the most important common aspects between a Safety Management System (SMS) and an Environmental Management System (EMS).

In 2025 are scheduled information sessions for the personnel of the Agency which is Seveso and IPPC inspectors and other inspections will be organized in Seveso establishments covered also by IPPC Directive, in order to improve the checklist previously outlined.

5 References

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[6] SNPA (2023) Guideline no. 48/2023: Guidelines for the development of the monitoring and control plan

[7] SNPA (2022) Guideline no. 39/2022: Controls on IPPC installations of regional competence

[8] Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006.

Fire in waste treatment plants in Piedmont Region: case studies and comparison

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Abstract
Following several outbreaks of fires within waste treatment and storage facilities, which have occurred in Italy over the last decade, in 2018 Law n. 132 was enacted in order to introduce new regulatory obligations for operators regarding the drawing up of Internal and External Emergency Plans, in analogy with major-accident hazards establishments under European Directive 2012/18/EU (Seveso III Directive). The study begins with the need of Arpa Piemonte to investigate and characterize the phenomenon of fires in waste treatment and storage facilities, with particular focus on regulatory aspects and the obligations of operators. In 2022, a source-term model was implemented to calculate fundamental parameters such as thermal power, average temperature, and flame height, which are useful for studying the dispersion of combustion fumes into the environment. The study was subsequently expanded with the application of the guidelines established by the External Emergency Plan, defined in Italy by the DPCM of August 27, 2021, to a real case in order to determine the safety distance through fire risk assessment. The obtained results will then be compared with modeling simulations to verify consistency.

1 Introduction

Fires in industrial sites represent one of the most significant events, as, in addition to thermal effects, they generate toxic scenarios related to combustion fumes. The main substances emitted during these fires include, for example, CO, NO2, H2S, NH3, HCN, Cl2, formaldehyde, SO2, CO2, HCl, HF, PCDDs, and PCDFs, all of which have significant effects on human health and the environment. Therefore, it is important to analyse the dynamics of complex fires, as it allows for the identification of key factors in the propagation of the fire and its thermal and toxic consequences.
The Regional Agency for Environmental Protection of Piedmont (Arpa Piemonte), within the framework of its institutional activities established by Regional Law no. 18/2016 [1], intervenes in cases of anthropogenic or natural emergencies, conducting sampling and measurements of pollutants emitted that may impact one or more environmental matrices (air, water, soil). This project begins with the need of Arpa Piemonte to investigate and characterize the phenomenon of fires in waste treatment and storage facilities. The final aim will be to evaluate the fallout areas of fumes and the safety distances downstream of a fire, with a specific focus on the fire phenomenon in warehouses. In 2022, the Agency had already investigated the

phenomenon, focusing on the characterization of the source term model to calculate key parameters such as thermal power, average temperature, flame height, and smoke composition [2]. To validate the model, the pile fire, implemented in Excel, was compared with a pool fire simulated using the PHAST software. The results obtained from both models (Excel and PHAST) were compared using the same substance, methanol, and a sufficiently low error was observed, confirming the validity of the developed model.

The study was subsequently expanded with a historical analysis of incidents, followed by the implementation of the guidelines for the External Emergency Plan (so called DPCM of August 27, 2021) [3]. Specifically, the study involved a historical analysis of incidents that occurred in Piedmont to collect significant data on the types of activities most involved in fires and the geographical areas most frequently affected by such events. This analysis allowed for the creation of a detailed framework, highlighting the distribution of incidents across the territory, and providing information to understand the dynamics of specific risks related to fires in local contexts. To investigate the study further, the attention was focused on four fire cases occurring in different industrial settings, examining the impact of pollutants emitted into the atmosphere during the incident and the locations where sampling was conducted to analyze toxic dispersions.

The aim of this study was to evaluate the reliability of the index-based method outlined in the guidelines for the External Emergency Plan, applied as a risk assessment tool for warehouses, with the intention of comparing the results obtained with those derived from field sampling. This method allowed for a semi-quantitative assessment of risk factors, considering key variables such as stored materials, building configuration, and the effectiveness of active and passive protection systems in place at the facility.

Finally, the application of two modeling software tools was introduced, which will be implemented in the next phase of the study to simulate the propagation and dispersion of combustion fumes. The results obtained from the model will then be compared with those from the simulations to verify the consistency between the different approaches.

2 Historical Analysis in Piedmont

Arpa Piemonte, as part of its institutional activities defined in Regional Law No. 18/2016, manages an on-call service for emergency interventions of both anthropogenic and natural origin, conducting environmental sampling during fires. During these events, substances defined as "tracers" are analysed to identify and characterize the fires and assess their impact on the environment and public health [4]. To manage the emergency activation service, since 2014, the Agency has developed the "Ispezioni non programmate" application, which allows for the registration of reports related to various types of events, such as pollution, ionizing radiation, fires, and waste abandonment, by citizens, operators, and other emergency

entities. The application has enabled the creation of a database containing 436 records related to fire reports in Piedmont between March 2014 and October 2024, aiming to simplify a systematic analysis of each report to highlight possible trends. Each report is registered as a record that includes various information: the report ID, used as a unique identifier to track and manage each event; the territorial department (North West, North East, South West, South East) in which Arpa Piemonte is divided; the report date, the entry date, and the status of the case. Data related to the reporting entity and its qualification are also recorded, specifying the organization or individual who made the report, the reporting method, and a description of the event. Data analysis revealed that the current database structure may not fully meet the specific needs of the study, particularly regarding data extraction and analysis. The review of the database led to a new structure with additional fields to improve event description, including details on the type of activity, location, and materials involved. Duplicate records were eliminated, and a “unknown” category was added for incomplete data. The updated database contains 361 events, with graphical analysis to identify trends and correlations. The activities have been classified to distinguish the context of the fires, including categories such as industrial plants, waste treatment and storage facilities, agricultural activities, warehouses, and a generic "other" category. The combusted materials are subdivided into specific categories for analysis: chemicals, waste, asbestos-containing structures, vehicles, electronic devices, wood, tires, and combinations of these.

2.1 Results and Discussion

Figure 1, which represents the trend of fires divided by department from March 2014 to October 2024, shows no linear or cyclical trend in the number of fire events. The department with the highest number of fires is the North West, followed by the South East, North East, and finally the South West. In general, the data show significant annual variability, with fluctuations suggesting an episodic behaviour rather than a stable or regular pattern in the number of fires. The oscillations in the annual values indicate that fires do not follow a continuous trend but rather occur discontinuously, with periods of increase deviating from historical averages.

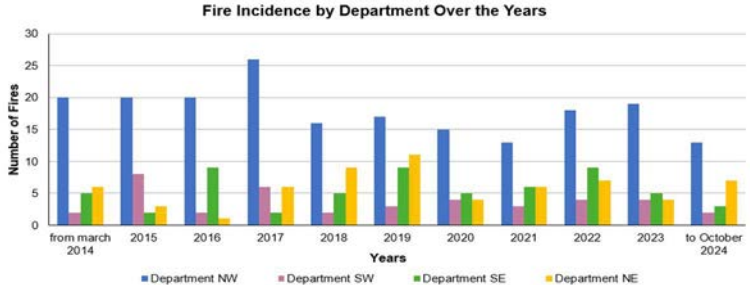

Fig. 1. Trend of fire incidents across the four ARPA Piemonte Departments from March 2014 to October 2024.

Figure 2 shows the distribution of activities recorded in the updated database, providing a detailed overview of the main categories. The analysis highlights that the "other" category is the most represented, with 36% of the 361 reports. However, excluding this category, it emerges that the most affected activities are industrial plants and those dedicated to waste treatment and storage.

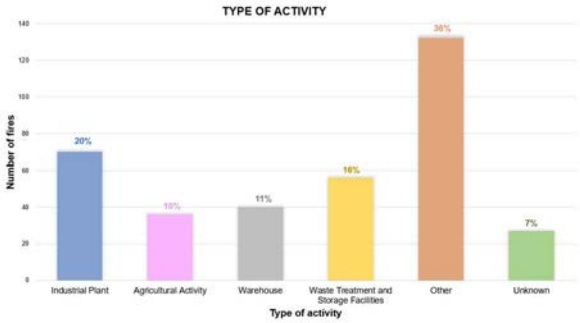

Fig. 2.Distribution of activity types involved in the 361 fires studied.

To focus the analysis on the most affected productive activities, the distribution of fires involving such activities, divided by province, is graphically represented in Figure 3. The data show that the province of Turin records the highest number of events, followed by Biella and Novara for industrial plants. Similarly, for waste treatment and storage facilities, the data indicate that the province with the highest number of incidents is Turin, followed by Alessandria and Cuneo.

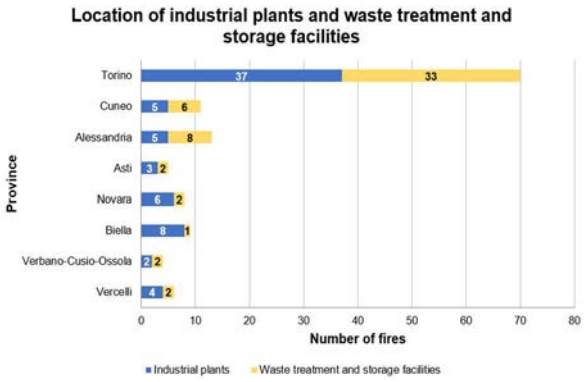

Fig. 3.Distribution of the number of fires in industrial plants and waste treatment and storage facilities, divided by province.

Regarding the combustible materials involved in the fire events analysed, the analysis shows that, excluding the "unknown" category, the most affected materials are waste and chemicals. Concerning the reporting entity, the data analysis reveals that the major sources are 118 (Emergency Health Service) and the Firefighters, which account for the majority of the reports. To a lesser extent, notifications are recorded from 112 (Single Emergency Number) and Arpa Piemonte operators themselves.

3 Analysis of Incidents

Four fire events that occurred in recent years across the various territorial departments were analyzed, with a particular focus on the results of the analyses conducted by the Agency personnel during the emergencies:

- North-West Department: An analysis was carried out on a fire at a facility that processes non-hazardous special waste, specifically plastic material from separate waste collection.
- North-East Department: The fire at a chemical plant specializing in the production of release agents, lubricants, and technical solutions for the molding sector was selected for analysis.
- South-West Department: The fire at a storage warehouse containing various materials, including plastic, clothing, electronic components, and toys, was analyzed.
- South-East Department: Two fires in a non-hazardous waste storage and disposal facility were considered.

An analysis revealed that the reports drafted following the Agency personnel interventions focus on the measurements of toxic fumes resulting from combustion, carried out in accordance with the technical procedure U.RP.T170 [5]. From the analysis of the reports, it emerges that, in line with the technical procedure, ARPA uses a sampling methodology that covers a comprehensive range of substances typically produced during fires. This approach was chosen because, in an emergency situation, it is impossible to predict the combustible material involved, which may vary depending on the type of structure and the materials present. However, a critical aspect highlighted in the reports is the lack of adequate information on the specific chemicals involved in the fire and the exact dimensions of the affected structures. This lack of detail prevented the comparison of the collected data with the guidelines for the External Emergency Plan and made it difficult to carry out simulations using modeling software.

4 Case Study: Tire Storage Warehouse

The historical analysis has highlighted that waste treatment and storage facilities are among the most affected by fires, in line with the numerous incidents recorded in Italy over the last decade. In response to this issue, in 2018 Law n. 132 [6] was introduced, imposing new regulatory obligations on operators regarding the preparation of Internal and External Emergency Plans, similar to the regulations for establishments at risk of major accidents, in accordance with European Directive 2012/18/EU (Seveso III Directive) [7]. Following Law no. 132/2018, an index-based method was developed, as described in the guidelines for the External Emergency Plan, formalized by the DPCM of August 27, 2021, specific to waste treatment and storage facilities. This study aims to assess the smoke fallout areas and safety distances downstream of a fire by preliminarily applying the index-based method to a real case. However, the lack of necessary input data for an adequate characterization of the fire source, as outlined in paragraph 3, has limited the

(1)

use of reports for case study applications. To overcome this limitation and simulate realistic scenarios for facilities in the Piedmont region, reference has been made to risk analyses of establishments subject to the Seveso regulations, for which the "Industrial Plants and Energy" structure has data. In particular, as a representative example, a fire in a tire storage warehouse was selected as a case study, for which useful information is available to reconstruct a realistic event model. Following a bibliographic analysis of fires in tire storage warehouses, it was decided to treat tires as a solid waste in order to estimate the fire risk and corresponding attention distance using the index-based method. This choice is justified by the complex and variable composition of tires, which consist of a mixture of natural and synthetic rubber, carbon black, steel, sulfur, aromatic oils, and various chemical additives, characteristics that make them similar to mixed waste. The index method, specific to waste treatment and storage facilities, allows for a semi-quantitative risk assessment by associating the results with different levels of hazard. This approach provides a foundation for designing mitigation and prevention strategies, thus improving the safety of warehouses and reducing the risks associated with fires involving complex materials such as tires. The method involves assigning specific scores to both the risk factors and the prevention and protection measures present in the facility, also considering potential threats to human health and the surrounding environment. The fire risk index (IR) is calculated according to the formula:

$$IR = Pr + Pt - FC + FD$$

The storage risk index (Pr) is determined by the specific fire load (q_f), which depends on various factors: the mass of the combustible material (g_i), its calorific value (H_i), the surface area of the operational zone (A), and parameters that consider, for example, the participation in combustion ($m_i$and Ψ_i). The index method includes a table that associates each value of $q_f$with the corresponding Pr index. The waste treatment risk index (Pt) is based on the operations and processes within the facility. The credit factor (FC) considers the protective measures adopted, such as extinguishing systems and physical barriers, while the debt factor (FD) evaluates the hazard to health and the environment in relation to the facility's proximity to sensitive areas. The resulting value from the risk index (IR) is then associated with a qualitative risk level, ranging from low to high, with intermediate categories such as low-medium, medium, and medium-high. Each risk level is associated with an attention distance, which represents the maximum distance between the boundary of the storage or waste treatment facility and the boundary of the relevant sensitive target area, or the end of a significant element.

Table 1 - Attention Distance Based on the Risk Level

IR	Risk Level	Attention Distance [m]
0-400	Low Risk	100
401-700	Medium-Low Risk	200
701-1100	Medium Risk	300
1101-1500	Medium-High Risk	400
>1500	High Risk	500

a. Application of the index method

A case study was selected regarding a warehouse containing 72000 kg of tires, with a total surface area of 108 m². The lower calorific value of the stored materials, equal to 25 MJ/kg, was derived from data provided by [8]. For the calculation of the specific fire load, not only these parameters were considered, but also the combustion participation factor and the participation limitation factor, both set to 1, in accordance with the provisions of the index method. The value of the specific fire load was determined using the following relationship: (2)

$$q_f = \frac{\sum_{i=1}^{n} g_i \cdot H_i \cdot m_i \cdot \Psi_i}{A} \left[\frac{MJ}{m^2}\right]$$

Two scenarios were analyzed: the first considers the actual conditions of the facility with the full implementation of prevention, protection, and safety measures; the second is a simplified scenario limited to basic measures, i.e., without any improvement interventions or advanced implementations of prevention, protection, and safety measures. In both cases, for the FD parameter, the proximity of a watercourse to the distances indicated in the General Regulatory Plan (PRG) was taken into account.

In the case study with complete prevention and protection systems, the analysis resulted in a risk index of 1045, placing the warehouse in a medium-risk category (Table 2). This value was obtained by considering various parameters and indices, which reflect the specific situation of the warehouse and the security measures in place. A risk index of this magnitude implies that, although prevention and protection measures are implemented, some vulnerability remains.

In the case where only basic prevention and protection systems are in place, the prevention measures (Pre) were defined by considering only the obligations set forth in Legislative Decree 81/08 and the plan for maintaining the fire safety level. As for active protection measures (Proa), only hydrants, both internal and external, and fire extinguishers were included. The security measures (Sec) and passive protection (Prop) remained identical to those analyzed in the previous scenario. For security (Sec), all provisions in the index method were adopted, including the perimeter fence, surveillance system, and access control. For passive protection (Prop), the only measure considered was the presence of water collection basins for firefighting. The analysis conducted with these configurations resulted in a new risk index of 1220, classifying the warehouse as a medium-high-risk level (Table 3). Below are the values of the parameters considered in the two case studies with complete and basic prevention and protection systems.

Table 2 - Parameters Obtained in the Two Case Studies.

Parameter	Case Study with Full Prevention and Protection Systems	Case Study with Basic Prevention and Protection Systems
q_f [MJ/m2]	12971.83	12971.83
Pr	1500	1500
Pt	0	0
FC	475	300
FD	20	20
IR	**1045**	**1220**
Risk level	**Medium**	**Medium-high**

b. Sensitivity Analysis

Since the initially calculated risk in the case study with complete prevention and protection systems was medium, it was deemed appropriate to further reduce it by focusing on the parameters that significantly influence the variation in the risk level. The main parameters for reducing risk include optimizing the prevention and protection measures. However, the only feasible intervention in this area would be the implementation of compartmentalization between indoor operational areas, which would help confine a potential fire, limit its consequences, and thus reduce the risk level. From the application of Formula (1), the introduction of compartmentalization would increase the passive protection value (Prop) by 100, leading to a reduction in the risk index. However, in none of the cases analyzed did this reduction prove sufficient to lower the risk index to a lower level. Therefore, an alternative was considered that focused on reducing the specific fire load (q_f), achieved by varying the mass of the stored combustible material. Initially, reductions of 10%, 20%, 30%, and 40% in mass were considered; however, even with these decreases, the specific fire load (q_f) remained within the high range (q_f> 1200 MJ/m²), keeping the risk at the medium level. For this reason, a targeted sensitivity analysis was conducted to identify a mass reduction that could bring the specific fire load value into a lower range. This analysis revealed that a mass reduction of up to 5184 kg, or 7.2% of the initial mass, was sufficient to achieve a specific fire load compatible with a medium-low risk level. Subsequently, the mass required to achieve a low risk level was found to be 2592 kg, corresponding to 3.6% of the initial mass.

The trend of the risk index, as a function of mass, was represented in the diagram below, illustrating the direct relationship between the mass reduction and the decrease in the risk index.

From Figure 4, it can be observed that the risk index (Pr) as a function of the mass of combustible material exhibits a stepwise behavior. This behavior is intrinsically linked to the calculation method of the Pr index, which is determined by the value of the specific fire load (q_f). The latter is classified into predefined intervals (q_f< 600, 600 < q_f< 1200, and q_f > 1200), within which the Pr value remains constant. When the q_f

value exceeds the threshold of one interval and enters the next, the Pr index increases by 500, resulting in a stepwise pattern in relation to the variation in the mass of combustible material.
In the case study using complete prevention and protection systems, two significant reductions in the fire risk index (IR) are observed. In the first phase, the index decreases from 1045 to 545, corresponding to a reduction in risk from medium to medium-low. Subsequently, the IR further decreases from 545 to 45, with a change in the risk level from medium-low to low (Table 4). In the case study with basic prevention and protection systems, the risk index follows a different trend. The risk index first decreases from 1220 to 720 and then more significantly from 720 to 220. These decreases correspond to a reduction in the risk index from high-medium to medium and then from medium to low (Table 5), while maintaining the same mass variation observed in the complete prevention and protection case. This three-level reduction in the risk index demonstrates that even with less advanced protection systems, it is possible to achieve a final risk level comparable to that achieved with complete prevention and protection systems. In fact, with the same mass of combustible material, the risk level is low in both case

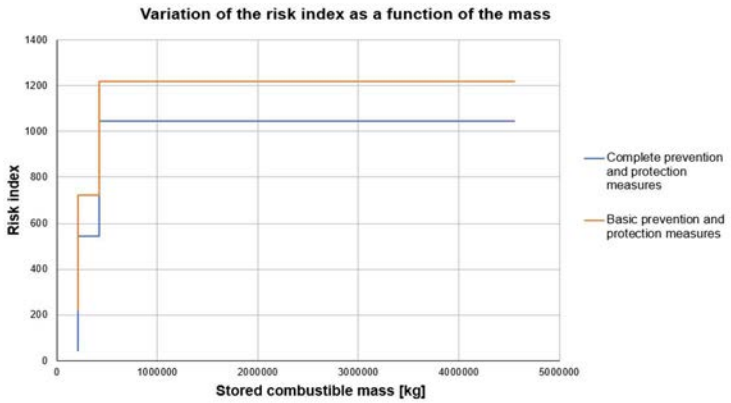

Fig. 4. Analysis of the variation in risk index relative to stored fuel mass.z

The analysis reveals that prevention and protection systems, even basic ones, are particularly effective in rapidly reducing the risk index, in contrast to the more gradual reduction observed with complete systems. However, this behavior does not meet initial expectations: it was anticipated that complete systems would result in a more significant reduction in risk. This discrepancy highlights a limitation of the adopted index-based method, which presents further critical issues, as discussed below. A first limitation concerns the warehouse structure: in the Guidelines for the External Emergency Plan, the risk index value remains unchanged regardless of whether the warehouse is open or closed, thus failing to account for different configurations that could influence fire propagation. Additionally, no distinction is made between the different types of active protection systems (Proa); for example, automatic extinguishing systems are considered generically, without distinguishing between

water-based and foam-based systems, even though this difference is crucial for the effectiveness of fire control and suppression, depending on the nature of the stored materials. An additional issue has emerged in the determination of the FD index, which assesses the distance between the facility's boundary and the external sensitive target, as the method does not account for the internal distance between the warehouse (potential source of the fire) and the facility's boundaries. In the event of a fire, the internal distance could, in fact, lead to a reduction in the risk outside the facility's perimeter.

c. Project development

Future work is planned to further investigate fire characterization in warehouses and the analysis of the dispersion of toxic fumes generated by combustion, using advanced modeling software such as CFAST (Consolidated Fire and Smoke Transport) [9] and PHAST (Process Hazard Analysis Software Tool) [10]. The primary goal will be to compare the results obtained from modeling software with those of the preliminary analysis conducted so far using the index-based method, in order to improve the understanding of fire propagation dynamics and the environmental and health impacts resulting from the dispersion of contaminants. In this preliminary phase, a detailed analysis of the inputs and outputs required by both software programs was conducted. The choice to use these software tools was motivated by the simplicity of the required inputs and the specific features of each: CFAST is a simulation software developed by the National Institute of Standards and Technology (NIST) for fire analysis, smoke, and heat transport within buildings. The results provided by the simulation include the mass flow rate of smoke emitted during combustion, the amount of pyrolysis products (defined as the amount of fuel undergoing thermal degradation per unit of time), the heat release rate (HRR) curve, indicating the power developed by the fire over time, as well as the intensity and height of the flame. PHAST is an advanced software tool used to analyze the risks associated with incidents in industrial facilities, particularly those involving hazardous substances that can cause fires or explosions. The results obtained from the simulation include pollutant concentration curves over time and space, the chemical composition of combustion products, dose and lethality probability curves, and smoke fallout curves. These outputs allow for the evaluation of environmental impact and health risks resulting from the dispersion of toxic substances, as well as the estimation of potential damage to the near structures and people.

5 Conclusions

This study provided an evaluation of the risks associated with fires in waste storage warehouses, with a particular focus on a case study involving a warehouse for used tires. The analysis adopted the index-based method for fire risk assessment, comparing scenarios with complete and basic prevention and protection systems, highlighting the importance of protective measures in reducing the risk level. In both

scenarios, reducing the mass of combustible material proved effective in decreasing the specific fire load, with significant impacts on the risk index. Despite the effectiveness of the method in providing a risk estimate and guiding the design of mitigation strategies, some critical issues emerged, including the failure to consider different warehouse configurations and the specifics of active protection systems. Furthermore, the risk index does not adequately account for internal distances, which may be relevant in case of fire, between the warehouse and the boundaries of the facility.

The index-based method, as described in the guidelines for the External Emergency Plan, has proven useful for a preliminary risk assessment with limitations. Comparing the results with field samples represents a goal for future studies, which could provide more concrete and verifiable data to optimize emergency management.

The historical analysis of fires in Piedmont revealed that industrial facilities and waste treatment and storage facilities are among the most affected activities, a trend that reflects the national situation. The results show that the provinces of Turin, Alessandria and Cuneo are the most affected, with materials most commonly involved, including waste and chemicals. This analysis allowed the identification of significant trends, highlighting the predominance of certain types of facilities and materials, as well as the concentration of fires in specific sectors and geographical areas.

Finally, the adoption of advanced modeling software appears to be a promising strategy for simulating fire scenarios and improving the prediction of toxic dispersion. Future work will aim to further investigate, through the use of advanced modeling software, the characterization of warehouse fires and the analysis of toxic smoke dispersion resulting from combustion. The goal is to compare the results obtained from modeling software with those from the preliminary analysis to improve the understanding of fire propagation dynamics and the environmental and public health effects arising from contaminant dispersion.

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Digital Solutions for Lone Worker

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Abstract:

Within the context of growing concern for worker safety and in compliance with current regulations, there has been an increasing adoption of innovative digital solutions to support their well-being. In particular, for lone workers, also known as solitary or isolated workers, safety needs are closely tied to the necessity of maintaining contact in emergency situations, providing information on the type and exact location of the event.

This study focused on developing a notification, alert, and rescue system based on voluntary SOS, automatic fall detection (mandown), and localization through dedicated IoT devices. The aim was to ensure maximum protection for workers in various work environments, leveraging different localization and communication technologies integrated into a single wearable solution.

As a result of this work, devices were deployed to many workers, operating in very different conditions and in a large geographical distribution, but all supported by a single centralized management and monitoring method based on a web platform. This system provides real-time visibility into worker safety and enables rapid and effective intervention in the event of incidents, providing detailed information about the event and its location.

Thanks to a highly configurable cloud platform, it is possible to collect and analyze data from devices and gather all related events. The platform generates reports and monitoring dashboards, integrates with enterprise systems, and allows for event analysis. Key figures such as health and safety managers can thus obtain a complete overview of events, easily identifying areas that require greater attention and promoting continuous improvement of safety conditions.

These devices are now part of a broader family of solutions which uses technology to reduce accidents and minimize their impact, placing the worker and their on-site safety at the heart of the solution. Within this family, systems such as geofencing, anti-collision systems, localization and monitoring systems, access control systems, and personal protective equipment (PPE) monitoring systems provide workers and managers with new and powerful tools for safety.

1 Introduction

Workplace safety is the cornerstone of every work environment. National and international regulations impose increasingly stringent requirements to ensure worker protection from hazards and risks. However, certain professional categories find themselves operating in particularly vulnerable conditions, such as lone workers. Lone worker safety presents a significant challenge in the context of occupational health and safety. Lone workers, defined as those who work without the presence of colleagues or supervisors nearby, are exposed to specific risks that require tailored protective measures[1].

According to INAIL data, in 2020 Italy recorded over 291,000 workplace accidents, with a significant number involving lone workers. Updated data from 2022 indicates that lone workers in Italy have a 20% higher risk of accidents compared to those who do not work in isolation[2].

These workers, often employed in various sectors and professions such as construction workers, delivery personnel, maintenance or repair staff, workers in remote agricultural or forestry environments, and healthcare services, may find themselves in dangerous situations without the possibility of immediate assistance in case of emergency[3].

The risks involved can vary, but among the most common are falls, cardiovascular accidents, exposure to dangerous substances, and road accidents[4]. However, isolation can increase the impact of even the lowest risks due to the lack of immediate support in the event of an accident. Adverse environmental conditions, such as working in high temperatures or cold environments, can aggravate these risks and their impact in isolated conditions. Work-related stress, resulting from loneliness and the pressure of having to manage critical situations alone, can negatively impact mental and physical health. Additionally, the use of dangerous machinery without supervision increases the risk of serious accidents[5].

The statistics of accidents at work in Italy involved isolated workers, highlighting the need for specific safety measures for this category[6]. Current regulations, such as the Consolidated Law on Health and Safety at Work (D.Lgs. n. 81/2008), require employers to take preventive measures to protect lone workers, including adequate training and the use of communication and warning devices[7].

The increasing adoption of innovative technological solutions based on wearable IoT (Internet of Things) devices, such as smartwatches or smart bracelets, and the management of real-time alarms through cloud platforms, is revolutionizing the way lone worker safety is managed[8]. These technologies allow for the automatic detection of emergency situations, the precise location of workers, and the immediate sending of alerts to rescuers, significantly improving the response to incidents. Typically, their use is that of emergency signaling devices, such as panic buttons or "man down" devices, which allow lone workers to signal an emergency quickly, simply, and effectively. However, these IoT devices also have the ability to transmit the position,

to communicate, and in some solutions to examine environmental conditions or the worker's physiological conditions. The same systems allow the employer or another designated worker to monitor the activity of lone workers in real time, in order to occur in case of need.

2 Methodology

Regardless of the implementation, all wearable IoT solutions for safety are based on two fundamental concepts: communication and localization. A review of the technologies and hardware and software solutions that implement these systems is shown in many popular articles[9,10,11,12].

Communication is essential to ensure that the lone worker can signal an emergency quickly and effectively. Through wearable devices or portable devices, equipped with cellular, radio, or other types of connectivity, the worker can send manual or automatic alarms in case of danger. These alarms can be displayed in a SCC (safety control center) that can alert the rescuers. In addition, two-way communication allows you to check the worker's status and provide clear instructions in case of need or to provide visual, acoustic, or vibrating warnings to alert them in case of danger. In some work contexts, it is not always possible to have a simple communication channel available: for example, consider areas outside the coverage of cellular communication or work situations in confined spaces or underground areas. Technology, even in this case, is able to provide alternative solutions that allow the worker to remain connected.

Localization is equally important, as it allows you to precisely locate the position of the worker in difficulty. Thanks to RTLS (Real Time Location System) technologies such as GNSS, RFID, UWB or BLE, it is possible to know the worker's position within a work area and generate detailed maps of their position. In case of emergency, this information is crucial to organize rescue operations promptly and direct teams to the exact point where the worker is located.

IoT technologies also offer numerous possibilities to improve the safety of lone workers, in addition to those mentioned. Sensors integrated into devices can detect operating conditions (e.g., falls from heights, prolonged immobility, collisions, etc.), physiological parameters (e.g. heart rate, respiratory rate) or environmental parameters (e.g. toxic gases, noise levels) and send alerts in case of anomalies. As mentioned, communication can be bidirectional, and it is possible to communicate to the operator that the safety conditions have changed in the area where they are located.

Cloud-based monitoring solutions offer numerous advantages for monitoring lone workers through IoT devices. First of all, they allow for centralized and real-time data collection, facilitating the management and analysis of information. The immediacy of the geospatial visualization of the worker allows for rapid decision support to coordinate the rescue intervention. Moreover, cloud solutions offer scalability,

allowing the management of a growing number of devices and users but also to coordinate and manage different safety operations centers with the same approach and shared data. Finally, thanks to their flexibility, they adapt to different operational needs and guarantee secure and remote access to data from any device connected to the Internet, even on the move during the rescue phase.
With a centralized and historical cloud approach, it is also possible to use artificial intelligence tools that can be used to analyze the collected data and provide useful information to manage potential hazards, suggest the best intervention methods, produce intelligent reporting and highlight latent situations. This allows for proactive intervention and specific improvement of safety equipment and operating environments.
The integration of advanced digital solutions represents a fundamental step towards improving the safety of lone workers, reducing the number of accidents and guaranteeing a safer and more protected working environment. The continuous evolution of safety technologies and their implementation in company policies are essential to face future challenges and promote a culture of safety at work.

3 Project Approach

The primary objective of this project is to introduce a solution for lone worker in a highly heterogeneous operational context, mainly related to maintenance and inspection activities. The focus was on utility companies providing services for the production and distribution of energy, water, and gas, as well as environmental services such as waste disposal and treatment.
The project considered 10 different types of activities representing approximately 4000 operators working in isolation for a society of services across the national territory (Italy). These activities take place in over 100 different types of industrial plants, as well as in urban environments, mountainous, and rural areas. The goal is to provide a large-scale, user-friendly, and unique solution for connection and localization, despite the characteristics of each work situation. The studied version implements man-down and voluntary SOS functions with indoor and outdoor localization capability, and provides a monitoring, support, and communication system in case of an incident. The control center is based on a cloud platform and a web-based interface.
This context highlights a real large-scale situation where isolated workers face not only known specific risks but also unknown situations (such as activities in environmental contexts), aggravated by isolation. The aspect of isolation is fundamental. Some work situations may have a relatively low level of risk but may involve difficult or even absent communication conditions, which significantly impact worker safety. This situation is more widespread in the workplace than daily perception may suggest. Some situations of lack of GSM signal may be typical of confined spaces or underground area, such as heat exchange substations, valve

chambers, gas network decompression chambers, BT/MT transformer substations, basements, inspection tunnels, etc. Other situations may not be covered by a telephone network or may not be reliably covered, such as in mountainous areas or in rural areas far from inhabited centers. In these cases, it is necessary to provide other communication systems at workers.

In the project presented here, the operational cases of personnel involved in isolated activities were analyzed, and four macro-operational conditions were identified:

- Isolated workers performing outdoor activities in areas covered by GSM connectivity and GNSS coverage.
- Isolated workers performing outdoor activities in areas where GSM connectivity is not guaranteed but GNSS coverage is guaranteed.
- Isolated workers performing occasional activities in industrial plants where GSM connectivity and GNSS coverage are only guaranteed outside of them.
- Isolated workers performing continuous activities in areas equipped with a connectivity infrastructure (presence of GSM, Wi-Fi, and/or LoRa coverage) but GNSS coverage is not guaranteed.

For each of these categories, the most suitable localization and communication technology solutions were analyzed among those available and applicable.

During the analysis of the conditions, it was necessary to delve into certain characteristics such as the size of the environments to be monitored in plant activities and the frequency of intervention in different types of sites. For the problems related to the size of the plant, considerations were made on large plants such as thermal or hydroelectric power plants, medium-sized plants, and small plants such as electrical substation cabins, while for the frequency of intervention, activities were considered in two classes that identify continuous activities, typically where there are isolated workers who man structures, and occasional activities, such as inspection or maintenance of autonomous plants.

In addition to these considerations based on work activity and the operating environment, which are focused primarily on communication and localization requirements, the specific risks involving the work sites and that influence the requirements of the solution were also taken into consideration. In particular, among these requirements, the operating conditions in ATEX environments are the most stringent, but also reliability in difficult environmental conditions, such as extreme temperatures or dusty environments, is fundamental.

Finally, in the analysis, in addition to technical factors, those that impact the use of these devices were also considered. For these devices to be truly effective, it is essential that they be intuitive and easy to use, even for those who are not very familiar with technology. Usability is a crucial aspect: the worker must be able to activate the emergency function with a simple and quick gesture, without having to consult manuals or complex configurations. Studies have shown that the human

factor in the correct use of wearable devices has a very high impact on the effectiveness of such devices[13].
In addition to this, it is essential that the worker feels safe and protected thanks to this tool, and does not perceive the device as an additional constraint. Ultimately, the goal is to create a device that becomes a true ally for the worker, guaranteeing their safety without compromising their operativity.

4 Solution

Previous study led to the next phase of the project with the definition of the optimal technological solution capable of meet all the requirements. The result is a solution based on a family of devices designed to interact and adapt to various working conditions. This family consists of:

- Wearable device
- Fixed infrastructure
- Mobile infrastructure

The wearable device is the device issued to the operator that is carried on is belt during their solitary work activities. It is the means by which the worker remains connected and that monitors falls or anomalous working conditions, as well as allowing the simple sending of a SOS voluntary call. The adopted solution is rechargeable, based on mobile networks connectivity, and uses BLE communication for indoor localization and GNSS for outdoor localization.
The fixed infrastructure refers to the technological solution for localization and communication adopted on sites or plants that do not natively have these capabilities due to their intrinsic characteristics. Typically, these are indoor situations with or without the possibility of mobile networks coverage that involve the continuous or semi-continuous presence of isolated workers. This infrastructure communicates with the wearable device and forms the spatial references associated with the localization called "anchors". In their simplest version, they are battery-powered beacons with BLE connectivity that allow for optimized battery management. In the more advanced version, these anchors can also act as a communication channel and convey the alarm signal to the outside area where there is an active communication system.
The mobile infrastructure is conceptually a novelty compared to conventional IoT approaches and serves to cover intermediate situations where it is not possible, or does not make sense, to implement fixed infrastructure or where conventional communication channels are not available. The implemented mobile infrastructure is a small transportable box that allows to expand the communication capabilities of the wearable device acting as a bridge to different communication systems such as Satellite, LoRa, but also Wi-Fi or latest generation mobile networks. The box generates a micro-network where wearable devices can connect and allows to convey message traffic to the communication channels among those available. The box also allows to

manage localization since equipped with GNSS it can provide information about its position operating, for example, outside a structure and remaining connected with the devices inside. To make the mobile infrastructure even more flexible it is possible to use extenders, devices similar to the wearable ones but with a mesh network function. These allow to create a connection throughout the work activity suitable for the specific intervention situation as it is completely mobile and self-configuring leaving during the work phase intermediate nodes that maintain communication. At the end of the work, both the mesh nodes and the mobile box can be removed and used in the next activity. The mobile infrastructure allows to easily solve two important operational problems using the same wearable device issued to the worker: it allows to provide support for solitary work operations in those sites where activities are rare or very sporadic to justify a fixed infrastructure; it allows to remain connected even in isolated operating conditions where there is no cellular coverage but where it is possible to exploit other communication systems.
Thanks to a highly configurable cloud platform, it is possible to collect and analyze data from devices and gather all related events. The platform generates reports and monitoring dashboards, integrates with enterprise systems, and allows for event analysis. Key figures such as health and safety managers can thus obtain a complete overview of events, easily identifying areas that require greater attention and promoting continuous improvement of safety conditions.

5 Conclusion

The proposed devices represent a valid solution for lone workers and become part of a broader family of solutions that use technology to reduce accidents and minimize their impact, placing the worker and his safety on site at the center of a new technology-based safety paradigm[14].
Within this family, systems such as geofencing, anti-collision systems, localization and monitoring systems, access control systems, and personal protective equipment (PPE) monitoring systems provide workers and managers with new and powerful tools for safety.
The integration of IoT technologies in the safety of isolated workers represents a significant step forward in the protection of occupational health and safety. Thanks to real-time monitoring, automatic alarms and precise localization, these systems are destined to revolutionize the way we protect workers who operate in solitude. With the continuous evolution of technology, we can expect even more sophisticated solutions capable not only of detecting emergencies, but also of predicting potential hazards and offering proactive interventions. The future of isolated worker safety is based on the ever closer integration of IoT devices, artificial intelligence, and advanced analytics to create intelligent and adaptable safety systems.

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Technological Innovation for Improving Electrical Safety: An Implemented Case in Paraguay

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Abstract
This article discusses the creation and implementation of SMARTLAB, an initiative aimed at enhancing electrical safety in Paraguay through a Laboratory for Testing Electrical Products and an Organism for the Inspection of Electrical Installations, carried out by a private company. Supported by the Inter-American Development Bank and Paraguay's National Council of Science and Technology, this initiative addresses critical needs within the sector, improving product quality and compliance with safety regulations. The article suggests that this collaboration and funding model could serve as a reference for other companies aiming to integrate technological advances into their processes, detailing the approach and considerations based on this experience.

1 Introduction

The Paraguayan Electrical Sector is one of the newest in Latin America [1]. In its short development time, it has not evolved at the same pace as other countries in the region, presenting significant challenges in terms of safety and quality concerning both specialized labor and products used in electrical installations. Currently, there is only one accredited laboratory for testing electrical products in the country, as certified by the National Accreditation Body [2], which limits the capacity for product testing and certification. On the other hand, the sector is making progress regarding the inspection of electrical installations, thanks to Law No. 5668/16 on "Verification and Control of Quality and Safety of Products and Services in Electrical Installations."
In this context, *Intec Ingeniería S.A.E.* aims to incorporate new technological capabilities to introduce urgent and necessary services for the electrical sector through the creation of a Laboratory for Testing Electrical Products and an Organism for Inspection of Electrical Installations within a Technological Development Center.
Considering that such a project requires considerable financial effort, the company applied for funding through the National Council of Science and Technology (NCST), via its Innovation Program for Paraguayan Companies – PROINNOVA, which is financed by the Inter-American Development Bank (IDB). This program aims to improve the productivity of the Paraguayan economy by promoting investment in applied research and innovation and increasing the quantity and quality of advanced human capital for innovation [3]. Awarded projects can access non-reimbursable

resources of up to USD 250,000 and must contribute at least 20% of the total project amount.
This article describes the creation and implementation of a Laboratory for Testing Electrical Products and an Organism for Inspection of Electrical Installations in Paraguay. It details the process, including equipment acquisition, consultancies for implementing the ISO/IEC 17020 and ISO/IEC 17025 standards, and personnel training. The work highlights the crucial role of international funding in developing infrastructure, human capital, and technological innovation to improve, in this case, the country's electrical safety.

2 Theoretical Framework

Paraguay is a country with a notable production of 100% renewable electric energy, coming from the *Acaray*, *Itaipú*, and *Yacyretá* hydroelectric plants. In contrast, the infrastructure for electrical safety faces substantial limitations, as evidenced by the number of electrical accidents that have occurred so far in 2024, resulting in an alarming number of 81 electrocution deaths by October [4]. This situation, a product of historic delays in implementing technical standards and best practices due to a lack of training and infrastructure, highlights the urgent need to strengthen supervision of electrical installations and create new testing laboratories.

2.1 Brief Historical Overview of the Paraguayan Electrical Sector

After the devastating War of the Triple Alliance (1865-1870), Paraguay was left with a decimated population, a destroyed economy, and ravaged territory. The initial reconstruction largely depended on foreign investment, which propelled the early steps of the electrical sector. Italian doctor Silvio Andreuzzi, the first electric light concessionaire (1890), abandoned the country following a series of failed business initiatives. Subsequent concessions, such as those granted to the American company "Asuncion Traction and Electric Company" (1900) and Gatti y Lloret (1903), were affected by legislative instability. Salvador Terrizzi's (1904) proposal to use alcohol for public lighting, although accepted, delayed the adoption of electric public lighting. In 1910, a law was passed granting concessions for the construction of electric trams and plants, awarded to Italian engineer Juan Carosio. Between 1910 and 1913, Carosio built a thermoelectric plant with a maximum voltage of 6,000 volts and a capacity of 7,000 kilowatts in *Puerto Sajonia*, and inaugurated the first electric tram in Asunción. After transferring his rights to the English company "The Asuncion Tramway Light and Power Company Limited," Carosio regained them in 1919 as president of the "American Light and Traction Company" (ALTC), a corporation with Argentine and Swiss capital [5].
The nationalization of the ALTC in 1948, which gave rise to the *Administración Nacional de Electricidad*[1] (ANDE), marked a turning point for the Paraguayan electrical sector.

[1] National Electricity Administration

The country's dependence on foreign technology and technical personnel from the former *Puerto Sajonia* plant became evident after their departure post-nationalization, leaving the country with a marked lack of technical capabilities. Starting in the 1960s, the growth of the sector accelerated with the construction of hydroelectric plants, beginning with *Acaray* (financed by the IDB, 1965-1968, 90,000 kilowatts, 220,000 volts). This momentum continued, thanks to the binational treaties with Brazil and Argentina, leading to the construction of the *Itaipú* (1975-1984, 14,000 megawatts) and *Yacyretá* (1983-1994, 3,200 megawatts) binational dams, respectively, marking a milestone in regional and global hydropower development.

The Paraguayan Electrical Sector is regulated by ANDE, established by Law 966 in 1964, which grants it a monopoly on the generation, transmission, distribution, and commercialization of electrical energy. ANDE conducted mandatory inspections of electrical installations until 1992, when its inspection department was disbanded, and this practice ceased.

In the regulatory framework, there is a large chronological difference compared to neighboring countries. In Brazil, the ABNT NBR 5410 Standard for Low Voltage Electrical Installations originated in 1914 with the publication of the Electrical Installations Code by the former General Lighting Inspectorate [6]. In Argentina, the *Asociación Electrotécnica Argentina*[2] (AEA) approved its first Regulation for Electrical Installations in 1924 [7]. In contrast, Paraguay took until 1971 to launch its Low Voltage Installations Regulation, and in 1996, the Paraguayan Standard for Low Voltage Electrical Installations NP 2 028 96 was created, drafted by the Technical Committee for Electricity CTN 02 and published by the *Instituto Nacional de Tecnología, Normalización y Metrología*[3] (INTN), using the same ANDE Regulation as a basis for its drafting. In April 2012, during the International Electrical Safety Symposium held in Asunción, it was agreed to reactivate CTN 02, leading to the updating of the standard in 2013, adopting IEC 60364. This event was coordinated by the Committee for Electricity of the International Social Security Association (ISSA), along with the Faculty of Engineering of the National University of Asunción and the Paraguayan German Chamber of Commerce and Industry.

2.2 Current Situation of the Paraguayan Electrical Sector

The National Institute of Technology, Standardization and Metrology, which has been the regulatory body for electrical safety at low voltage in Paraguay since 2016, is implementing control mechanisms to ensure safety in electrical installations throughout the country, as mandated by the World Trade Organization (WTO) and in accordance with National Law No. 5668/16. The INTN's Electrical Safety Directorate has made the necessary tools available to the public so that Inspection Organizations for Electrical Installations can carry out their activities. This has been the result of

[2] Argentine Electrotechnical Association

[3] National Institute of Technology, Standardization and Metrology

extensive management by the INTN, with the support of various stakeholders in the sector, including those from the business, union, academic, and public sectors.
With these advancements, the ability to conduct tests accurately and under international standards, such as ISO/IEC 17020, will not only enhance electrical safety but also complete a control loop, covering both the certification of electrical products and the verification of installations.

3 Project Description

Founded in 1989, *Intec Ingeniería S.A.E.* has extensive experience in electromechanical, electrical, civil, and road engineering projects, both in the public and private sectors. With the aim of diversifying its services, the company has decided to modernize its Technological Development Center, established in 2014, through the implementation of SMARTLAB, a business unit comprising a Laboratory for Testing Electrical Products and an Organism for the Inspection of Electrical Installations, which addresses the need to improve safety and quality in the Paraguayan electrical sector, strengthening its infrastructure.

3.1 Role of International Organizations

International collaboration has been fundamental for the development of this project. The support from the IDB, channeled through the National Council of Science and Technology of Paraguay and its program PROINNOVA, has been key to its success. This program, aligned with the National Policy for Science and Technology (2002) and the National Development Plan 2014-2030, seeks to improve Paraguayan economic productivity by promoting innovation and the development of human capital. The IDB loan (No. 3602/OC-PR) of USD 10 million offers a maximum of USD 250,000 in non-reimbursable resources for each proponent.
Within the PROINNOVA Program, there is a call for Technological Service Strengthening Projects, which is aimed at universities, technological centers, or research centers located in the country, that have links with the productive sector. The project presented by *Intec Ingeniería S.A.E.* is titled *"Modernization and Strengthening of the Intec Technological Development Center for the Electric Industrial Sector"* and was awarded with code SERT20-68 in 2021. This international collaboration has been crucial for the creation of technological infrastructure and the start-up of this project. It has enabled the acquisition of state-of-the-art equipment, the implementation of a Quality Management System, and personnel training, contributing to strengthening the country's electrical sector and improving its global competitiveness.

3.2 Laboratory for Testing Electrical Products

The laboratory is equipped with state-of-the-art technology for testing electrical products, ensuring compliance with quality and safety standards. This advanced equipment enables a wide range of tests, including resistance and durability

assessments. The laboratory's primary goal is to guarantee that only products meeting stringent safety standards enter the market, thus minimizing risks associated with defects. Initially, the laboratory can test cables (Fig. 1) and sockets using 41 pieces of equipment, facilitating 26 different tests, with potential for expansion in the future. Applicable standards for these tests include regional and local equivalents of IEC 60227, IEC 60811, and IEC 60884. Notable tests include electrical tests, requirements related to construction and dimensional characteristics, mechanical properties of insulation, hot deformation, thermal shock, water absorption, vertical burning, and others.

Fig. 1. Cable Flexibility Tester

Initially, the laboratory has three testing rooms that were arranged in such a way as to separate hot deformation tests, mechanical properties tests, and tests that require special conditions for measurements with analytical balances, profile projectors, among others. Additionally, a designated space was reserved for the growth of the laboratory, considering the next products to be tested. This will depend on the advancements of the INTN and the country's legislation regarding product certification.

3.3 Organism for Inspection of Electrical Installations

The Inspection Organism aims to supervise and certify electrical installations in the country. Equipped with advanced evaluation and diagnostic tools (Fig. 2), this organism ensures that electrical installations comply with established safety standards, reducing risks and enhancing safety. Inspections are conducted following strict protocols, supported by technologies that improve the precision and efficiency of the evaluation process. The tests are performed in three stages: Initial Inspection, Intermediate Inspection, and Final Inspection. The equipment acquired in this project is used to carry out the tests for the final inspection, including the continuity test of protective earth conductors (PE) and the main and complementary equipotential bonding, insulation resistance of the electrical conductors presents in the electrical installation, insulation resistance of parts of the installation, automatic disconnection of supply, and measurement of earth resistance. This advancement places the

company among the first Inspection Organisms authorized by the INTN to operate in the market [8], marking an important milestone in strengthening electrical safety in Paraguay.

Fig. 2. Testing equipment for Inspection of Electrical Installations

3.4 Staff Training and Quality Management System

To ensure the effective operation of both components, detailed training of the staff has been conducted on the international standards ISO/IEC 17020 and ISO/IEC 17025. This training guarantees that the technical team is fully capable of conducting tests and inspections with maximum precision and compliance. Additionally, an integrated quality management system based on both standards has been implemented, ensuring that processes are consistent and reliable across all operations of the laboratory and the inspection organism. This system helps maintain high standards of quality and continuous improvement, in view of accreditation by national and international bodies.

4 Methodology

The methodology employed for the development of the project was based on the Execution Guide of the Program PROINNOVA. This regulatory framework structured the project into three phases: initiation, execution, and closure. The initiation phase covered project application and approval, contract signing, and the transfer of allocated resources. The execution phase, the most extensive, included the periodic submission of progress and final technical reports detailing the activities carried out, the results obtained, and the corresponding verification methods. Specific procedures for accountability were established, including the delivery of the necessary documentation (invoices, receipts, etc.) and an internal audit report for public institutions. Protocols for procurement management were defined, covering different methods based on the type of goods or services (individual consultancies, contracting works, purchasing equipment, etc.). Project monitoring and evaluation were carried out using the Instrument Application System of the National Council of Science and Technology, with periodic reviews by the technical team. The closure phase included the submission of the final report, the final accountability, and the

return of unused funds. Adherence to the practices outlined in this guide ensured proper management and administration of resources, transparency, and the project's success.

4.1 Planning and Execution

The methodology applied to the project began with meticulous planning that included a thorough analysis of the needs and opportunities present in the electrical sector of Paraguay. Consultations were held with key stakeholders in the sector, including electrical companies, unions, governmental organizations, and academic institutions, which allowed for the identification of existing gaps in safety and quality in the services and products used in electrical installations.

After this initial phase, specific project objectives were outlined, including the establishment of the Laboratory for Testing Electrical Products and the Organism for the Inspection of Electrical Installations, now known as SMARTLAB. Detailed timelines were developed that established the project's phases, necessary resources, and assignment of responsibilities. This meticulous planning facilitated the management of the various activities, ensuring that all areas were aligned with the project objectives.

The execution of the project was carried out in phases, starting with the acquisition of laboratory equipment and inspection tools. These acquisitions were made following technical and regulatory criteria, ensuring that the equipment met international standards while adhering to the Procurement Policies for Projects Financed by the IDB: GN 2349/9 for the acquisition of Goods and Works, GN 2350/9 for the selection and contracting of Consultants [9].

Most of the laboratory equipment has been acquired from international suppliers due to the unavailability of these items within the country. They needed to meet the technical specifications required through a bidding process launched by *Intec Ingeniería S.A.E.*, in accordance with IDB policy. Simultaneously, during the importation period, the necessary infrastructure was built to house the Laboratory and the Inspection Organism, adapting workspaces to promote operational efficiency and safety.

4.2 Technologies Used

Within this approach, equipment with automated testing and analysis technologies was incorporated into the Laboratory for Testing Electrical Products. These technologies include advanced systems that allow for various evaluations, such as electrical resistance measurements and durability and reliability analyses of products. Automation not only increases the precision of the tests, avoiding human error in automated processes, but also optimizes the time required to complete the tests, allowing the laboratory to handle a greater volume of requests.

Furthermore, the Inspection Organism implemented advanced diagnostic and evaluation equipment to facilitate the verification of compliance with safety

standards in electrical installations. The acquisition of these equipment was based on the Guide for the Inspection of Low Voltage Electrical Installations [10], which stipulates the mandatory tests to be conducted in the inspection processes.
In summary, the combination of strategic planning and the implementation of cutting-edge technologies has been fundamental to the success of the project, preparing SMARTLAB to effectively face the challenges in electrical safety and helping to position the company as a benchmark in the electrical sector in Paraguay.

5 Expected Results

Although improvements cannot yet be quantified as SMARTLAB is currently in the implementation phase, these new capabilities are expected to reduce risks associated with electrical failures in installations and enhance the overall quality of products and services available to consumers. This project, which includes a Laboratory for Testing Electrical Products and an Organism for the Inspection of Electrical Installations, is expected to have an impact on electrical safety in Paraguay.
One of the key outcomes will be the improvement in the quality and safety of electrical products in the market, which will drastically reduce the number of defective or unsafe products. Additionally, the establishment of a new testing laboratory will expand the market offer, favoring competition and improving prices for consumers. This, in turn, will reduce costs for manufacturers seeking certification for their products, considering that currently, there is only one accredited laboratory for testing electrical products in the country.
Moreover, the presence of an active inspection organization will allow for constant evaluation of electrical installations, ensuring compliance with safety regulations. This will result in a notable reduction of risks associated with electrical failures, helping to prevent serious or fatal accidents and fires. The supervision and certification capacity offered by SMARTLAB will strengthen consumer confidence in the safety of installed electrical systems, a critical need in a context of growing concern for electrical safety.

6 Analysis and Discussion

The significance of SMARTLAB in the electrical sector cannot be overstated, as it accompanies the reestablishment of electrical inspections in Paraguay after a pause since 1992. This initiative is a crucial step toward enhancing safety standards and compliance for electrical installations, addressing a long-standing gap in the sector.
This project represents a major advancement for the electrical sector in Paraguay, but it has also faced various obstacles. Among the main challenges were the planning of activities, considering procurement timelines and the climatic conditions associated with imports. Communication with manufacturers also presented challenges due to time zone differences and language barriers, which necessitated a detailed analysis of suppliers to establish trust in the products acquired.
A key element in this process was the practice of documenting each step taken, which ensures transparency and serves as a reference for future projects. Additionally,

since this involved external funding, compliance with the requirements set by the funding entity has been a top priority. This entailed a rigorous reading and understanding of these demands to guarantee the success of the process.
The lessons learned indicate that in future projects, a comprehensive analysis of the time required should be conducted prior to application. Additionally, it would be beneficial to reduce the number of planned activities. Strengthening communication channels with suppliers is also advisable to mitigate potential challenges related to time zones and language. These are just some of the important considerations that should be considered for effectively developing such projects.

7 Conclusions

The creation of SMARTLAB, which includes a Laboratory for Testing Electrical Products and an Organism for the Inspection of Electrical Installations, marks a pivotal moment in enhancing electrical safety in Paraguay. This project not only fosters the growth of the Paraguayan electrical sector, which is currently facing significant needs and urgencies due to developmental delays but also addresses the pressing requirement for a more robust regulatory framework in a sector undergoing serious challenges.
By establishing the foundations for a safer and more efficient use of electrical energy, this project is anticipated to have a substantial positive impact on the industry. This initiative will reduce the risks associated with defective electrical products and ensure compliance with safety regulations for installations, thereby potentially transforming the landscape of electrical safety in the country.
In particular, the expansion of service offerings through the new testing laboratory will benefit manufacturers and consumers alike by facilitating more affordable access to certification. Additionally, the creation of a supportive innovation ecosystem, fostered by the National Council of Science and Technology and embraced by adaptive companies, underscores the collaborative effort needed to address the country's developmental challenges.
Moreover, the successful implementation of this initiative rests on the proper training of personnel and a commitment to a quality management system that integrates the ISO/IEC 17020 and ISO/IEC 17025 standards. This dual focus will ensure that it not only meets its immediate objectives but also remains relevant amid ongoing technological and regulatory evolution.
Ultimately, the proactive approach to managing electrical safety from this initiative will foster a culture of prevention and awareness in Paraguay. Additionally, the project's success may serve as a model for other countries in the region, emphasizing the importance of investment in innovation and collaboration among public and private stakeholders. International funding has been essential for realizing the project’s vision and improving infrastructure and technical capacity. Consequently, SMARTLAB is poised to enhance electrical safety and act as a catalyst for sustainable development in the region's electrical industry.

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Machinery regulation and remanufacturing: a link between machinery safety and sustainability

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Abstract
On June 14, 2023, the European Parliament adopted Regulation (EU) 2023/1230 on Machinery, which came into force on July 19, 2023, and will apply from January 20, 2027, replacing the Machinery Directive 2006/42/EC. The main innovative elements introduced by the Machinery Regulation (MR) compared to the Machinery Directive (MD) are critically analysed here, with a focus on those related to the concept of sustainability. Some of these issues are covered by various international standards (such as BS 8887, ISO 10987, or DIN 91472), which also define the criteria and requirements for the remanufacturing process, although some technical gaps remain. Using the example of agricultural machinery, this paper proposes a methodology to determine the areas of acceptability for remanufactured products; these are expressed in terms of: performance, functional, and safety requirements of the original machine. In this way, the issue of "substantial modification of machinery," already implicit in the MD and made explicit in the MR, is explored in terms of the safety obligations that remanufactured machines must meet. The paper thus contributes to circular design by providing general criteria for extending the useful life of machinery, while also addressing safety issues.

1 Introduction

On June 14, 2023, the European Parliament and the Council formally adopted and published the new Regulation (EU) 2023/1230 on machinery (the Machinery Regulation, MR), which will be applicable starting January 20, 2027. The new MR repeals the Machinery Directive (MD) 2006/42/EC and transforms it into a regulation, directly applicable in the same way across all Member States upon its entry into force, eliminating any modifications or different interpretations by Member States, thereby removing ambiguities in its transposition, increasing legal certainty, and eliminating trade barriers for machinery between Member States.
Despite this, the MR, like the MD before it, contains a series of references to harmonized technical standards to provide a more practical guide for designers in creating a “safe” machine. These technical standards offer designers a highly useful guideline for solving the various design issues (how) posed by meeting the various

requirements (what), which are described in general (but not vague) terms. The MR is an evolution of the MD and clarifies several concepts that were implicit in the MD or required proper interpretation, reflecting developments in the field over the past two decades. One of these concepts is that of “Substantial Modification”, which in this work is analysed from a remanufacturing perspective, interpreted and understood from a mechanical design standpoint. The regulation defines a modification as substantial if it affects the machine’s safety level. In such cases, the regulation mandates the addition of devices or protective measures to restore the machine’s safety levels. When this definition is applied in the context of Remanufacturing, safety levels must be evaluated through an accurate assessment of the condition of the components, allowing their structural performance to be compared with that of an equivalent new component.
The paper is structured as follows: in §1 there is an introduction about Remanufacturing – from both process and product design perspective – and the Machinery Regulation, delves into the concept of substantial modification along with the interpretation provided by the sector's regulations concerning the “as-new” condition; in §2, the methodological framework for evaluating the usability conditions of a remanufactured component is proposed and organized, based on the required structural performance; in §3 conclusions and further developments are discussed.

1.1 Remanufacturing

Sustainable development plays a primary role in national and EU policies. The European Union has approved the Climate Law, aiming to reduce greenhouse gas emissions by at least 55% by 2030 and achieve climate neutrality by 2050. As outlined in the “European Green Deal: Circular and Climate-Neutral Manufacturing” and the “2030 Agenda for Sustainable Development,” the economic and environmental sustainability of manufacturing must be achieved through technological enhancement and the transition of the manufacturing/production sector towards genuinely circular models, characterized by environmental neutrality and minimized dependence on natural resources [1]. In this context, remanufacturing plays a crucial role as a strategy for minimizing the environmental impact of the production cycle of goods and contributing to the gradual shift from linear to circular production [2]. For this purpose, a more robust regulatory and directive framework is indispensable. An industrial regulatory system that is both cross-cutting and sector-specific, with unified guidelines, can increase business opportunities, ensure the quality and safety of remanufactured products, and, in turn, foster consumer confidence. Without standardization, remanufacturing (and, more generally, the second-life use of structural components) will not be able to fully exploit its theoretical potential, which, according to European Remanufacturing Network forecasts, is expected to triple by 2030, reaching an overall value of 100 billion euros in Europe, while remaining confined solely to the aftermarket and used parts sectors [3].

1.1.1 Definitions

There are numerous definitions of remanufacturing. Essentially, these definitions describe a process in which a product, having reached the end of its life cycle, is recovered and reintroduced into an industrial process aimed at restoring its functionality, performance, and reliability to a level equal to or even greater than that of an equivalent new product, and then reintroduced to the market with a warranty that is at least equivalent to that of the original product. This is achievable because, unlike other practices such as reconditioning, repair, and reuse, remanufacturing requires the complete disassembly of a product and the verification of each of its components before it is reassembled.

In the Table 2 remanufacturing definitions provided by the main industry standards will be reported.

1.1.2 The Process: Phases and Requirements

For these definitions to materialize, it is necessary for a product, once it has reached the end of its life cycle and has been recovered, to undergo a series of operations. The exact type and sequence of phases will naturally depend on the type of object being processed. However, particularly in the case of mechanical systems, a remanufacturing process can be generalized according to the following phases, as shown in Figure 1 [4]:

(1) Identification and Sorting: The recovered cores are registered to determine their product identity and overall quality level.
(2) Disassembly: This involves breaking down a complex product into all its individual parts, enabling all subsequent operations.
(3) Washing and Cleaning: The disassembled components are cleaned of foreign substances accumulated during their use.
(4) Inspection: Components that continue through the process are analysed using visual inspections or non-destructive testing to assess their condition.
(5) Restoration: This phase involves components that require the restoration of specific properties and specifications. The main operations include general repairs, surface grinding and finishing, restoration of geometries, and removal of surface cracks.
(6) Reassembly: Recovered and restored components are integrated with new parts and pass through the entire assembly line as a new product.
(7) Functional Testing: The finished and assembled product undergoes functional testing to ensure that the reassembled components operate correctly and that the performance of the assembly matches that of a new product.

Fig. 1. The Remanufacturing Process of a Mechanical Product

1.1.3 Design for Remanufacturing

To enable such a sustainable and circular industrial model, products must be designed with circularity in mind. Successful remanufacturing relies on criteria such as the availability of technology to restore the product, interchangeable standard parts, and a favourable cost structure relative to savings [5]. Nick Morley's model (2006) highlights three factors affecting remanufacturing feasibility: the intrinsic value of the components, the rate of product evolution, and recoverability [6-7]. Design plays a critical role, impacting product evolution and reconstruction potential. Slow technological change, durability over multiple lifecycles, and a long lifespan make products suitable for remanufacturing, which the Automotive Parts Remanufacturing Association endorses [8]. Following these considerations about product aspects integrated into design for remanufacturing, it is essential to emphasize a concept related to the goals of this practice from a machinery construction perspective. It is clear that the success of remanufacturing is closely linked to a product's ability to endure over time. This capability, given that technological interventions are not always possible, strongly depends on the sizing and material selection made during the initial design phase. What appears to be missing within the current scientific, industrial, and regulatory landscape on this topic is the ability to assign to a component/product, which has reached a certain point in its first useful life, a classification or designation for second use based on its operating conditions, design technique, and reliability and safety requirements. Design for Remanufacturing (DfRem) should be interpreted, among other things, as a technical practice capable of determining the suitability of an existing component that has already undergone operational use. This suitability of a machinery can be assessed with criteria applicable both to existing components and to future product developments, and it must not compromise its safety, which remains the foremost priority for manufacturers for meeting the safety certification requirements imposed by regulations.

1.2 European Regulatory and Directive Framework

In this work, environmental sustainability and safety of machinery are addressed from the perspective of mechanical construction and design. Both aspects are primarily discussed here with a regulatory approach, referencing standards and

directives, to highlight gaps or points of intersection on which to develop the proposals presented in this article.

1.2.1 The Substantial Modification in the MD and MR

The principle of "substantial modification of machinery" is implicitly present in the current MD. According to the guide for the application of the MD [9], the MD also applies to machines based on used machinery that have been transformed or rebuilt so substantially as to be considered new machines. Furthermore, any modifications made to a new machine, even before it is put into service, if substantial (e.g., a modification of the machine's function and/or performance), and not foreseen or agreed upon with the manufacturer, will result in the invalidation of the original CE marking. The entity that made these modifications must therefore carry out a new risk assessment in accordance with the MD regarding the changes made [10]. It is therefore clear that the introduction of a "substantial modification" to a machine results in such a change that the machine is considered as if it were a new machine, and thus subject to a new conformity assessment under the MD. The new MR clarifies and explicitly defines the concept of "substantial modification" and what it entails in relation to risk assessment and the resulting obligations. The definition of "substantial modification" is provided in point 16 of Article 3 of the MR as follows: *A modification of a machine or related product, by physical or digital means, after such machine or related product has been placed on the market or put into service, which is not foreseen or planned by the manufacturer, and which impacts the safety of the machine or related product by creating a new hazard or increasing an existing risk, and that requires*:

a) *the addition of guards or protective devices to the machine or related product, an operation that necessitates modification of the existing safety control system, or*
b) *the adoption of supplementary protective measures to ensure the stability or mechanical strength of such machine or related product.*

The objective is to ensure that the machine or related product affected by the substantial modification complies, in all cases, with the applicable essential safety requirements [11].

For instance, EHSR 1.3.2 Risk of break-up during operation, in Annex III of MR, establishes and clarifies a fundamental principle: the risk of failure of a structural component is associated with a potential safety hazard. Therefore, the design of a machine must ensure that the required structural performance for the specific application is met, even for the second life application.

1.2.2 Functionality, Performance, and Warranty of the Remanufactured Product: The "As New" Condition

The premise of this study is that, from an engineering perspective, a remanufactured product/component, or more generally one in its second life, to be considered equivalent to a new product, must guarantee, for at least a second (or generally n-th) life cycle, performance that is:

- For the same application: at least equal to the equivalent new component in terms of efficiency and reliability for at least the same duration as the first service life (the service life estimated during the design phase, not the actual service life, which will depend on real conditions).
- For "downgraded" applications: at least equal, again in terms of efficiency and reliability, to a new product/component for the new application for which it is intended.

Based on these considerations, Table 1 presents the interpretations and guidelines provided by the main technical standards (some of which have already been mentioned) in the field of remanufacturing at the international level, concerning the interpretation and guidelines for the "*As New*" condition.

Standard	"As New" Definition	Criteria
BS 8887-220:2010 [12]	The Remanufacturing process must transform a used product into an "as-new" product, with performance and warranty at least equivalent to a new one, including and detailing the various process phases to be followed and the component treatment options to restore its "as-new" condition: Functional remediation, Cosmetic remediation or Replacement.	The proposed criterion for verifying the performance of the component/product is through an inspection and functional testing during the process.
DIN SPEC 91472:2023-06 [13]	Remanufacturing in the highest quality value-retention process at the component level. The product of such a process is considered new and has at least the same functionality and performance as the original product. A remanufactured product always comes with a standard market warranty and can be composed of restored components from different used parts as well as new components.	The criterion for a product to be considered "As New" with, is that the product has undergone all the phases of the process described in the standard itself.

ISO 10987:2 – 2017 [14]	A remanufactured product is one that, after undergoing the process, is restored to a "like new" or "better than new" condition in terms of both quality and performance. The remanufacturer must ensure that all safety improvement programs have been completed.	No criteria are defined to establish the performance and quality level of an item.

Table 1. "*As New*" definition in the main Remanufacturing Standards

The critical issue observed and highlighted in this study is that, although the regulations and standards on remanufacturing agree that a product undergoing such a process should and can be considered as new, there are fewer guidelines on the criteria to be adopted for verifying this condition: once again, the "what" is specified, but not the "how." Moreover, there is no indication of the performance criteria being referenced, and one might question whether structural performance can always be verified through inspection or non-destructive testing. In relation to the structural performance of the components within an assembly, it is also fair to ask whether ensuring the quality and performance of the product/component can be achieved merely by demonstrating and assuring compliance with the process. In the absence of predefined technical requirements and acceptance criteria for components, the "As New" condition of the remanufacturing process seems to be taken as an assumption: how, then, can the safety level of a remanufactured product be scientifically established without precisely knowing the condition of its components? Although the current regulatory framework, as formulated, may be well-suited for verifying and satisfying requirements related to a product's functionality, it is deemed insufficient for addressing its structural requirements, as these are often not verifiable through non-destructive means. Given that the structural performance of a machine component (and, more generally, of a structural element) is intrinsically linked to safety, the following sections will propose an approach based on constructing acceptability domains for a mechanical element intended for remanufacturing. This approach will be based on the type of structural performance required and the criteria used during its design.

2 Proposed Methodology

The fundamental principles and calculation methodologies of design are encompassed within a comprehensive regulatory framework. For this study, reference was made to the Eurocodes, specifically to the standard EN 1990:2023 [15] and EN 1993 series [16], which describe the principles and requirements for safety, functionality, and durability of steel structures.

The first necessary step, in formulating a methodological framework for the evaluation and acceptability of mechanical components used in a second life, is to differentiate the performance of a product into functional and structural

categories. While the former ones (such as power, torque, energy efficiency, and so on) in almost all cases can be verified at the end of the assembly line through non-destructive functional tests, structural performance (related to failure prevention) cannot always be assessed. Structural performance is intrinsically linked to the safety of structures since the failure can result in hazardous conditions. For this class of performance, non-destructive testing techniques are limited in their ability to accurately determine the integrity of a used component at the time of its reuse in a remanufactured product. This technological limitation necessitates an evaluation criterion for residual capacity that considers the design model with which a given component was originally designed and, if possible, to determine the load history it experienced during its previous service life. For this reason, the proposed approach includes, as its second main element, the categorization of the structural performance of a generic structural component or machine element, along with the respective verification criteria, as reported in Table 2.

Performance			**Criteria**	**Standard**
Static Strength	**In the absence of damage**		$\sigma_{ED} \cdot \gamma_P \leq \frac{f_y}{\gamma_M}$	EN 1993 1-1
	In the presence of damage	SIF criterion	$K_I \leq K_{ICR}$	
		Energetic criterion	$\left\|\frac{dU}{da}\right\| \geq \frac{dW}{da}$	
Fatigue Strength	**Fracture Mechanics**	Paris Low	$\frac{da}{dN} = C(\Delta K)^m$ à $a \leq a_{cr}$	
	High-Cycle fatigue (*Stress Life*)		$\Delta\sigma_{E,2} \cdot \gamma_{Ff} \leq \frac{\Delta\sigma_L}{\gamma_{Mf}}$	EN 1993 1-9
	Cumulative Damage Fatigue	Palmgren-Miner Damage Model	$D_d = \sum_i \frac{n_{Ei}}{N_{Ei}} \leq 1$	
			$\Delta\sigma_{E,2} \cdot \gamma_{Ff} \leq \sqrt[m]{D_d} \cdot \frac{\Delta\sigma_C}{\gamma_{Mf}}$	
Surface Fatigue Resistance (Surface Shear Resistance)			$p_{max} = \frac{2F}{\pi bl} \leq S_c$	
Creep			$\varepsilon_{tot\ creep} \leq \varepsilon_{lim}$	ISO-899-1-2017
Instability			$N_{Ed} \leq N_{b,Rd} = \frac{\chi \cdot A \cdot f_y}{\gamma_{M1}}$	EN 1993 1-1
Structural Reliability			$p_f \leq p_{fmax}$	EN 1990

Table 2: Structural Performance and Respective Verification Criteria

The acceptability of a machine component, that has already undergone one life cycle, with respect to its potential reintegration into an assembly that will be defined as "Remanufactured," depends on its ability to meet both functional and structural requirements. Since requirements such as residual strength, service life (understood as the number of cycles before failure), and the reliability of an assembly depend on those of its individual parts, it follows that the "As New" definition must be satisfied by each individual part.

2.1 The Remanufactured Product: Classification, Characteristics and Design

When analysing the remanufactured product at the component level, in the broadest possible sense, it is an assembly composed of three categories of elements, whose definitions are presented in Table 3 [17]. This work focuses on the third category of components in the table, for which accumulated damage, due to technological, economic, or simply process-related reasons, may not be traceable. It should be noted that, in the context of remanufacturing, when a device replaces a new one and this device contains a component with accumulated damage in a structural part, this replacement represents, potentially, what the MR defines as a *substantial modification*, as it reduces the material's residual resistance capacity. In such cases, it is necessary to ensure that the machine's safety level is not compromised by the reused component.

Component	Description
New/Replaced	Single component which has had no prior life cycle
Restored	Single component, recovered from a non-new assembly, which has thus undergone at least one operational cycle, and subjected to any treatment aimed at restoring damage
Used/Reused	Single component, recovered from a non-new assembly, which has thus undergone at least one operational cycle. It is not subjected to any operation that alters its condition before being reintroduced into the assembly

Table 3. Categories of Components in a Remanufactured Product

The potential accumulation of damage in a mechanical component, and consequently its residual structural performance, depends on the way it was designed and falls into two main categories:

- **Infinite Life Design**. This category includes products or individual parts designed to last indefinitely under nominal operating conditions. These products are usually subjected to loads well below their maximum capacities to ensure long life and safety. For all such products, if the verification/design rule provided by the standard is valid for the initial use, and if all the parameters and variables of the

criterion remain unchanged over time (e.g., if the geometries and dimensions have not changed, there is no surface corrosion, and the chemical properties of the material have not changed), from an engineering standpoint, there is no reason to believe that the criterion would not be verified again in its second life with the same result. The semi-probabilistic approach used by the standards can still be valid for the verification of the second life cycle. If the result is positive, it ensures, by definition, infinite life under the given operating conditions.

- **Finite Life Design**. This category includes products designed for operating conditions where damage accumulation is unavoidable, or for which a specific number of load cycles or a defined period of use is expected before showing signs of deterioration or failure. A significant portion of mechanical applications inevitably leads to the degradation of residual properties (strength, number of cycles, reliability, etc.) of machine components. For this type of application, scientific literature models and standards (where available) help estimate the time-dependent decrease in residual properties, and the verifications (or design) will necessarily be valid within a certain finite time interval.

Since, under certain operating conditions, for $t \geq t_0$, the initial structural properties (in t_0) will necessarily decrease over time, to assert that a second-life component can have the same performance as a new one, it is advisable to establish thresholds that define *Acceptability Domains for Remanufacturing*, or more generally, for reuse. Expressing this concept qualitatively, conditions such as those presented in Table 4 can be utilized:

Condition of Structural Properties	**Acceptability Criterion**
$\sigma_{lim}(t_0) \geq \sigma_{lim}(t)$	$Acceptability\ Threshold \leq \frac{\sigma_{lim}(t)}{\sigma_{lim}(t_0)} \leq 1$
$N(t_0) \geq N(t)$	$Acceptability\ Threshold \leq \frac{N(t)}{N(t_0)} \leq 1$
$R(t_0) \geq R(t)$	$Acceptability\ Threshold \leq \frac{R(t)}{R(t_0)} \leq 1$

Table 4: Acceptability Domains Definition

Formalizing the issue of the suitability of structural components for reuse in this way allows for the consideration of all possible options that may occur at the industrial level concerning the origin or destination of a remanufactured item. In these scenarios, the numerator, which represents the residual capacity at a time greater than or equal to the time of commissioning, and the denominator, i.e., the residual capacity evaluated at the time of commissioning, take on values that fall within the cases presented in Table 6.

	Value
Numerator	Equal to the theoretical value expected if the component has operated within the intended operating conditions
	Different (either greater or lesser) from the value estimated during the design phase if it has operated outside the intended operating conditions
Denominator	Equal to the theoretical value estimated during the design phase for the operating conditions foreseen in the original application → like new original
	Equal to the theoretical value estimated during the design phase for the operating conditions foreseen for a different application → like new "downgraded"

Table 6: Possible case value

Such an approach, although demanding in terms of validation for identifying appropriate acceptability thresholds or their combinations, provides a high level of flexibility and specificity when evaluating individual cases based on specific applications.

3 Conclusions and Future Developments

Remanufacturing is confirmed as a key strategy for achieving the sustainability and climate neutrality goals set by the European Union. However, significant challenges remain in defining, especially at the regulatory level, clear technical criteria for assessing the structural capacity and related safety levels of structural components with at least one service life, particularly when it comes to ensuring their strength and reliability over time. Safety remains a priority and crucial aspect to be guaranteed when machinery is put into service, which is why the integration of remanufacturing practices with the requirements of the Machinery Regulation (MR) could form the basis for a solid regulatory framework that ensures remanufactured products not only comply with sustainability standards but also maintain safety levels equivalent to those of new products, thereby expanding the applicability potential of second-life components.

This paper highlights the need to develop methodologies for assessing structural performance based on design models, verification of technical standards and essential safety requirements. Approaching the issue of the second-life reuse of mechanical components in remanufacturing, damage accumulation requires criteria based on threshold definitions that establish Acceptability Domains, ensuring that remanufactured products fully meet functional and structural safety requirements. Looking ahead, the identification of precise and specific threshold values for individual applications and the standardization of a certification system that places safety at the centre of the remanufacturing process could further strengthen the confidence of companies, end consumers, and legislators in remanufacturing.

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