

RESEARCH ARTICLE

Sustainability Balance for ICT Infrastructures: A Time-Scale Analysis of the Dynamic Fourth Lane on the A4 Italian Motorway

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ABSTRACT This paper addresses the measurement of the environmental impact of Information and Communication Technology (ICT) infrastructures. The methodology used, aligned with ISO standards and guidelines for the expression of uncertainty in measurements (GUM), involves several steps. First, a checklist is prepared, encompassing all the elements necessary for the infrastructure's implementation, operation, and end-of-life stages. Then, the environmental impact of each element is modeled in terms of probability distributions, which, in the metrology framework, indicate the lack of complete knowledge about the *true* amount of emissions associated with the related element. The obtained distributions are aggregated through Monte Carlo simulations to yield an overall distribution of the infrastructure's environmental impact. Upon determining the resulting emissions, this paper presents the novel concept of the *Sustainability Balance*. This concept is introduced by comparing the emissions generated by the considered infrastructure with those mitigated through its use. This balance is critical for determining the actual environmental sustainability of the infrastructure. As a practical case study, this methodology is applied to a real and complex monitoring scenario, namely the *dynamic fourth lane* of the Italian A4 motorway, which represents a comprehensive example of an ICT infrastructure. The dynamic fourth lane allows the emergency lane to be used as an additional traffic lane based on traffic volume, thereby reducing congestion and emissions from idling vehicles. The obtained results highlight the potential for significant environmental benefits, demonstrating the effectiveness of the proposed methodology in evaluating and enhancing the sustainability of ICTs.

INDEX TERMS Agenda 2030, carbon footprint, environmental sustainability, ICT, LCA, measurements, measurement uncertainty, sustainability, sustainability measurements.

I. INTRODUCTION

In recent years, *Sustainability* has become a cornerstone concept, emphasizing the mindful and efficient management of available resources to ensure that the needs of future generations are not compromised by present-day practices [1]. This concept encompasses three interconnected dimensions,

The associate editor coordinating the review of this manuscript and approving it for publication was Ajit Khosla¹.

namely social, economic, and environmental, which are explicitly addressed within the *Sustainable Development Goals* outlined in the United Nations' *2030 Agenda* [2]. Among these dimensions, the environmental aspect is particularly critical due to the extensive exploitation of resources over the last century, which has led to a significant surge in greenhouse gas (GHG) emissions, widely recognized as the primary driver of the alarming increases in global land and sea temperatures [3].

The need to pursue environmental sustainability has motivated various sectors to explore and adopt innovative solutions, moving away from conventional approaches [4], [5]. In this regard, Information and Communication Technologies (ICTs) play a two-fold role in environmental sustainability.

On one hand, ICTs are key facilitators in enhancing energy efficiency, optimizing resource usage, and contributing to the reduction of GHG emissions across diverse domains [6], [7]. This role, often termed *Green by ICT*, underscores the potential of these technologies to drive emission reductions. For example, research in [8] investigated how smart systems can improve the sustainability of buildings, demonstrating ICTs' capability to simultaneously lower emissions and increase the cost-effectiveness of operations. Likewise, how ICT-based energy management in data centers could lead to significant reductions in emissions was addressed in [9].

On the other hand, the deployment and operation of ICTs come with their own environmental impacts, collectively referred to as *Green of ICT* [10]. As discussed in [11] and [12], the environmental burden associated with ICTs arises from processes such as material extraction for manufacturing, energy-intensive operations, waste management challenges, and the short lifecycle of many ICT devices.

These factors underline the need for a balanced approach that maximizes the environmental benefits of ICTs while minimizing their adverse impacts. Starting from this *double-edged sword effect* of ICTs for environmental sustainability, this paper introduces the concept of *Sustainability Balance* for ICT infrastructures, with the goal of understanding their actual environmental sustainability. The methodology employed aligns with both i) the guidelines outlined in the Guide to the Expression of Uncertainty in Measurement (GUM) [13] and ii) the sustainability standards established by the International Organization for Standardization (ISO), particularly the ISO 14000 family of standards [14], [15], as well as the recommendations summarized by the International Telecommunication Union (ITU) [16], in order to provide a thorough assessment.

The integration of a metrological approach allows considering the estimation of the environmental impact of an ICT infrastructure as a fully-fledged measurement operation, thereby enhancing the reliability of the outcome.

After delineating the methodology, as a practical case study, this methodology is applied for the first time in a real and complex monitoring scenario, namely the *dynamic fourth lane* of the Italian A4 motorway. This infrastructure comprises a variety of equipment, including sensors, actuators, and Internet of Things (IoT) technologies, and is designed to enhance traffic fluidity by dynamically adjusting motorway capacity in real time. Specifically, it enables the emergency lane to be utilized as an additional traffic lane depending on traffic volume, thereby mitigating congestion and reducing emissions associated with vehicle idling.

The paper is organized as follows. Section II provides a background of environmental sustainability assessment.

Then, Section III details the employed methodology. Section IV describes the considered case study for the Sustainability Balance, namely the *dynamic fourth lane* infrastructure. The experimental results are discussed in Section V. Finally, the Conclusions are drawn and Future Work is outlined.

II. BACKGROUND

The primary objective of Sustainable Development Goal 13 (*Climate Action*) within the United Nations *Agenda 2030* is to tackle the contemporary challenges posed by global warming and, consequently, climate change.

To support this goal, ISO published a series of regulations for organizations and companies to follow, which are included in the ISO 14000 family of standards [14], [15]. Based on these standards, the ITU has outlined a set of recommendations for evaluating the environmental impact of ICT infrastructures [16].

Basically, the evaluation of the environmental impact involves assessing the amount of GHG emissions over a defined period.

This amount of emissions is known as *Carbon Footprint* and is expressed in terms of kilograms of equivalent carbon dioxide ($\text{CO}_{2,eq}$), namely *the measurement unit for comparing the radiative forcing of a GHG to that of carbon dioxide* [15].

Typically, the estimation of the Carbon Footprint cannot be carried out by directly measuring the quantity of emissions generated by the product or service of interest, as these emissions result from upstream processes. Consider, for example, a laptop: during its use phase, energy consumption leads to GHG emissions, but it is not feasible to directly measure the $\text{CO}_{2,eq}$ emitted by the laptop as the emissions result from energy production and distribution. Therefore, it is necessary to use models that enable indirect estimation. This is generally performed through the Life-Cycle Assessment (LCA) methodology [14], a well-established approach that allows for a comprehensive evaluation of the environmental impacts associated with a system throughout its entire life cycle. This is achieved by employing mathematical models that account for the manufacturing, distribution, use, and end-of-life phases.

According to the aforementioned standards and recommendations, three main steps should be considered:

- 1) The first step involves creating a comprehensive inventory of all elements of the specific ICT infrastructure considered. This inventory serves as the foundational database for the procedure, ensuring that every aspect is accounted for in the evaluation process. Clear boundaries are defined in this phase to specify what is included and excluded, along with the reasons for these decisions. These boundaries are case-specific, with certain general considerations applicable to components involved in the measurement process. Typically, a checklist with six categories can

- be employed: (i) hardware; (ii) software; (iii) consumables and supportive products; (iv) site infrastructure; (v) movements of goods; and (vi) movements of people.
- 2) For each item of the inventory, a differentiation between *embodied* and *operational* impacts is made. Embodied impacts encompass those associated with production, transport, packaging, and disposal of the item. Thus, this type of impact can be mitigated or eliminated by considering the reuse of existing items, in alignment with the principles of circular economy [17]. In contrast, operational impacts are related to the item's use over a specified period, particularly its energy consumption, hence they cannot be eliminated. By assessing both embodied and operational impacts through LCA, comprehensive quantification of an item's environmental impact within the considered time interval can be achieved.
 - 3) Finally, the environmental impacts associated with all items are aggregated to determine the Carbon Footprint of the specific ICT infrastructure under consideration.

Overall, this ISO/ITU framework provides a foundation for conducting sustainability assessments. However, the estimation of environmental impacts is typically addressed superficially, without adequate consideration of the reliability and quality of the estimates produced. For this reason, integrating metrological principles can enable these estimates to be regarded as actual measurement results.

III. METHOD

The methodology adopted in this study builds upon the preliminary proposal presented by the Authors in [18]. It constituted an initial attempt to integrate the ISO/ITU framework with the GUM framework, with particular reference to Supplement 1, which details the Monte Carlo Method (MCM) [19], for the purpose of exploring, through fully-fledged measurement models, the sustainability-aware selection of measuring systems. In the present work, the scope of the methodology is extended to encompass ICT infrastructures. The methodology comprises the following steps:

- 1) *Checklist of the items*: this step aligns with the first stage of the LCA approach described in Sec. II, which involves identifying all the elements that characterize the specific ICT infrastructure. Hardware and Software elements are essential categories to consider. Other categories, such as consumables, site infrastructure, and movements of goods and people, may be included depending on the specific case.
- 2) *PDFs assignment*: in this step, the embodied and operational impacts associated with all items are determined. Specifically, a probability density function (PDF) is assigned to each impact. These PDFs, representing the incomplete knowledge of the Carbon Footprint associated with each item, can be derived

from information obtained through literature, technical reports, or by using specific tools for LCA.

- 3) *PDFs propagation*: the assigned PDFs are propagated by conducting MCM simulations with a finite number of samples for each input quantity. These samples are aggregated, resulting in an output PDF that represents the distribution of the overall Carbon Footprint of the considered ICT infrastructure. Finally, a coverage interval associated with a specific coverage level is derived from the output PDF by identifying the shortest interval that encompasses the desired percentage of the area under the curve. This coverage interval serves as the measurement results of the Carbon Footprint of the considered ICT infrastructure.

This methodology enables the measurement of the environmental impact of the ICT infrastructure under consideration. Building on this, the innovative contribution of this work is the introduction of a final step, the Sustainability Balance, to address the true sustainability of the considered system.

- 4) *Sustainability Balance*: this additional step involves the measurement of the amount of GHG emissions saved by the use of the considered ICT infrastructure (instead of traditional alternatives). This approach allows for a determination, with a specified level of coverage, of whether the implementation and operation of the ICT infrastructure contribute to mitigating climate change.

It is important to note that, since the embodied impacts are related solely to the beginning and end of the life cycle, covering production, transport, and disposal, they can be considered as *fixed contributions* of the ICT infrastructure in terms of GHG emissions. In contrast, operational impacts depend on the selected time period for evaluating the system's usage, representing *variable contributions* of the infrastructure. For this reason, the Sustainability Balance cannot be separated from the temporal dimension within which both the environmental impact and the saved emissions are evaluated.

For the sake of clarity, Fig. 1 provides a graphical representation of the described steps.

IV. CASE STUDY

The proposed methodology for conducting the Sustainability Balance is applied to a relevant manifestation of ICT infrastructures, namely the *dynamic fourth lane* of the A4 Italian motorway (Torino-Trieste), developed by *Movyn S.p.A*, a company of the *Autostrade per l'Italia* group. This represents a substantial advancement compared to the preliminary findings reported in [20], in which only the embodied contributions were considered in an exploratory manner, with no information provided on operational contributions or the time-scale balance between generated and avoided emissions.

The primary objective of this infrastructure, sketched in Fig. 2, is to enhance traffic flow and improve road safety [21]. This is achieved by utilizing the emergency lane as an additional lane during specific situations, based on

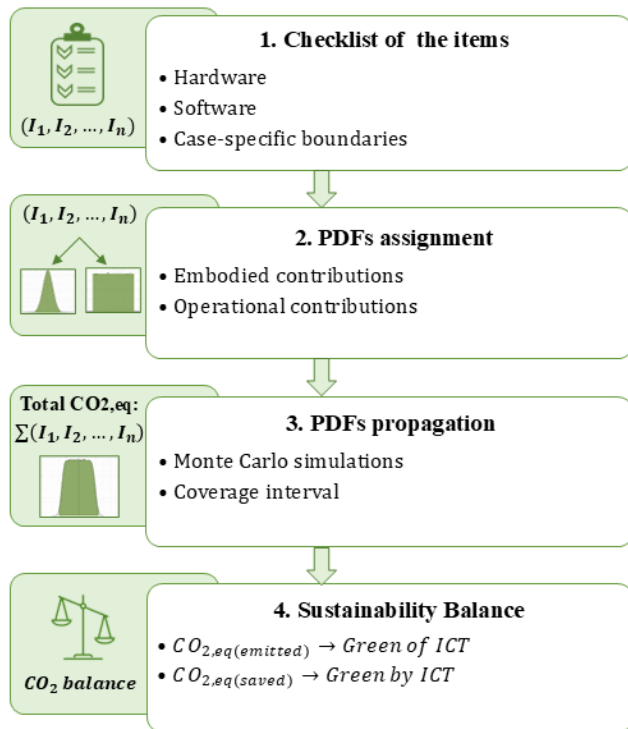


FIGURE 1. Graphical presentation of the proposed methodology.

real-time traffic monitoring, thereby optimizing the use of the existing infrastructure. The intervention section spans 10 km, extending from km 126 (Viale Certosa) to km 136 (Sesto San Giovanni), both located north of Milan, Italy. The activation of the additional lane can be independently triggered for each direction of traffic. To accomplish this goal, the infrastructure includes various pieces of equipment, including sensors, actuators, and IoT technology. These can be grouped into six major categories: monitoring systems, camera systems, weather stations, signposting devices, power supply and control, and data management.

A. MONITORING SYSTEM

The *Monitoring System* includes devices for vehicle counting and classification, speed assessment, and traffic status detection. Among these devices are radars and laser scanners, such as the Navtech CTS350X radar [22], the Comark RSR 4001 laser scanner [23], and the Comark LSR 2001 laser scanner equipped with radar [24].

B. CAMERA SYSTEM

The *Camera System* supports the monitoring activities, enhancing data collection and information gathering. Specifically, the Axis P3807-PVE [25], Axis P5655-E [26], and Bosch MIC-7502-Z30W [27] cameras are employed.

C. WEATHER STATIONS

These are installed to enable the analysis of various meteorological parameters, so as to identify potential

emergencies related to adverse weather conditions. Each weather station includes two sensors: the VS2k-UMB visibility sensor [28], which measures visibility, and the WS600-UMB smart weather sensor [29], which measures environmental parameters such as air temperature, pressure, humidity, and precipitation amount.

D. SIGNPOSTING DEVICES

These include prismatic variable message signs, full-color pictograms, and alphanumeric panels. These devices display textual and numerical information, graphics, and easy-to-understand symbols for quick and immediate communication to motorists.

E. CONTROL AND POWER SUPPLY SYSTEM

This provides the necessary energy for the operation of the infrastructure. It includes shelters and control units. The shelters, positioned alongside the infrastructure, ensure continuous operation even during outages through generators and supplementary power sources. Each shelter features cables, control cabinets, isolation transformers, access points, and switches. Instead, control units monitor the infrastructure components and manage signals to inform users of any lane changes.

F. DATA MANAGEMENT SYSTEM

This unit processes and manages information acquired from the monitoring and camera systems. It incorporates Bluetooth spotters that transmit real-time data to data centers. Within these centers, mid-range laptops process the data and run the software required to control the entire infrastructure.

The description of each piece of equipment is summarized in Table 1. Overall, such infrastructure has the potential to contribute to environmental sustainability, as reduced traffic is associated with decreased emissions. However, it is essential to conduct a sustainability balance to understand: i) the environmental impact of all the considered components, and ii) the amount of GHG emissions saved by using the *dynamic fourth lane* compared to its traditional use solely for emergency purposes.

V. RESULTS AND DISCUSSION

The measurement of the Carbon Footprint followed the four-step methodology outlined in Section III.

A. CHECKLIST OF THE ITEMS

Regarding the checklist of items, it was possible to separate, from Table 1, the hardware components from the software ones, the latter considered only in the *Data Management* equipment. Items not listed in Table 1, which are used for the operation and management of the existing dynamic lane and are integral to the overall highway infrastructure (e.g., the home-to-work travel of *Movyon* workers), were excluded from the evaluation as they were not considered critical for comparing the impacts observed before and after the implementation of the fourth dynamic lane.

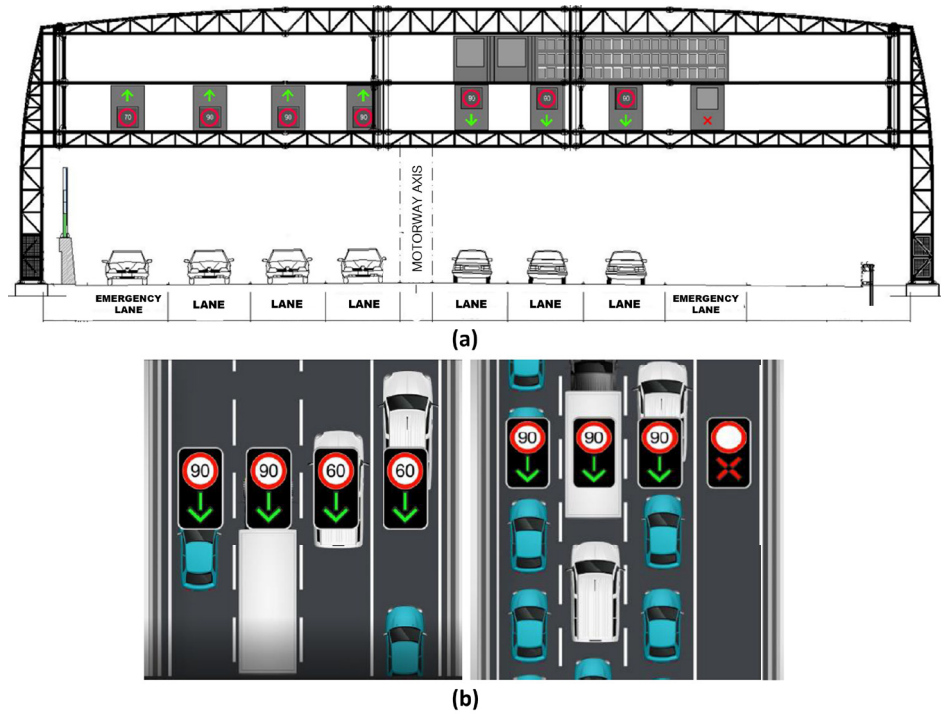


FIGURE 2. Graphical representation of the *dynamic fourth lane*: (a) a cross-sectional view, and (b) a top-level view.

TABLE 1. Summary of each equipment used for the operation of the dynamic fourth lane.

Equipment	Items
Monitoring Systems	Radars Navtech CTS350X Laser Scanners Comark LSR 2001 Scanners & Radars Comark RSR 4001
Camera Systems	Cameras Axis P3807-PVE Cameras Axis P5655-E Cameras Bosch MIC-7502-Z30W
Weather Stations	Visibility Sensors VS2k-UMB Smart Weather Sensors WS600-UMB
Signposting Devices	Prismatic Variable Message Signs Full-Color Pictograms Alphanumeric Panels
Control & Power Supply	Shelters Control Units
Data Management	Bluetooth Spotters Mid-Range Laptops Software Application

B. PDFs ASSIGNMENT

The impact assessment of each item, encompassing both embodied and operational impacts, was conducted as follows.

- The embodied impacts, representing as *fixed* contributions in terms of GHG emissions, were assessed using

the *OpenLCA Tool* [30], an open-source software that provides access to a large set of freely and commercially available databases for employing the LCA approach. Among the different databases offered by *OpenLCA*, the open database *Environmental Footprints* (EF) [31] was employed. This database is provided under the guidance of the European Commission and its Joint Research Centre. The available EF data for the representative products is in line with the current product environmental footprint category rules (PEFCR) as well as the organization’s environmental footprint sector rules (OEFSRs). The EF database provides a comprehensive set of information about the manufacturing and disposal of different materials. In this way, it was possible to model each item of the checklist in terms of mechanical and electronic parts, retrieved from the respective datasheets.

The incomplete knowledge of all the internal components of the various physical items led to the derivation of a PDF associated with the environmental impact of each item. In general, uniform PDFs were considered for the items, with the only exception being the laptop, whose modeling followed a normal PDF as it provides a more accurate representation of the market scenario for mid-range laptops. With specific regard to the embodied contribution of the software items, they were decoupled from physical devices (whose embodied contribution was assessed separately) and derived from an estimation of the work hours required for their development and

TABLE 2. Embodied Carbon Footprint assessed for each equipment of the dynamic fourth lane at 99 % coverage level.

Equipment	Embodied footprint CO _{2,eq} [kg]
Hardware	
Monitoring	3464 ÷ 5153
Camera	2121 ÷ 2902
Weather stations	351 ÷ 402
Signposting Device	829766 ÷ 1160196
Power Supply & Control	234309 ÷ 246235
Data Management	3652 ÷ 4863
Software	
Infrastructure Management	89 ÷ 182

deployment (information provided by *Autostrade per l'Italia*).

- The operational contributions, representing the *variable* contributions in terms of GHG emissions, were assessed by considering a one-year time period, assuming that all items were operating continuously to ensure the proper functioning of the infrastructure, except for the supplementary power sources, for which usage of approximately two hours was considered based on historical data regarding power outages in the northern Milan area. The energy consumption of each item was determined based on power data obtained from datasheets or websites. In some cases, these sources provide a single power value, while in others, they present a range of values reflecting different operating conditions. In the first case, the single power value was treated as a delta PDF, while in the latter case, the range of values was modeled using a uniform PDF. The resulting power-related PDFs were weighed by considering the selected time frame to derive energy-related PDFs. Finally, the energy-related PDFs were translated into carbon-related PDFs by considering a conversion factor derived from emission values in Italy [32]. Based on the historical data of 2023, each kilowatt-hour of energy can be associated with a range of emissions equal to 0.29 ± 0.02 kg CO_{2,eq}, assuming a normal PDF. Notably, the operational contributions of the software-related items were not considered, as they are already included in the contributions associated with the laptop.

C. PDFs PROPAGATION

Following the third step of the proposed methodology, the PDFs for each item of the checklist were aggregated using MCM simulations, by considering a number of extractions equal to 10^6 . The aggregation was performed separately for embodied and operational contributions to discriminate between fixed and variable emissions associated with the infrastructure.

- The results for embodied impacts are presented in Table 2, which shows the 99 % coverage interval for the

TABLE 3. Operational Carbon Footprint assessed for each equipment of the dynamic fourth lane at 99 % coverage level.

Equipment	Operational footprint CO _{2,eq} [kg/year]
Hardware	
Monitoring	1054 ÷ 1451
Camera	1410 ÷ 2615
Weather Stations	324 ÷ 396
Signposting Devices	306238 ÷ 357502
Power Supply & Control	430638 ÷ 670258
Data Management	25227 ÷ 29034

output PDFs. The results indicate that the Signposting Devices and the Power Supply & Control systems have significantly higher impacts. This is primarily due to the considerable weight of the components (in the order of 10^3 kg) as well as the complex electronic and mechanical structures of the elements within these systems.

- Similar to the embodied impacts, the operational impacts are detailed in Table 3, showing the 99 % coverage intervals for the output PDFs. The results show that the Power Supply & Control system exhibits the highest operational impacts. This outcome aligns with the system's structure and functionality, including control units and high-power components.

In this way, the methodology allowed for the estimation of both the fixed and variable contributions to the emissions of the fourth dynamic lane.

D. SUSTAINABILITY BALANCE

The final step of the proposed methodology involves introducing the Sustainability Balance to assess the effectiveness of the infrastructure in achieving environmental sustainability goals. After evaluating the environmental impact, in terms of both fixed and variable contributions, it was crucial to determine the amount of GHG emissions saved by using the current infrastructure compared to the pre-existing one. To achieve this, key variables before and after the introduction of the infrastructure were considered, including the average speed of vehicles using the lane and the presence or absence of congestion. An assessment was conducted over two sample weeks in 2022 and 2023, respectively. In these two weeks, a one-hour observation period was selected to estimate the average speed of vehicles in transit. The outcomes showed a significant increase from approximately 77 km/h to 100 km/h when the fourth dynamic lane was active (+31 %). This increase in speed, resulting from a reduction in congestion events and the number of tailbacks, led to substantial CO_{2,eq} savings. A χ^2 test was applied to the acquired samples to assess whether the data followed a normal distribution ($\alpha=0.05$), and the results confirmed the assumption of normality. Consequently, the normal PDF obtained from the two sample weeks was propagated by considering the total

TABLE 4. Generated and avoided emissions of the dynamic fourth lane at 99 % coverage level.

Quantity	Unit	Coverage interval
Embodied Impact	CO _{2,eq} [kg]	1073819 ÷ 1419869
Operational Impact	CO _{2,eq} [kg/year]	765893 ÷ 1059419
Emission savings	CO _{2,eq} [kg/year]	7140996 ÷ 9077390

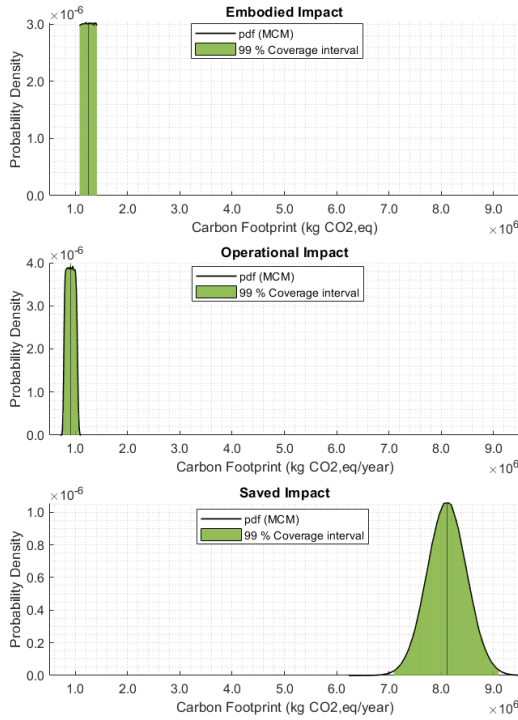


FIGURE 3. PDFs related to the Carbon Footprint of the *dynamic fourth lane*: embodied impacts (top); operational impact over one year of use (middle); saved impact over one year of use (bottom). In green, the 99 % coverage interval is shown.

amount of weeks in a year. Hence, the GHG emissions savings were expressed in terms of kg CO_{2,eq} per year.

Overall, Table 4 reports the measurement results related to the emissions generated by the infrastructure and the emissions saved due to its implementation. In addition, Fig. 3 shows the output PDFs related to the overall embodied impact (top), the operational impact per year (middle), and finally the saved impact per year (bottom). Each impact is represented in terms of 99 % coverage intervals. These results enable us to understand the true sustainability of the Fourth Dynamic Lane. As shown in Fig. 4, the Sustainability Balance was assessed over a period of three years of operation. In Year 0, which corresponds to the realization of the Fourth Dynamic Lane, the only impact that should be considered is the embodied one, as it represents a fixed contribution. In subsequent years, both the operational contributions (associated with the use of the Fourth Dynamic Lane), along with the saved contributions (due to its use compared to the traditional infrastructure) have to be considered. As can be

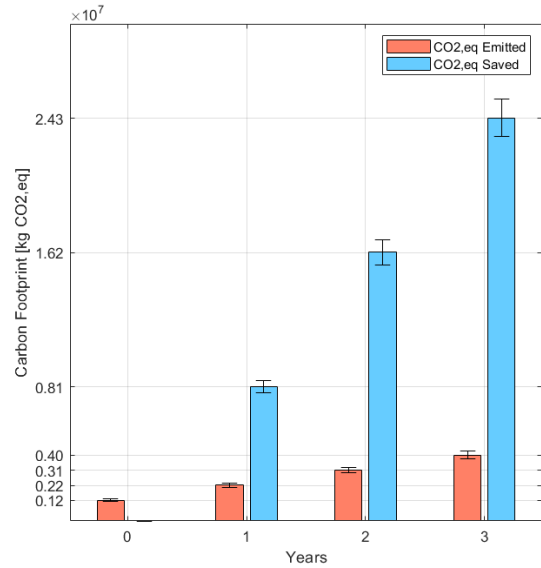


FIGURE 4. Sustainability balance in terms of CO_{2,eq} emitted and saved over a time horizon of three years.

seen, the amount of emissions saved allows for a reduction in Carbon Footprint starting from the first year, thereby contributing to climate change mitigation.

VI. CONCLUSION AND FUTURE WORK

This work described a methodology, compliant with both ISO/ITU and the GUM framework, for providing a sustainability balance for ICT infrastructures. The methodology adopted in this study follows a structured four-step approach. First, a checklist is developed, comprising all elements necessary for the implementation, operation, and end-of-life stages of the infrastructure. Subsequently, the environmental impact associated with each element is modeled using probability distributions, which represent the uncertainty due to incomplete knowledge of the true emissions linked to each element. The resulting distributions are then aggregated through Monte Carlo simulations, yielding an overall probability distribution describing the environmental impact of the infrastructure. A coverage interval is applied to this probability distribution according to the chosen coverage level. Finally, after quantifying the environmental impact, a Sustainability Balance is performed by accounting for the emissions avoided through the use of the infrastructure over its operational lifetime. The integration of a metrological approach allows considering the estimation of the Carbon Footprint of an ICT infrastructure as a fully-fledged measurement operation, thereby enhancing the reliability of the outcome. As an illustrative case study, this methodology was applied to the *dynamic fourth lane* of the Italian A4 motorway. The experimental results demonstrated that after one year of operation, a significant reduction in emissions can be achieved, contributing to the environmental sustainability goals outlined in the United Nations’ 2030 Agenda. Overall, this approach provides insight into how

ICTs can contribute to climate change mitigation in the specific scenario under consideration. Future work will focus on reducing uncertainties related to the measurements of Carbon Footprint to foster a deeper understanding of the environmental impacts associated with ICT products and services.

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