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Review

Existing assets maintenance management: Optimizing maintenance procedures and costs through BIM tools

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ABSTRACT

Control and maintenance strategies are essential to preserve and ensure an adequate level of safety and functionality of civil or historical assets. In recent years, digital transformation is promoting new operational methods for Facility Management (FM) with the use of Building Information Modeling (BIM) systems. The research proposes a method supported by BIM tools to improve maintenance processes in terms of efficiency, quality and speed. The method consists of the integration of Building Condition Assessment (BCA) with Building Information Modeling (BIM) in order to collect, digitize and evaluate the physical and performance conditions of assets to improve management and maintenance processes. The results show two procedures for data collection and integration into the BIM model. The first procedure uses mobile devices and Excel spreadsheets as databases imported into the BIM model through a Visual Programming Language (VPL). The second procedure uses a system of Common Data Environmental (CDE) that capture data from on-site monitoring sensors and link them to the BIM model. The case studies concern an existing building of historical and cultural value, the Brunelleschi's Cloister, and a viaduct belonging to a road infrastructure.

1. Introduction

According to the ISO 15686-1:2011 service life is the "period of time after installation during which a building or its parts meets or exceeds the performance requirements". All buildings and infrastructures have a limited service life because they deteriorate due to natural and anthropogenic causes [1]. Therefore, technicians and managers have to deal with problems of physical and performance preservation of assets to maintain high quality standards. At the same time, when a material achieves its estimated service life, it should be replaced. However on the Architecture, Engineering, Construction and Operation (AECO) sector, the materials service life almost relies on the economic factors [2].

Existing asset management is an ongoing concern for technicians and managers due to the complexity of maintenance operations and increasingly limited economic resources. In this situation, it has become a common standard to carry maintenance works only when actual emergencies occur. This causes inefficiencies in the planning of Facility Management activities, an increase in maintenance costs and a risk of elevate damage and loss of life in the worst cases.

For these reasons, it is important to consider preventive maintenance as a strategy to counteract the deterioration of all buildings and infrastructures. The preventive maintenance procedure consists of simple actions, continuous in time, characterized by a low cost that allows a profitable use of resources on a greater number of assets [3]. In the law context, the Italian public procurement code (Legislative Degree no.50 of 2016) introduces the mandate to develop maintenance plan during the execution phase. At the same time, the decree transposes the European directive (2014/24/EU) on the progressive use of specific electronic methods and tools, such as BIM, by using interoperable platforms.

For these reasons, the ISO 19650-3 "Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 3: Operational phase of the assets" clarify the use of information models in the construction sector for the management of the assets during the entire life cycle. The ISO propose tools such as Project Implementation Model (PIM) and Asset Information Management (AIM) that are able to distribute information in a correct way according to the phase of the construction process of the work. Therefore, the BIM design model evolves into the constructive PIM and consecutively into the operational AIM model throughout the

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life of the project, enriching itself with information and data useful to the Facility Manager in his operating activities and asset maintenance.

The paper shows two procedures for managing data in a BIM environment for all types of assets in order to optimize maintenance processes and costs. One process is applied to cultural heritage assets, while the second one is applied to road infrastructure.

1.1. Facility Management and BIM

According to the ISO 41011:2017 Facility Management (FM) is the "*organizational function which integrates people, place and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business*" [4]. While, the IFMA (International Facility Management Association) defines it as "*the design, implementation and control process through which the facilities (the buildings and services necessary to support and facilitate the company's activity) are identified, specified, found and supplied in order to provide and maintain those levels of service able to meet business needs, creating a quality work environment with a cost as low as possible*". It is a complex discipline in which knowledge of information is the basis for management activities.

In the literature, maintenance management is known as the operations and maintenance (O&M) phase and represents the activity that generates the highest expenditure during the life cycle (about 60% of total costs [5]). However, managing maintenance activities is quite complex therefore BIM-FM integration could be useful to improve the performance of a building and manage operations more efficiently by reducing O&M costs [6].

According to ISO 29481-1:2016 BIM is a shared, digital representation of the physical and functional characteristics of any existing object that facilitates the design, construction and management processes [7].

In Facility Management, BIM includes a unified information base, consisting of a Big Data database, which provides a building owner's manual, useful support for analysis, support for emergency response, safety management and scenario planning [8,9].

In this regard, the idea that BIM integrated with FM is an operation directed towards sustainability is spreading, to the point of coining the term Sustainable Facility Management [10]. However, it is often the case that the technology does not keep up with the requirements. In fact, BIM software authoring is not always prepared to contain all the information characterising O&M activities, which is why it is necessary to introduce new software to complement the former in order to manage maintenance information.

FM requires strong interaction and sharing of the information collected. In recent years, the tools that have supported FM have been Computerized Maintenance Management System (CMMS) and Computer Aided Facility Management (CAFM). However, both of them have limited visualization capabilities, as the traditional use of paper or 2D digital plans limits the facility manager to identify the exact location of maintenance and the history of changes [11,12]. In this regard, the BIM model could be a useful tool to interact with the FM as a source for data entry, providing material/spatial data, reports or technical analysis, or as an interface to a repository, providing data acquisition, monitoring, processing and transformation [13,14].

1.1.1. Regulatory Framework – UNI EN ISO 19650 1 - 2 - 3

The International Organization for Standardization (ISO) has been working for years with the aim of implementing a digital transformation in the construction sector. The ISO 19650 "Organization of information about construction works – Information management using building information modelling" defines all the principles and concepts for the management of information during the entire life cycle of the buildings [15].

The ISO 19650, characterized by two parts, was developed in collaboration with the European standardization body CEN (Comité Européen de Normalisation or European Committee for Standardization). For this reason, an ISO standard developed and implemented by CEN is compulsorily adopted by the Italian Standards (UNI).

Real estate dealers and owners using these standards obtain numerous advantages in terms of risk reduction and optimization of maintenance costs.

The ISO 19650 procedures are applicable to construction assets of all sizes and of all levels of complexity. It is necessary to highlight that ISO 19650 is closely linked to ISO 9001 dedicated to the quality management of processes and organization of companies, to ISO 55000 which characterizes asset management systems and to ISO 21500 dedicated to Project Management (Project Management).

It is possible to define that the construction sector finally has its standard for the quality management of building processes and this quality system can be implemented through the Building Information Modeling and the interoperable platforms connected to it.

If requested by the asset managers and applied by the private companies operating in the sector, these procedures can support the digital transformation process of the new and existing real estate assets.

The task of defining the information requirements and the resulting information models is among the most important of the various principles and concepts developed in the ISO 19650 [15].

This section describes the main documents supporting digitization processes of works, which are useful for both managers and economic operators:

- *OIR (Organizational Information Requirements)* is a strategic document that al-lows to define the information requirements, on a large scale, necessary for the managers of groups of construction properties who need to standardize, unify and centralize the control and maintenance of their assets. For example, this document must be prepared by managers, in order to define the information necessary to manage their assets, and dis-tributed within their internal organization, especially if this organization is located in different regional or local departments.
- *AIR (Asset Information Requirements)* is a document that defines the specific in-formation requirements of the asset subject to intervention. In this document, it is necessary to define all the data, useful to characterize the information models, which are strictly related to the nature of the property or to heterogeneous groups of assets.
- *PIR (Project Information Requirements)* is a document that defines the information necessary to respond to the requests presented in the OIR, but on the scale of the individual project. Therefore, this document starts from the information requirements de-fined in the OIR and specifically describes them for the single project. For this reason, it is a document that defines the relationship between the manager and the organization designated for the asset management service.
- *EIR (Exchange Information Requirements)* defines the information requirements of the single project and should be defined every time a contract is awarded.

According to the phase of the building process, in a digitization process a transfer of information takes place between the manager and the person in charge of developing the service. This transfer of information can also take place through information models developed by other parties, therefore, it is necessary defining an EIR.

Other definitions introduced by the ISO 19650 concern:

- *Asset Information Model (AIM)* deals with the information model concerning the state of the property. The nature of the information presented in the AIM (maintenance costs, installation and maintenance dates, etc.) provides support for the strategic and maintenance management of the property during its entire life cycle.
- *Project Information Model (PIM)* is the information model generated during the order and therefore contributes to the compliance with the AIM. This information model is characterized by all the

Table 1
State of the art about BCA.

No.	Authors	BCA definitions
1	Yacob et al. 2016 [29]	Reflects the physical state and performance of the building from defects and failures
2	Re Cecconi et al. 2017 [30]	BCA is a field of study that aims to improve knowledge about an asset. It provides stakeholders in the construction industry with Key Performance Indicators (KPIs) that can help them make the best decisions when acquiring, managing, maintaining and repairing a building. All through an implementation in a BIM environment.
3	Zuraidi et al. 2018 [31]	The purpose of the assessment is to evaluate the state of the physical elements and services of the building and to assess the requirements of the maintenance facilities.
4	Anuar et al. 2019 [32]	Building Condition Assessment (BCA) is an effective tool to determine the physical state or condition of buildings. We present a comparative study of building condition assessment methods used in Asian countries. The following methods were compared: a Malaysian method for assessing the condition of buildings, an Indian, Hong Kong and Singapore method of assessing the condition of buildings, and methods of assessing the condition of buildings.
5	Rahman 2020 [33]	The building condition assessment is a real-time assessment that provides information on building defects and problems. The methodology of this research uses the JKR standard building condition assessment form of each defect in the civil, electrical and mechanical system of the building.
6	Matos et al. 2021 [25]	Building Condition Assessment (BCA) should be the basis for management and maintenance decisions in the built environment towards sustainable construction. They propose to assess building performance and prioritise maintenance actions using key performance indicators using Building Information Modeling (BIM) as a support tool for BCA and maintenance management.
7	Faquih and Zayed 2021 [34]	Building condition assessments are carried out in order to identify defects and assess the health of the building. They propose a defect-based condition assessment model for existing concrete buildings, considering both the physical and environmental conditions of the building.

digitization processes and by all the information necessary to develop an optimal facility management of the asset.

1.2. Research goal

Digitization of buildings and infrastructure are essential for monitoring the decay state. For this reason, it is necessary to increase the knowledge about the building assets to support sustainable maintenance and conservation strategies through the development of easy-to-use resource management tools.

Maintenance of existing buildings is a complex decision-making problem due to limited economic resource. Therefore, technicians need to have standard methods and procedures.

The FM design requires a great retrieving data work, and the present study brings a new proposal through the use of Visual Programming Language (VPL) and Common Data Environmental (CDE) to improve the FM/BIM activity. Furthermore, an "ad hoc" platform for data management based on the CDE has been developed, capable of managing information models in the open format ifc (industry foudation classes).

This last aspect is among the main contributions that the research intends to introduce in the current state of the art. The proposed procedure working on open ifc formats could be used on a large scale thanks to the rapid diffusion of the BIM methodology in the AEC sector.

The development of Dynamo script in the study brings innovative perspective in BIM as it allow to manage data within BIM models in an adequate way depending of the objective required in FM.

The research proposes a method to support the decision-making for facility managers in maintenance activities through Building Condition Assessment (BCA) processes integrated with Building Information Modeling (BIM) systems to support Facility Management. The main goal is to develop a maintenance management strategy, giving technicians the necessary support to identify maintenance intervention priorities in a practical, simple and automated way in order to optimize maintenance procedures and costs.

For this purpose, the BCA process needs the following tools:

- Asset Hierarchy System
- Asset decay valuation method
- BIM model with Revit software (Autodesk)

The method shows two possible procedures for data collection:

- Dynamo: mobile devices collect data in Excel spreadsheets that act as a database connected BIM model through a visual programming language (VPL).
- Common Data Environmental (CDE): data collection with UsBIM Facility

The research highlights the importance of BIM in Facility Management for existing buildings and road infrastructures allowing the permanent update of information in a single BIM model. The research shows a great potential of the method to support facility managers in managing building maintenance activities and optimizing costs.

The method proposed in this paper is applied to two case studies. The first case study concerns a historical cultural building, the Cloister del Brunelleschi, in the monumental complex of Santa Croce, Florence (FI). The second case study is applied to a road viaduct. The research was developed to respond to the needs of engineers expressing the need for a decision support system using new technologies to optimize the management of maintenance procedures and costs. The first case study was completed during a doctoral thesis [16] and also contributed to the research of an EU-funded project (WARMEST) [17].

2. Background

Several studies have addressed the issue of maintenance. Many researchers have used multicriteria analysis techniques to support managers in their decision-making choices according to different criteria and alternatives [16,18–22]. Other authors, instead, have deliberately simplified the procedures of designers and technicians, using the well-known Building information Modeling systems for the assessment of the building conditions to investigate the state of preservation and facilitate decision-making choices for maintenance [23–25].

BIM models are transforming the way facilities are conceived, designed, constructed and managed. But current use of BIM focuses on preplanning, design, construction and project delivery rather than maintenance and operation management [26].

2.1. Building Condition Assessment

Building Condition Assessment (BCA) is an effective tool for decision support in maintenance procedures. It is part of the asset management system defined in ISO 55000:2014 [27] and as such should be conducted in combination with other important activities, such as inspections and maintenance operations. Inspections, however, often cause excessive costs if they are not organised efficiently and have to be planned considering the object of the inspection [8]. On the other hand, maintenance operations, both in terms of schedule and cost, have to be planned after the building assessment in order to be as effective as possible [28].

The BCA is a process that aims to collect as much information as possible about the physical and performance status of a building. Its

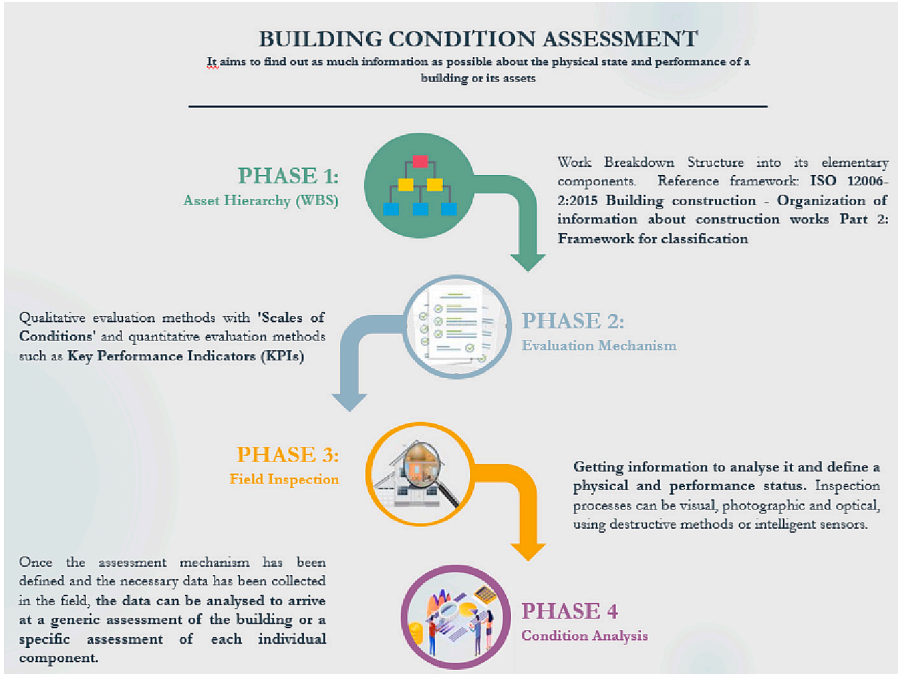


Fig. 1. Database Master Structure.

Table 2
International Classification System.

Classification system	Country
OmniClass	(North America)
MasterFormat	(United State e Canada)
UniFormat II	(USA e Canada)
UniClass NBS	(UK)
European CEEC building classification	(Europe)
Canadian CIQS classification	(Canada)
CoClass	(Sweden)
CCS	(Denmark)
TALO 2000	(Finland)
UNI 8290	(Italy)

Table 3
Evaluation method in literature.

Evaluation method	Authors
Dutch standard	[29,35]
Distress method and Direct-condition rating survey	[36]
JKR 21602–0004-13	[37]
National Health Facilities Audit	[38]
BREEAM and LEED	[39]
Key Performance Indicators (KPIs)	[6,40–42]
BUILDER, RECAPP, TOBUS	[43]

Table 4
Key Performance Indicators in literature.

Categories	Indicators
Economic	FCI (Facility Condition Index) [44,45]
	MEI (Maintenance Efficiency Indicator) [46]
Technical	BPI (Building Performance Indicator) [47]
	BEI (Building Efficiency Index) [48]
	A (Degradation Index) [49]
Functional	Document index [2]
User satisfaction	I_{ins} (Dissatisfaction index) [50,51]

proper planning is important to help engineers have a better understanding of the criticalities and behaviours that a building may have, facilitating decision-making in maintenance activities [2]. The BCA is useful to rank priorities for intervention and the number of repairs and costs require. In asset management and supporting the decision-making system of managers, it is very important to save time and costs and to improve the knowledge of the whole building and its physical components.

The BCA is an important process not only to support decision making but also to achieve the quality standards of the maintenance service. Infact, a low level of performance of the building or works in general can have a negative impact on the organization and lead to an increase in operational costs.

In the literature we find many scientific studies defining the assessment of building conditions.Table 1 shows a list of scientific articles that can be found in the Scopus, ScienceDirect and Google Scholar platforms by entering the keyword “Building Condition Assessment” (Table 1).

BCA process is divided into four phases (Fig. 1):

- Asset Hierarchy consists of a Breakdown Structure into its elementary components. In the literature there are different classification systems that in general allow each object represented to be coded through a decimal numerical system that associates each pair of numbers with its specific characteristic (Table 2).

- Evaluation methods can be qualitative or quantitative. In the literature there are several studies on building condition assessment techniques (Table 3):

The UNI EN 15341 standard defines the Key Performance Indicators (KPIs) of the Maintenance Function and provides guidelines for defining a set of suitable indicators to assess and improve the effectiveness, efficiency and sustainability in the maintenance of existing physical assets whether industrial, infrastructure, civil buildings or transport systems, etc. in the context of external and internal influencing factors. Therefore, KPIs could be a valuable tool to monitor the condition of the building over time, even better if controls are planned periodically through the life cycle of the asset [2]. According to Dejaco et al. (2017) and Marmo et al. (2019) [6], KPIs are the best way to measure building performance

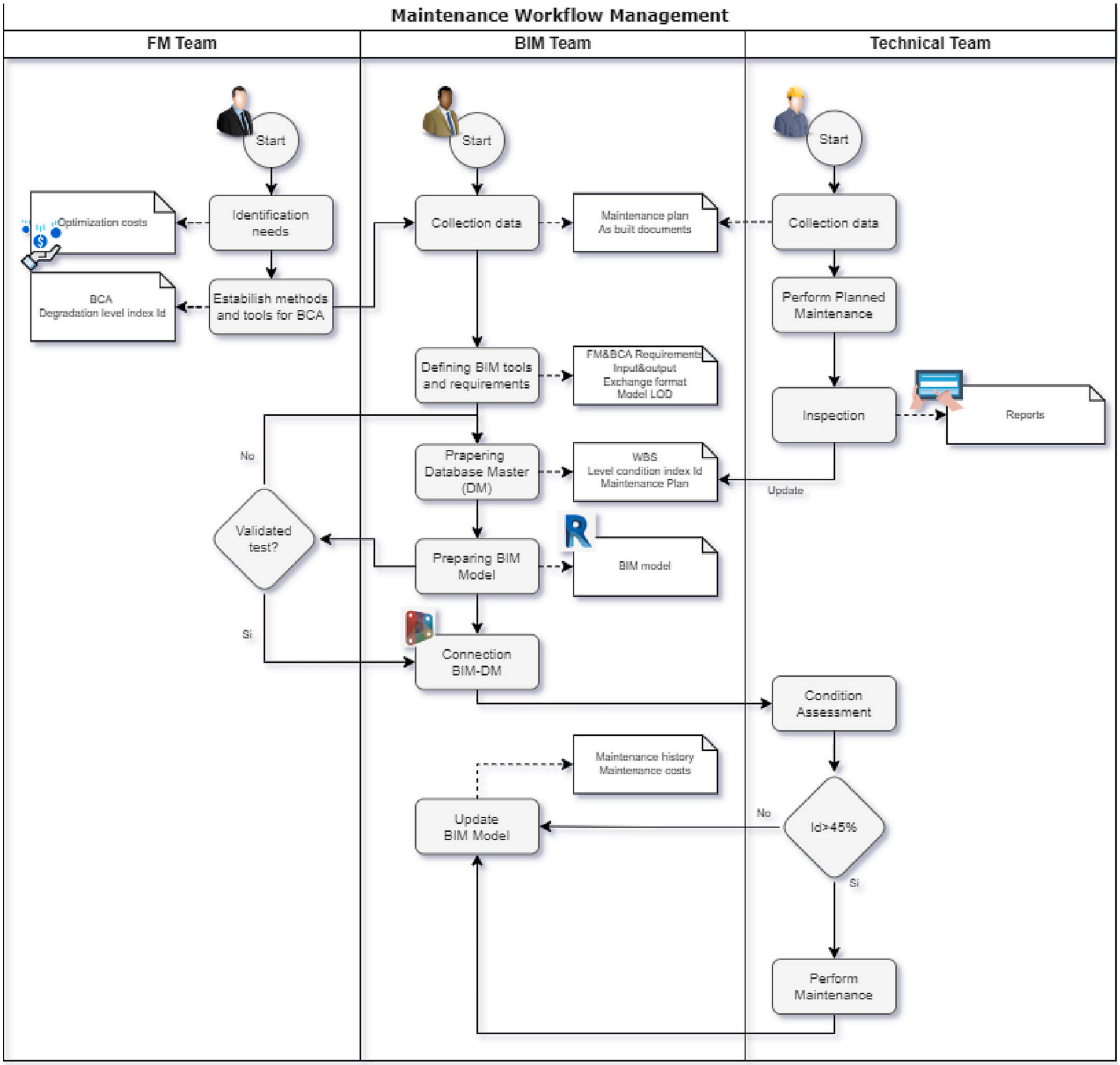


Fig. 2. Maintenance Workflow Management.

by allowing accessible and useful information about buildings and their parts (Table 4).

- Field Inspections aim to gather as much information as possible about the object of study. Obviously, the assessment method conditions the choices of data collection tools. However, inspections often cause excessive costs if they are not organised efficiently and must be planned taking into account the characteristics of the asset [8]. Data collection, storage and processing determines geometric characteristics and current physical state, defects or pathologies, etc. [52–54]. Some researchers have used data collection systems on specially designed digital devices to digitize information directly in situ without the need to re-process it later [55].
- Condition analysis phase is the application of the chosen evaluation method to study the condition of the artefact. As the data provided by the inspection process is collected in the form of damage measurements of a component, careful analysis is required to translate these measurements into a qualitative and/or quantitative condition value.

2.2. BIM for Building Condition Assessment

Maintenance management of buildings and infrastructures is one of the greatest challenges of Facility Management and its key to success is accurate knowledge of the building's condition. [56]. However, a limitation of traditional building condition assessment techniques is the outdated procedure of data collection, recording and reporting of information stored on paper and rarely linked to the as-built model. This causes the potential loss of information and therefore the overrun of performance and costs. So, it is important considering the potential of integrating the BCA process with Building Information Modeling (BIM). BIM solves the problem of collecting and managing data about the

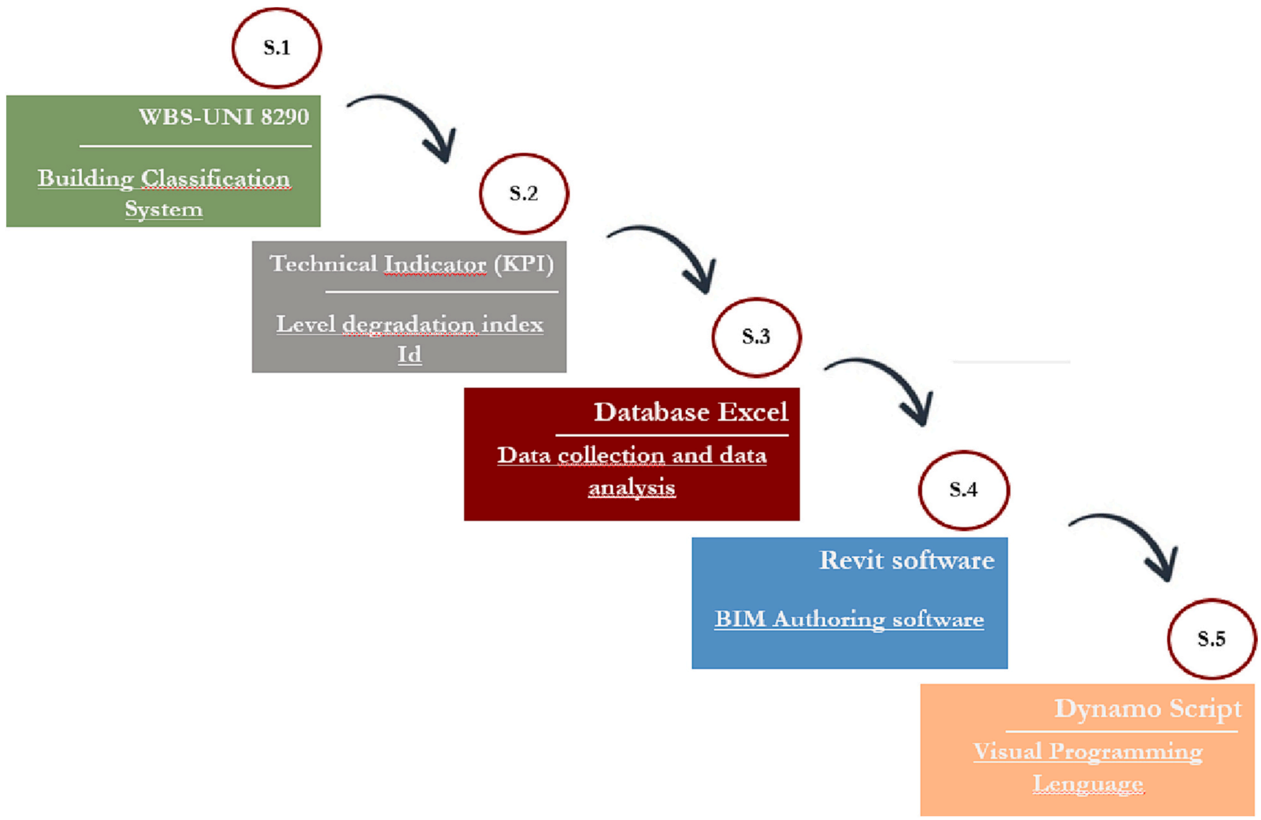


Fig. 3. Tools for maintenance management through BIM model.

Table 5
Proposed breakdown into classes of technical elements.

Levels	Parameter	Groups of parameters
LEVEL 1	Technological Unit Class	ID
LEVEL 2	Technological Unit	
LEVEL 3	Maintenable element	
LEVEL 4	ID_Element	
LEVEL 5	Material	
	Exposure	
	Position	
LEVEL 6	Type of decay (UNI 11182)	Decay Assessment
	ID	
	Conservation state	
LEVEL 7	Type of control	Maintenance Plan
	Description of control	
	Frequency of control	
	Type of Maintenance	
	Description of Maintenance	
	Frequency of Maintenance	
	Inspection cost (€/h)	
	Maintenance cost (€/mq)	
LEVEL 8	Inspection sheets	Schedule link
	Intervention sheets	
	Price analysis sheets	

Table 6
Level decay index.

$i_d = 0$	Level 0	No decay
0%< $i_d \leq$ 15%	Level 1	Good condition
15%< $i_d \leq$ 30%	Level 2	Light decay
30%< $i_d \leq$ 45%	Level 3	Moderate decay
i_d > 45%	Level 4	Generalized decay

current condition of the work under investigation by implementing it directly within a single digital model. Thus, the as-built model will not only be a three-dimensional model, but will also contain semantic (non-geometric) information that can be updated throughout the life cycle of the building. The updated database of the BIM model will facilitate the work of managers in the maintaining [57].

The difficulties in implementing an asset management process in a BIM environment are mainly due [58]:

- To the identification the necessary and sufficient information for management and maintenance operations;
- To the management of this information on platforms that are interoperable with those proper to FM;
- Reducing the effort to update the model.

In the recent literature, there are several studies about integration of BCA in a BIM environment [59–61]. These are mostly studies that target university campuses [30].

Some researchers have had to expand their competences in the IT sector, developing web platforms or plug-ins in .net language to add further functionalities to existing BIM Software Authoring [6,25,44,54]. This scenario is also occurring in the context of studies concerning the management of transport infrastructures throughout their life cycle [62,63]. In the literature it is possible to find that the BIM process, applied to infrastructures, has not yet reached adequate levels of maturity for design management and therefore, for the maintenance phase, we are still at an experimental level [64,65].

3. Materials and methods

3.1. Tools and procedures

The research is based on national and international guidelines

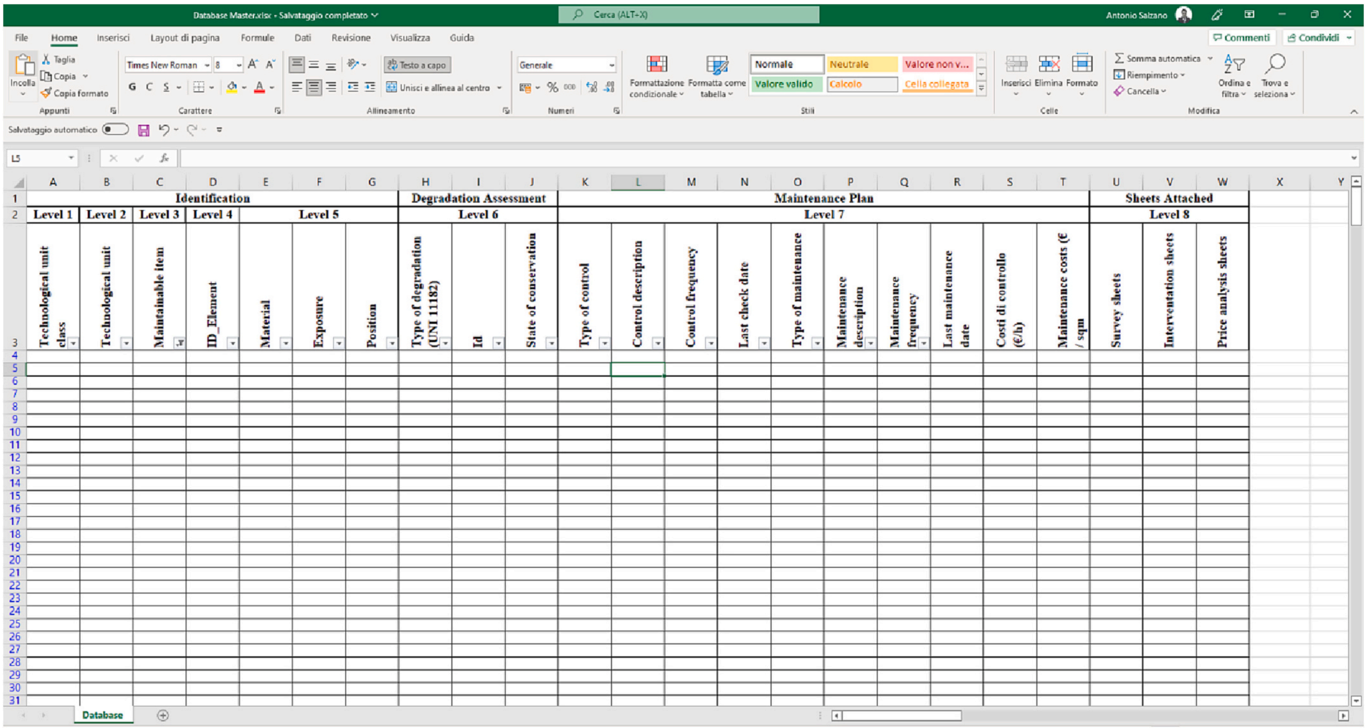


Fig. 4. Database Master Structure.

[66–70] and literature related to the implementation of BCA and FM in the BIM environment [6,41,44] and identifies tools and procedures to support a method that integrates BCA processes in the BIM environment.

Fig. 2 shows a Maintenance Workflow Management that summarises the research method and the tools that were used for its application.

The maintenance management process involves several actors:

- The FM team consists of the managers (public or private) of the building who define the needs of the building and keep track of the budget available for maintenance activities. They are responsible for the technical-economic-organizational decisions on maintenance management during the building's life cycle, and thus implement the methods, criteria and processes by which these activities are to be carried out based on the suggestions of technical experts.
- The BIM team is a working group of experts in BIM methodologies. They are responsible for the collection of data for the as-built BIM model of the building. For the particular objective of optimizing maintenance costs, this team defines the tools and requirements that the BIM model must possess (FM&BCA requirements, input and output information to and from the BIM model, data interchange modes, and level of detail (LOD). Data interchange takes place through the connection between a Database in Microsoft Excel (acting as an external database) and Scripts in Dynamo to facilitate and speed up the processes of updating data to and from the BIM model. The team will check and update the BIM model each time the building maintenance plan is implemented or updated.
- The technical team consists of technicians who will design and implement the maintenance plan, checking its effective operation and updating the data if necessary. The technicians implementing the maintenance plan carry out periodic checks on the technical components of the building to assess their state of preservation. Information is recorded during the field inspection phase using electronic tools (tablets or smartphones) that support Microsoft Excel systems.

The maintenance management process described in Fig. 2 presupposes the use of following tools:

- S1 - The building is broken down into its elementary parts by adopting the UNI 8290 standard and adapting it to the individual items of the technical elements.
- S2 - The degradation assessment consists of calculating the level degradation index for each technical element so that the most degraded elements can be promptly identified;
- S3 - Technicians collect data in situ with mobile devices on Excel spreadsheets connected to a master database also on Excel.
- S4 - The building is created through the use of Revit Software
- S5 - The information contained in the master database is linked to the BIM model through Script in Dynamo (Fig. 3)

3.1.1. *UNI 8290: Italian Building Classification*

This classification is based on the following criteria: the breakdown has three levels and gives rise to three sets called:

- Classes of technological units (first level);
- Technological units (second level);
- Classes of technical elements (third level)

The terms which make up the various sets are called headings. For operational purposes, the breakdown is extended to further levels (fourth level and higher). Each level is characterized by a numerical code that identifies the requirements and/or systems of requirements that are attributed to that specific technical element. The purpose of coding is to uniquely identify the components of the building and to enable the recording of all information available or generated over time, whether during maintenance or inspection. The proposed breakdown by classes of technical elements is as follows (Table 5):

3.1.2. *Level degradation index*

The degradation level of each technical element can be assessed according to a numerical 'degradation level' indicator expressed as (Eq.

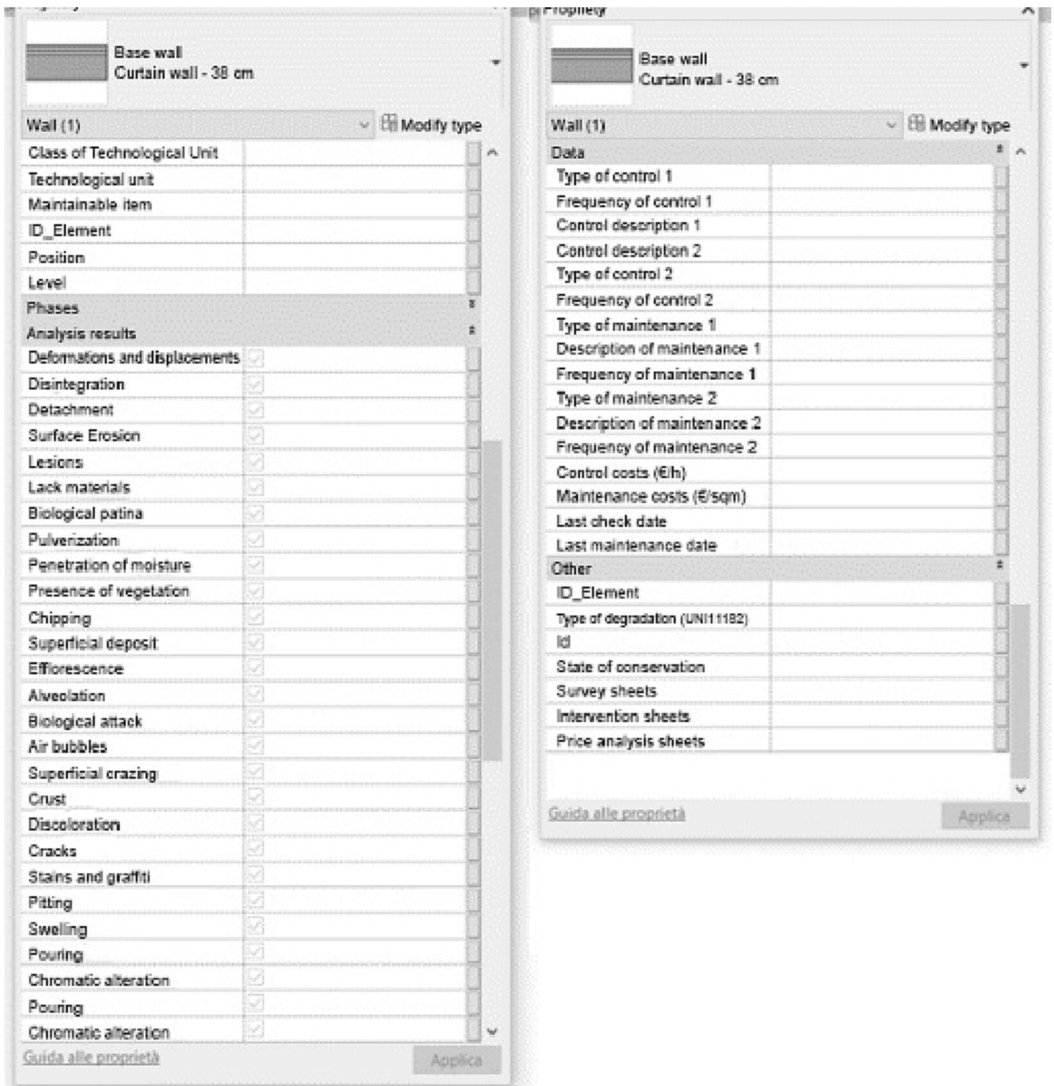


Fig. 5. Shared parameters.

1):

$$i_d = \frac{A_d}{A_t} K_d K_c \tag{1}$$

- Ad/At ratio of the area of degradation to the total area of the technical element;
- Kd is the factor that takes into account the type of degradation. Its value varies from 1 to 4 (slight, medium, serious and very serious) depending on the damage it may cause to the material in terms of loss of historical and cultural value and risks to humans.
- Kc is the weight factor that takes into account the importance of degradation in the sense of the complexity of restoration/maintenance operations and related costs. Its value is the ratio between the costs of ordinary maintenance (cleaning operations), material consolidation costs (material recovery) and the costs of complete material replacement (restoration of missing or no longer recoverable assets).

Similar approach was used in [6–59]. The level decay index will establish the state of conservation of each technical element according to its value in percentage terms as shown in Table 6:

3.1.3. BIM model with Revit software (Autodesk) and Dynamo script

Revit is a software for the design and management during the construction phase of any type of infrastructure. It is a software that, in a single and specific multidisciplinary BIM platform, allows to implement and design all phases of the life cycle of a building or infrastructure.

In addition to the 3D and 2D architectural representation, BIM models contain all the information that the software is able to provide automatically (calculation of surfaces, volumes, product quantities, etc.) plus alpha-numeric information that can be entered manually or automatically through the use of the Dynamo programming language that connects external databases (e.g. Excel or Access spreadsheets) with the Revit BIM model.

Dynamo reads and writes data to and from the Revit database via the Revit API. The data could be anything, parameter values, family geometry and family placement. Basically, Dynamo manipulates the Revit database in ways that the UI (user interface) could not.

Any Revit user could learn Dynamo (since it uses visual programming it is very easy to learn) and could access the Revit API and perform simple tasks that previously could only be done by writing an add-on or writing a macro with the .net language for Revit.

Specifically with regard to Facility Management activities, the model will be able to contain information relating to scheduled maintenance and cost management. To this end, the software returns information

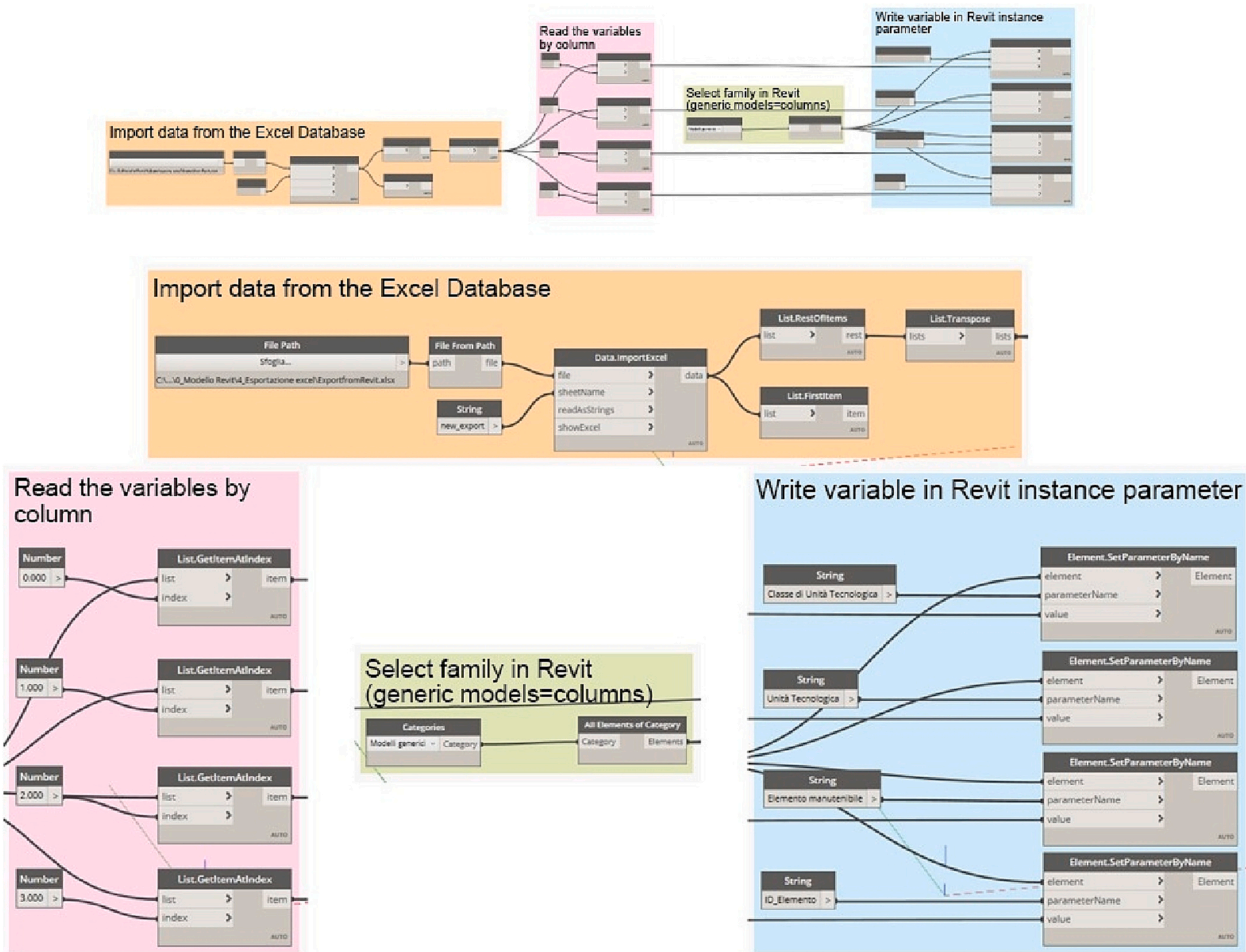


Fig. 6. Dynamo script: importing data from Master Database to BIM Model in Revit.

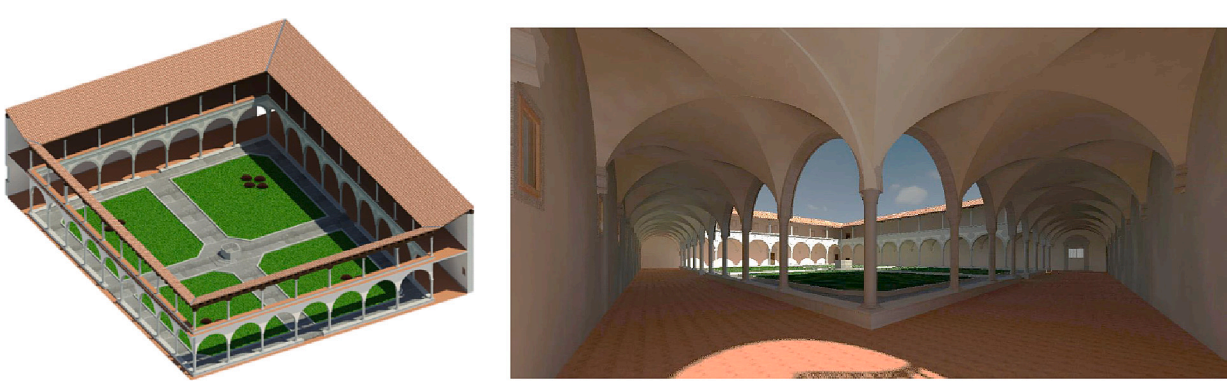


Fig. 7. Brunelleschi's Cloister BIM model and rendering.

regarding the maintenance operations carried out over time and any feedback regarding the need to update the maintenance plan. This has made it possible to organize a maintenance plan that involves carrying out several operations for each element, then assigning priorities and scheduling the frequency (maintenance schedule). With the organization of this information, it is possible to make an estimate of the annual expenses, divided by maintainable elements, which take into account the architectural maintenance costs.

The BIM model can be created with the "CAD to BIM" technique from existing plans or with the "SCAN to BIM" technique from point clouds created from photographs and videos taken during inspections.

The information for each technical element was imported into the BIM model through the use of the Dynamo programming language (VPL) which links the BIM model with the inspection sheets.

During the inspection phase, technicians fill in inspection sheets through devices mobile devices supporting Excel software. Each

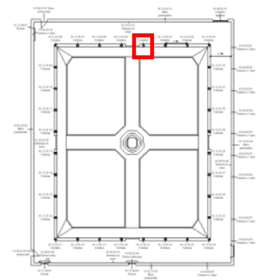
CONTROL SHEET				
B1 - WBS				
EP VALUABLE ELEMENTS			**ID sheet**	
01.11 Stone elements			**SC01.11.01.04**	
01.11.01 Facing stone columns: gray sandstone				
01.11.01.04 Column				
				
B2 - CHECKS AND MAINTENANCE				
Type of control 1	01.11.01.C01 Surface control			
Control description 1	Control of the surface layer of the columns and in particular of the exposed stone elements. Check for any anomalies. In the event of failures, check the origin, the extent and the consolidation work to be carried out.			
Control frequency 1	EVERY 2 YEARS			
Type of maintenance 1	01.11.01.I01 Surface restoration			
Maintenance description 1	Cleaning of the surface layers and in particular of the exposed stone elements by washing with deionized water at low pressure. alternatively, clean manually using scrapers, scalpels, brushes, spatulas with water.			
	IF NECESSARY			
B3 - LEVEL OF DEGRADATION INDEX				
Material	Stone material			
Exposure	Sud-Ovest			
Type of degradationKd	Chromatic alteration	Exfoliation	Erosion	
	LOW	VERY SERIOUS	SERIOUS	
	1	4	3	
Extent of degradation Ad/At	25%	33%	1%	
Importance of degradation Kc	0,18	1,71	1	
Degradation index	29%			
State of conervation	Moderate degradation			
Need for urgent action	No	PREVENTIVE		
Possible causes	Rising humidity			
Performance decline	Aesthetic			
Control date				
Name of the technician				

Fig. 8. Inspection report ID_Element "01.01.01.04 Column".

inspection report is linked to the Master Database.

The Database Master is used to link the collected data to the BIM model. It consists of a table (Fig. 4) where the columns contain the same parameters created in the BIM model (shared parameters Fig. 5).

Fig. 6 show the script created in order to import data from Excel datasheets into BIM model.

3.1.4. BIM model and UsBIM Facility collaborative platform for the Information Management

An alternative solution to the dynamo is the use of an information management platform based on the Common Data Environment. Once the BIM model has been developed, it is possible to export the IFC file with the relevant information for asset management. After setting up the IFC file correctly, it is imported into the common data environment platform to manage the operational information.

In this project, the Acca Software UsBIM.platform was used with some integrations developed "ad hoc" for research. The customization of the platform concerns graphic aspects of the "dashboard", the insertion of degradation data according to the defect schedule and for the addition of data deriving from sensors and cameras on site. These aspects are described in the paragraph 6.3.

This collaborative environment enables us to organize a Common Data Environment, in accordance with the standards (e.g. UNI 11337 and ISO 19650) and allows us to share information between different participants in the management process.

In this platform it is possible to define workflows for process control with advanced task management functions (usBIM.workflow), it is also possible to revise or validate the information associated with the models.

Furthermore, the platform is characterized by advanced functions for BIM Data Management and integration of significant data (in each entity of the BIM model and through the use of synthetic dashboards), as well as a specific editor for creating data acquisition web-forms, which can be associated with BIM objects (usBIM.data). Other functions (in particular the "link" function) enable the integrated management of the model data, allowing the association and storage of some of the documentary information collected during the various sub-processes that constitute the management phase (inspection, structural safety assessments, interventions, etc.), as well as the analysis of significant information and their georeferencing. Thus, as mentioned above, usBIM.platform was

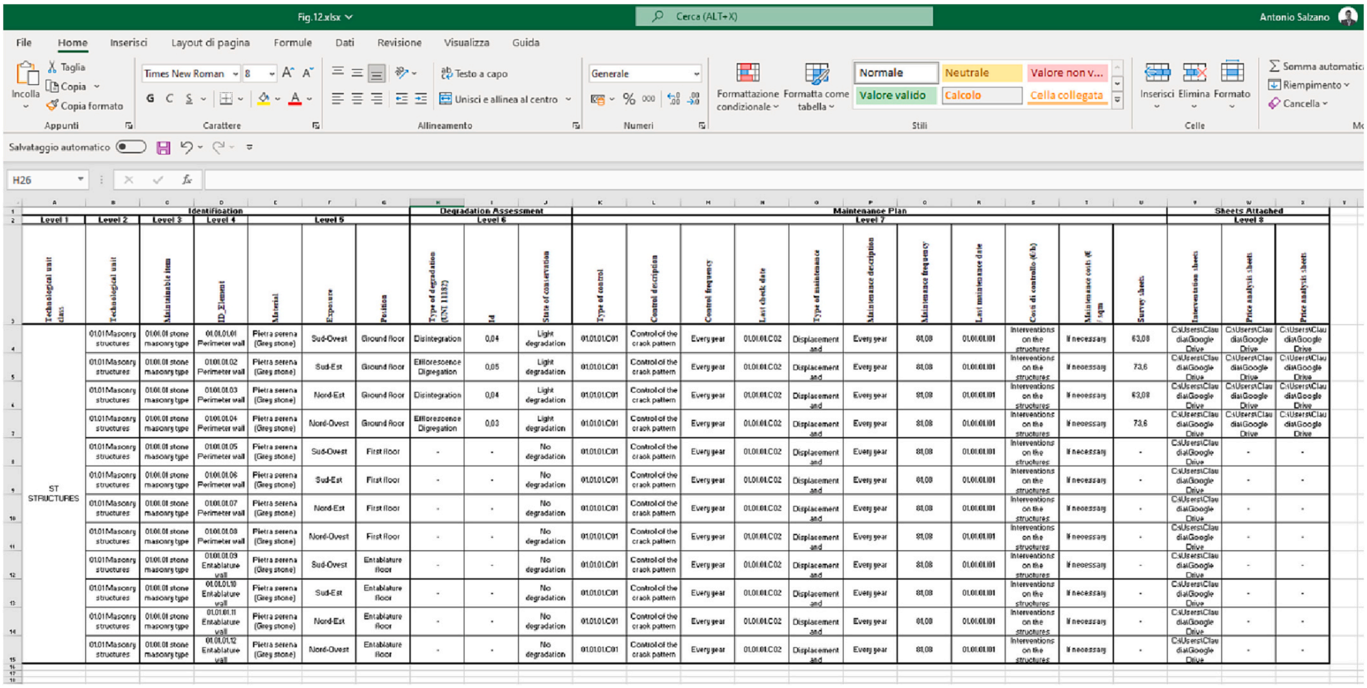


Fig. 9. Database Master completed.

used to record and associate documentation with the structure of individual elements, specifically: reports (relating to inspections, structural or geotechnical assessments, etc.), photos (relating to the overall condition of the asset or that of an individual structural component), manuals, documents, and other items.

4. Results

4.1. Brunelleschi's Cloister

Brunelleschi's Cloister is in Santa Croce Monumental Complex in Florence. Its name comes from its architect Filippo Brunelleschi. It was built at the request of Tommaso Spinelli. It was the centre of community life with the friars' cells, the library, the rooms for manual work. Today it is occupied by the National Library. The cloister is 31 m wide and 38 m high. The lower part is formed by round arches and cross vaults, resting on columns of pietra serena. The upper part consists of stone columns on which rests the single-pitch roof in wood and terracotta.

The BIM model was created on the basis of the technical datasheets collected in the technical offices of Santa Croce and the point cloud elaborated by American researchers as part of a study called "Florence as it was". The software used to create BIM model was Revit by Autodesk (Fig. 7).

4.2. Procedures applied to the Cloister

The data collection of the Brunelleschi Cloister started in 2018 within the WARMEST project and continued until 2020.[1] During the field inspection, control sheets Fig. 8 (were compiled for each of the technical elements making up the building, for a total of 515 sheets, all of which were entered in the Master Database (dimensions 23 columns × 515 rows) (Fig. 9).

The BIM model was built using the "CAD to BIM" technique on the basis of existing plans provided by the Opera di Santa Croce technicians and photographs taken during the inspections.

By importing the data from the Master Database into the Revit BIM model it is possible to query each technical element individually or to create abacuses that group together in a single table the information that has been collected during the inspections and imported into the BIM model through the script in Dynamo (Fig. 10).

Thanks to the import of data within the BIM model, it is possible to have an immediate view of the level of degradation Id of each technical element through a Revit view set according to filters with a color (Fig. 11) scale. The range of Id values varies from white to red according to the conditions in Table 6. (See Fig. 12.)

Figs. 16 show the main types of degradation in the columns, arches and decorative coats of arms of the cloister respectively. Thanks to the data collection and the creation of the Master Database, it was possible to group together the main conservation issues of the most degraded technical elements.

4.3. Second case history: Infrastructure asset

The purpose of this case study is to define, in a concrete way, a coherent process, to be adopted with the available technology, in order to be able to monitor the state of a bridge and to manage its maintenance more efficiently and in an automatic manner.

Such a procedure can be applied to newly built bridges, in order to delay the onset of deterioration for as long as possible, and to existing structures, by identifying the timing and the methods of carrying out maintenance operations.

It is necessary to analyze and to break down the entire process in detail as follows:

- Identification, Collection and Integration of Data;
- The digitization of data and the definition of elements and goals;
- Management and Monitoring of the Model on the Platform;
- Planning and execution of maintenance.

All the phases of the proposed process for the control and monitoring of the infrastructures will be described in the following paragraphs.

[1] Some slowdowns were caused by the overcoming health crisis that made inaccessible all public places where studies could be carried out (offices, archives, libraries, superintendences, etc.).

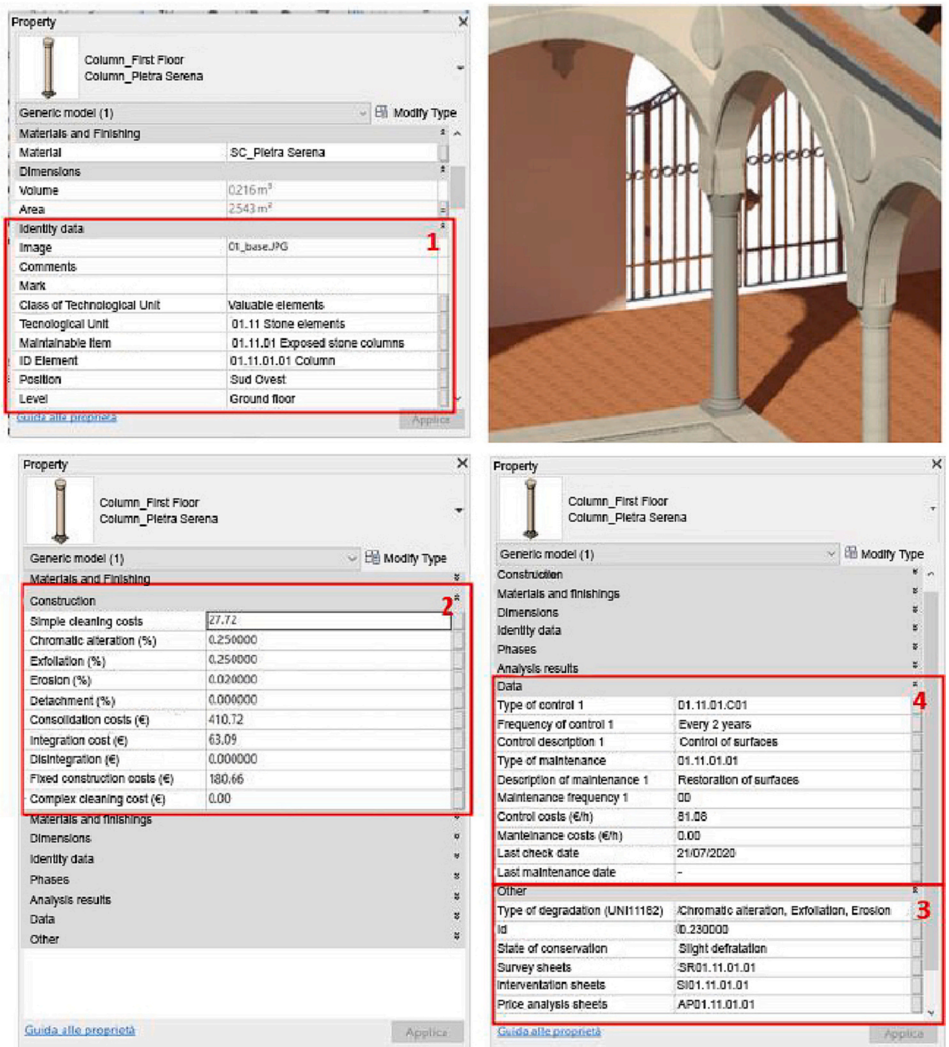


Fig. 10. Technical schedule imported from Database Master into Revit Software.

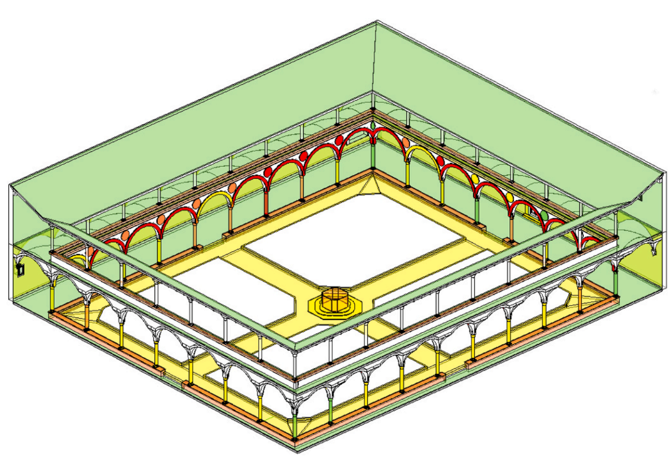


Fig. 11. Digital visualization of the degradation level "Id" of Brunelleschi's Cloister.

4.3.1. Identification, collection and integration of data

The case study examines a viaduct located on a high-speed road. The infrastructure, built in the 1960s, is a bridge classifiable as a viaduct whose length is approximately 40 m.

From a structural standpoint, the static scheme used is a continuous girder bridge, made of reinforced concrete. The deck is supported by main beams arranged longitudinally which, in turn, are supported by abutments and piers (Fig. 13).

The viaduct is composed of the following main elements (Table 7):

In the first instance, all available paper data have been collected. Administrative, testing and descriptive documentation has been collected. The design drawings (Fig. 14) and the "as built" documents used for the construction of the viaduct have been analyzed .

Inspections were carried out on the viaduct in order to find all the information necessary for BIM modeling.

The following information has been found during the inspection:

- Complete dimensional configuration of the viaduct;
- State of conservation of the viaduct.

The inspections showed the types of damage present, the damaged surface, the damaged elements and the presence or absence of anti-seismic devices. Photos have been attached to all the information provided for completeness. Furthermore, a drone with a high-resolution camera has been used to reach blind spots of the Viaduct, that were normally inaccessible, so as to return of all the necessary information (Fig. 15).

After the data collection, carried out during the inspections, it is necessary to be able to divide the structure into elementary parts in

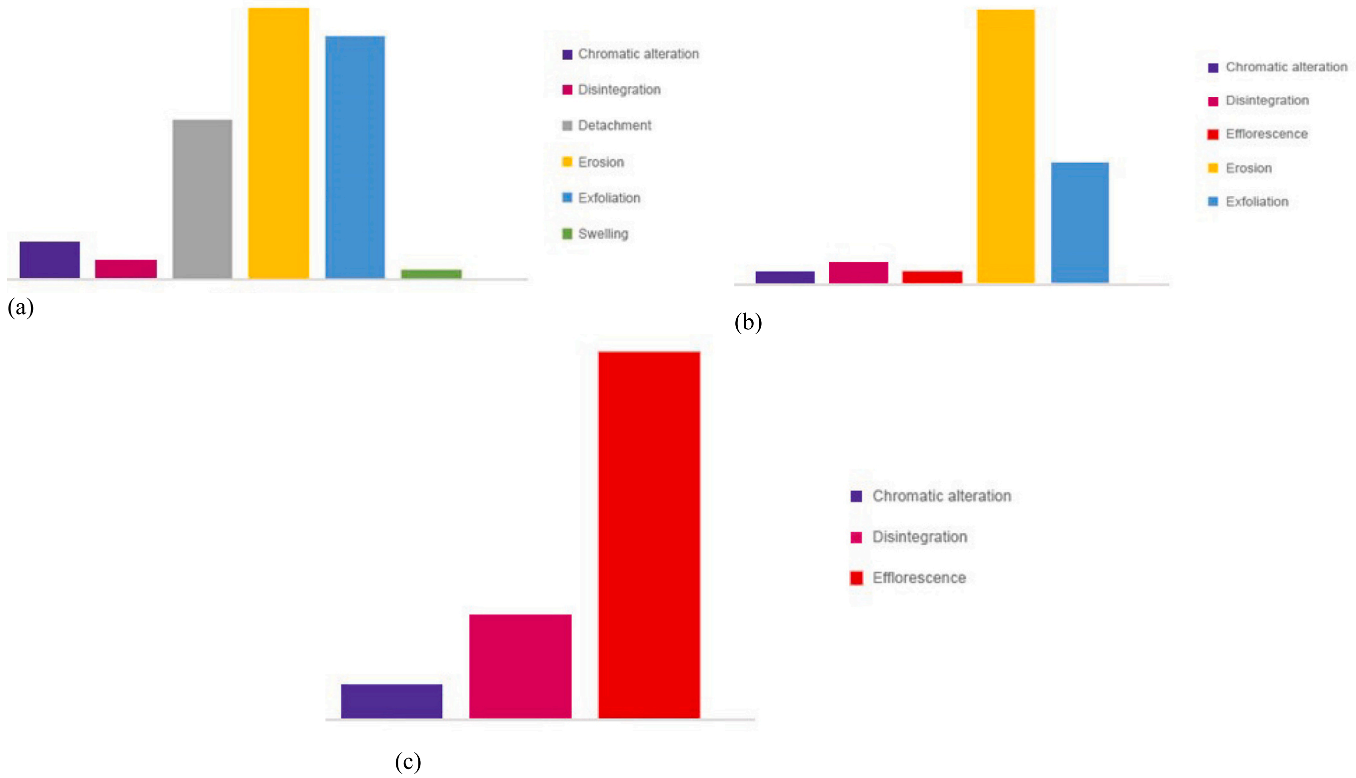


Fig. 12. (a) Column decay; (b) Coat of arms decay; (c) Arch decay.

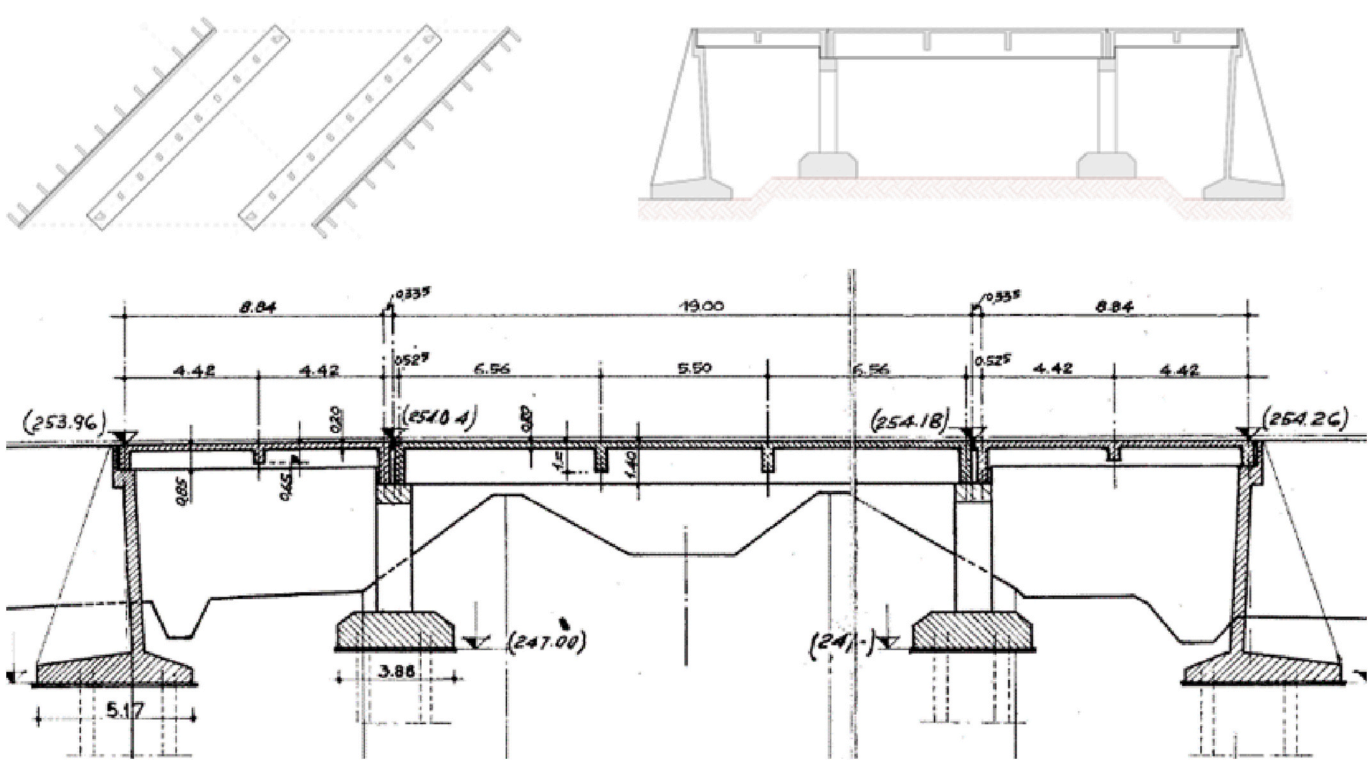


Fig. 13. Existing paper documentation.

order to associate an identification code (ID) to each element. it is important to define a specific I.D. in order to monitor and maintain the elements during the entire life cycle. The coding is represented by an identification alphanumeric string for each category and subcategory according to the belonging of the single element. The ID is defined in the following way: (Table 8):

Table 7
Viaduct element breakdown.

Element type
Superstructure
Street superstructure
Road pavement
Safety and signage
Safety barriers
Road markings
Substructure
Deck
Transverse beams
Reinforced slab
Longitudinal beams
Support beams
Pier Cap
Pile connection beams
Joints
Wall fill
Expansion joint
Pile
Shoulder elevation structure
Foundations
Shallow foundation
Foundation plinth

4.3.2. Data digitization and definition of elements and goals

After the breakdown of the complex elements and the collection of all the data of the viaduct, the "BIM Modeling and Digitization" has been performed.

The chosen BIM authoring software is Revit by Autodesk. The process started with the creation of the BIM objects of each element and then proceeded to the composition of the entire viaduct. All the parameters and data previously collected were associated with each BIM object (Fig. 16):

- I.D. W.B.S.;
- Material;
- State of art;
- Previous maintenance interventions;
- Defectiveness statement;
- Diagnosis statement (if necessary);
- Multimedia material.

In the data digitization phase it is important to define the type of sensors to be used. After a careful study of the viaduct, sensors were chosen being able to predict or to ascertain the origin of a deterioration

Table 8
Breakdown of the viaduct.

ID	Element type	Coding
SV01	Superstructure	
SS01	Street superstructure	
PV01	Road pavement	V01.SV01.SS01.PV01
SCS01	Safety and signage	
BS01	Safety barriers	V01.SV01.SCS01.BS01
SO01	Road markings	V01.SV01.SCS01.SO01
ST01	Substructure	
IP01	Deck	
TT01	Transverse beams	V01.ST01.IP01.TT01
SA01	Reinforced slab	V01.ST01.IP01.SA01
TL01	Longitudinal beams	V01.ST01.IP01.TL01
TR01	Support beams	V01.ST01.IP01.TR01
PL01	Pier Cap	
TC01	Pile connection beams	V01.ST01.PL01.TC01
AG01	Joints	
RM01	Wall fill	V01.ST01.AG01.RM01
GD01	Expansion joint	V01.ST01.AG01.GD01
PIL01	Pile	
SEP	Shoulder elevation structure	V01.ST01.SP01.SES01
FD01	Foundations	

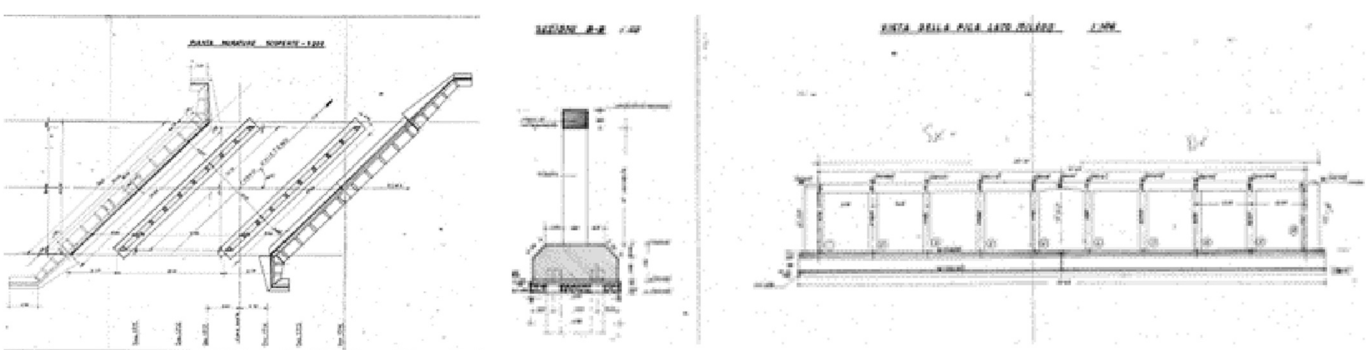


Fig. 14. Extract of the design document found.

Fig. 15. Photographs taken with the Drone.

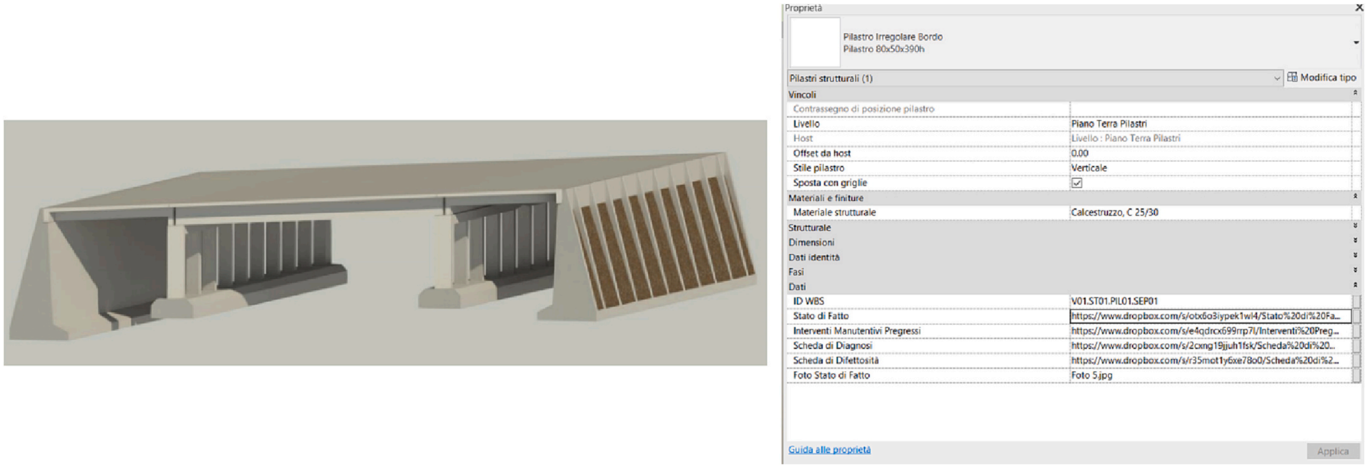


Fig. 16. (a) Render of the viaduct performed with software Revit (b) Properties associated with the software Revit.

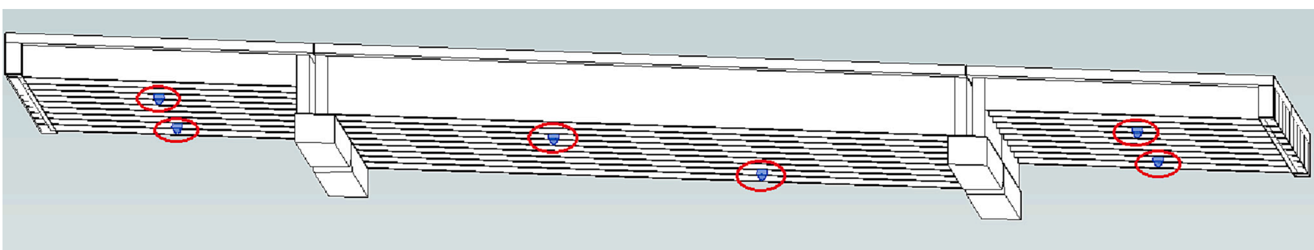


Fig. 17. Positioning of the cameras in the model.

```
*DefaultUserDefinedParameterSets 1 - Blocco note di Windows
File  Modifica  Formato  Visualizza  ?
#
PropertySet:    NomeElemento    I       IfcElement
        ID WBS  Text
PropertySet:    NomeElemento    I       IfcElement
        Stato di Fatto  URL
PropertySet:    NomeElemento    I       IfcElement
        Interventi Manutentivi Pregressi        URL
PropertySet:    NomeElemento    I       IfcElement
        Scheda di Diagnosi      URL
PropertySet:    NomeElemento    I       IfcElement
        Scheda di Difettosità   URL
PropertySet:    NomeElemento    I       IfcElement
        Foto Stato di Fatto     Image
```

Fig. 18. Txt file used for properties export.

phenomenon:

- Plinth - Biaxial inclinometer positioned on the extrados of the plinth;
- Pile - Displacement transducers to measure relative vertical displacements;
- Pier Cap - Displacement transducers to measure relative vertical displacements;
- Transverse Beam - Displacement transducers to measure the relative vertical displacements corresponding to the beam axis; topographic targets for the survey of the arrow;
- Longitudinal beam - Displacement transducers to measure the relative vertical displacements and in correspondence of the beam axis, topographic targets for the survey of the arrow;
- Deck - Geophone to evaluate vibrations and at the centerline of each span, topographic sights for the survey of the deck arrow;
- Thermal sensors for measuring temperature and humidity;
- Drainage channel - Flow reader to check the proper functioning of the drainage channel;
- High resolution cameras for visual monitoring of degradation.

Once the sensors and cameras were chosen, they were inserted into the BIM model in specific points as reported in the example below Fig. 17.

Once the modeling of the viaduct has been finalized, the BIM model has been exported in IFC format. The .ifc file can be read by a Common Data Environment (CDE) platform which displays all the information that has been previously implemented in the model. Therefore, it is necessary to properly set the export options in the Revit tool, so as to correctly show all the properties within the Platform (Fig. 18).

4.3.3. Management and monitoring of the model on the platform

Once the IFC file has been set up correctly, it is imported into the data sharing platform, namely the CDE. The platform chosen in this research is ACCA Software's USBIM Platform.

This application allows the import of an ifc file and the display and management of all the elements and parameters connected to the BIM model via a browser application, in a complete and immediate way.

It provides the possibility of hosting multiple users who can simultaneously operate on different parts of the project and facilitating communication between different operators via a built-in messaging service inside the platform (Fig. 19).

In this way it is possible to view and manage all the information associated with each element of the BIM model.

From this stage onwards, the platform "UsBIM" was developed "ad hoc" for research purposes to associate the defect statement with each element. This application has been developed to update and monitor the conditions of each parameter and therefore of the viaduct in real time.

An important customization is the creation of a schedule for each

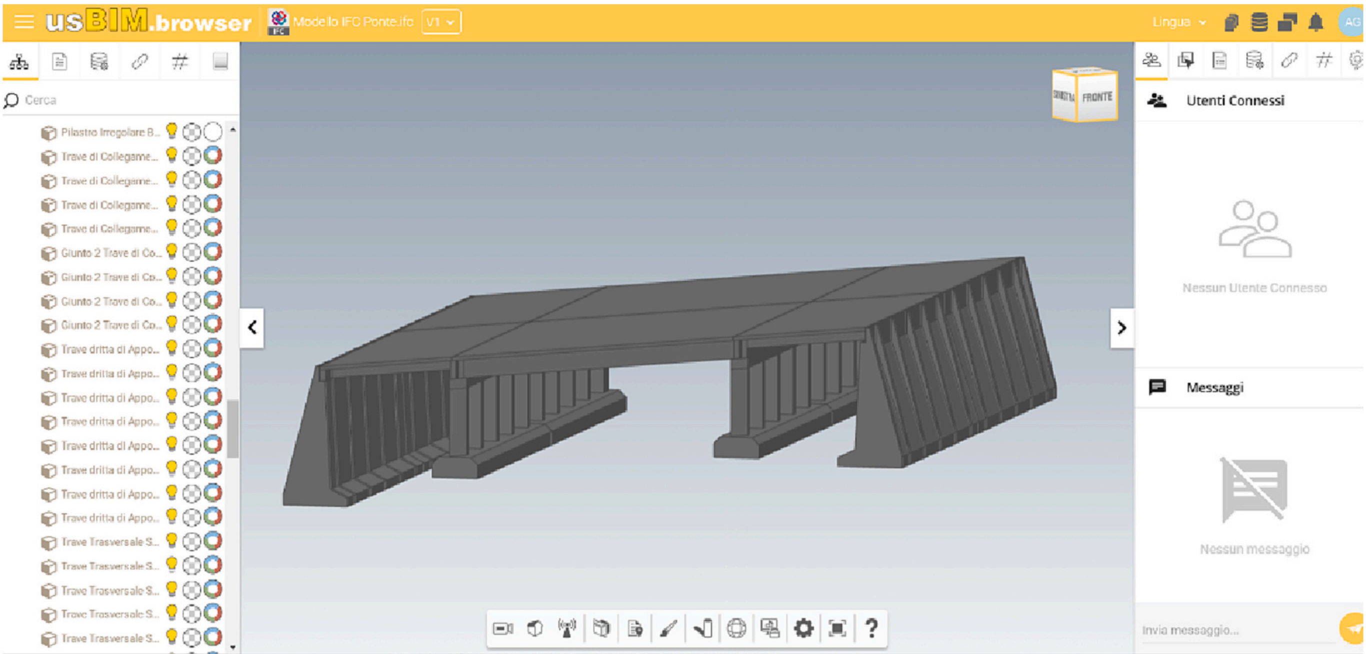


Fig. 19. Visualization of the model in UsBim Browser.

Level 1 Bridge Inspection Form

3	Pile N _____ Concrete			Location:_________________________ Survey technician __________________							Progressive km:__________ Inspection date: __/__/__			
Damage code	Damage description	Checked	G	Extension K_1			Intensity K_2			N° photo	PS	NA	NR	NP
				0,2	0,5	1	0,2	0,5	1					
c.a/c.a.p._1	Passive moisture stains	☐	1	☐	☐	☐	☐	☐	☐			☐	☐	☐
c.a/c.a.p._2	Active moisture stains	☐	3	☐	☐	☐			☐			☐	☐	☐
Dif. Gen_1	Traces of drainage	☐	3	☐	☐	☐			☐			☐	☐	☐
c.a./c.a.p._3	Deteriorated concrete	☐	3	☐	☐	☐			☐			☐	☐	☐
Dif. Gen_2	Stagnant water	☐	2	☐	☐	☐			☐			☐	☐	☐
c.a./c.a.p._4	Crawl spaces	☐	2	☐	☐	☐	☐	☐	☐			☐	☐	☐
c.a./c.a.p._5	Detachment of the concrete cover	☐	2	☐	☐	☐			☐			☐	☐	☐
c.a./c.a.p._6	Oxidized steel	☐	5	☐	☐	☐	☐	☐	☐		☐	☐	☐	☐
c.a./c.a.p._7	Widespread lesions	☐	1	☐	☐	☐	☐	☐	☐			☐	☐	☐
c.a./c.a.p._15	Injuries to the stirrups	☐	2	☐	☐	☐	☐	☐	☐			☐	☐	☐
c.a./c.a.p._8	Horizontal cracks	☐	2	☐	☐	☐	☐	☐	☐			☐	☐	☐

Fig. 20. Example of a defect schedule for a pile.

element the defect statement proposed in the "Guidelines for the classification and management of risk, the evaluation of safety and the monitoring of existing bridges" [71]. These defect schedules are different for each type of structural element (piers, beams, support elements, etc.) and for the various construction materials (reinforced concrete, steel, etc.).

A G value between 1 and 5 is attributed to each defect. This value represents the intensity of the defect as a function of: (a) possibility of danger and reduction of the bearing capacity; (b) the risk of triggering other defects and the high economic cost for the repair. The following image shows a typical evaluation form Fig. 20:

Once the form has been completed, a final number is obtained which represents the state of the single element of the overall structure. The condition of the element will be worse if the number is higher. This value is given by the sum of the weights "G" determined by the damages of the individual elements, multiplied by the coefficients "K1" and "K2". The extension coefficient can assume values of 0.2–0.5–1.0, which have the following meaning:

- K1 = 0,2, the analyzed defect is present, but affects only a minimal part of the area;
- K1 = 0,5, the defect affects a percentage of the area between 30 and 70;
- K1 = 1,0, the defect affects the entire area.

. The Relative Defeet(Dr) is calculated using the coefficients discussed above, given by (Eq. 2), and represents the condition of the single structural element. It takes into account that the same damage can weigh differently depending on the involved structural element:

$$Dr = \sum (G^{*}K1^{*}K2) \tag{2}$$

Where the sum is extended to all the damages of the single structural element.

The "Absolute Defect (Da)" defines the overall deterioration of the

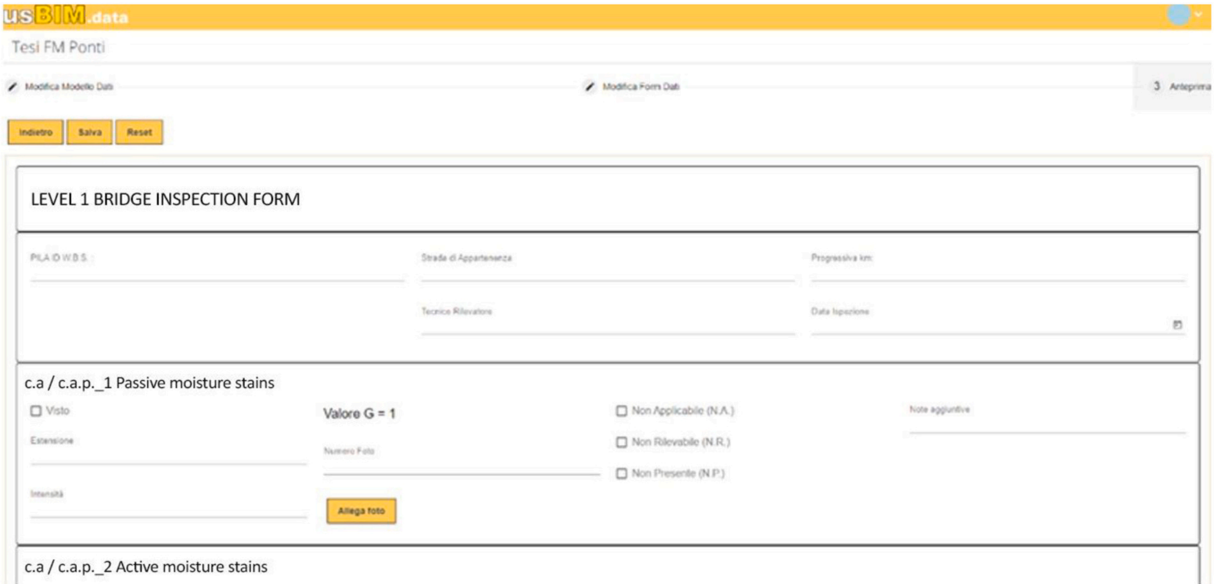


Fig. 21. C.a. Pile defect card created with UsBIM data.

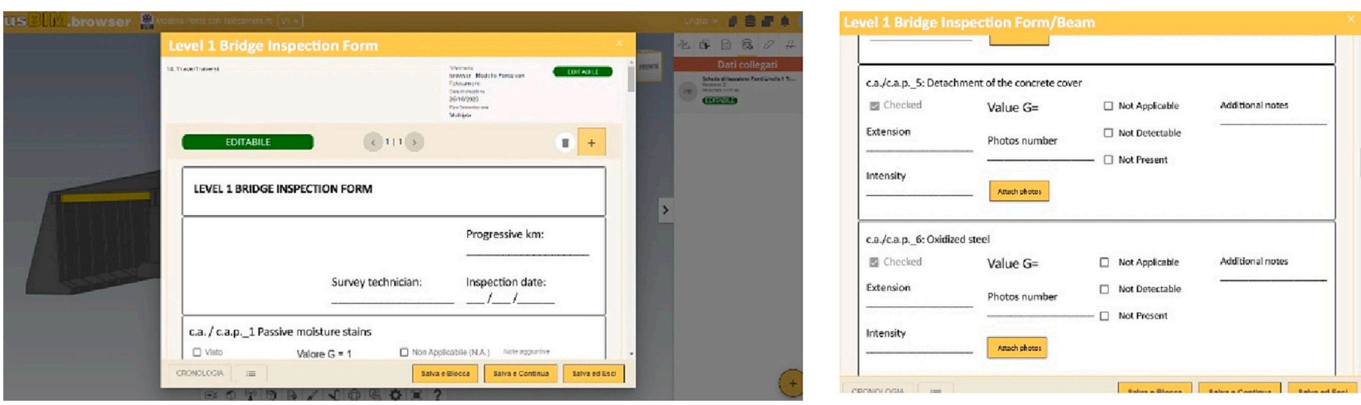


Fig. 22. Display of the defect sheet in the general information.

structure and is calculated using the previous formula by multiplying, within the sum, the number of individual structural elements (Eq.3).

$$Da = \sum(G^*K1^*K2^*N) \tag{3}$$

These defect schedules have been created in the UsBIM data platform (CDE) (Fig. 21). The parameters compiled in the sheets are directly associated with each single element of the viaduct and are displayed using the UsBIM browser (Fig. 22):

In this way the facility technician can draw up the defect sheet on site, using tablets or smartphone, and transfer the data directly to the model and then to the operation center.

4.3.4. Planning and execution of interventions

The monitoring phase of the viaduct over time begins after inserting the defect sheets for each element in the BIM model. The monitoring of the viaduct is developed using the UsBim Platform application: UsBim I.O.T..

The UsBIM I.O.T. has already been created for building applications. However, in this research project, the application has been specifically customized for an infrastructure project and the monitoring system has been implemented "ad hoc". In this way, the monitoring of all the sensor instruments previously foreseen is possible. An important customization is that the connection to the telecare circuit allows real-time monitoring of the degradation or the conditions following unexpected events (Fig. 23).

The goal of monitoring with sensors is to continuously update the indices of degradation connected to the elements. As a result, it is also possible to manage alert conditions by instantly reporting the infrastructure element subject to crisis. This situation therefore requires an on-site inspections to collect more precise data.

In this phase another aim of the research is analyzed, which concerns the development of an automatic intervention system. To achieve this goal it is necessary to set acceptability threshold limits for the parameters monitored by the sensors.

The choice of threshold values to be associated within the platform depends on the selected key performance indicator (KPIs) and on the type of maintenance that needs to be carried out. Key performance indicators are specific time dependent quantifiable and allow for evaluation the performance of the system with respect to objectives, whether technical, environmental or financial [72,73]. The KPIs selected for the present case study derive from a careful analysis of the Level 1 Bridge Inspection Form. The following KPIs have been derived for the present case study:

a) Single dangerous damage: in this case we intend to monitor the single damage which has a G value of 5. This damage could affect the behavior of the entire system. When the values of K exceed 0.6, the

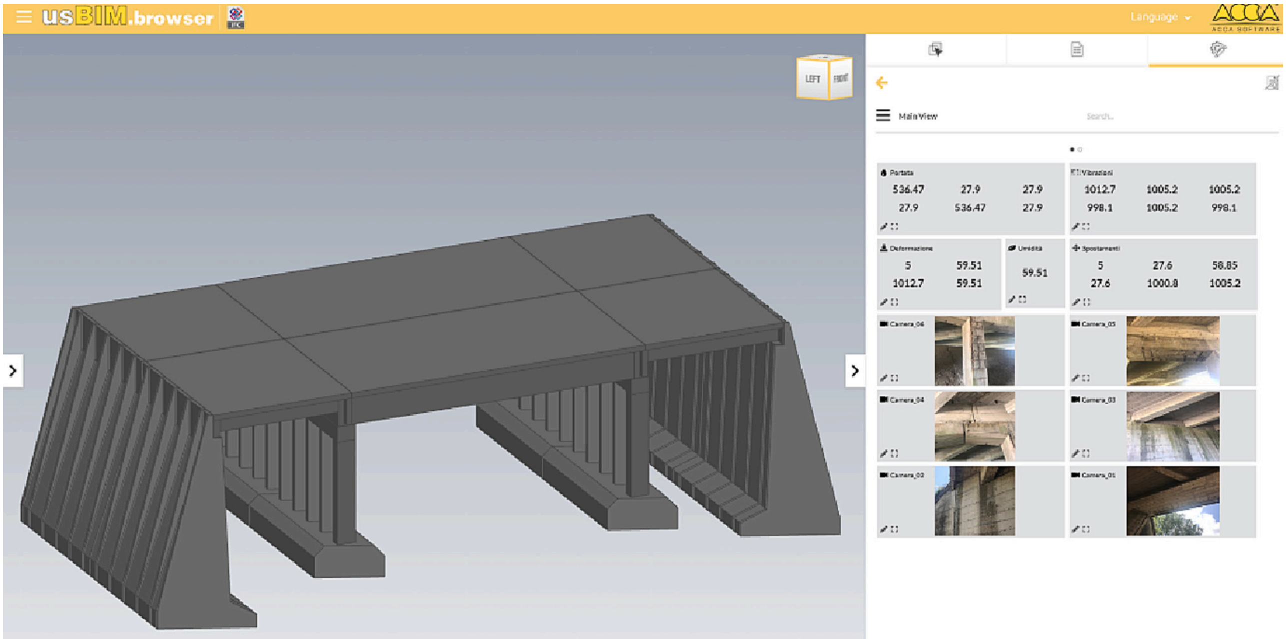


Fig. 23. Display of the model and sensors on UsBim I.O.T.

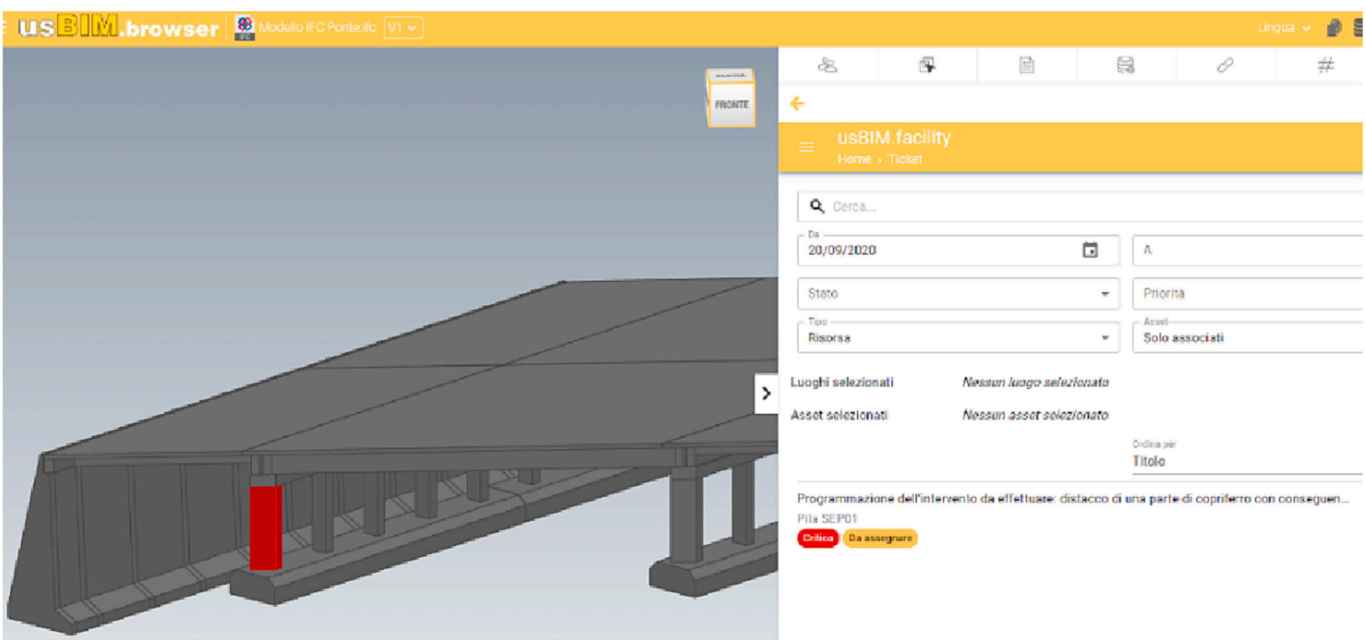


Fig. 24. Opening of the ticket due to detachment of concrete cover.

defect affects a percentage of the area between 50 and 70, the threshold limit is exceeded

b) Single structural element damage: in this case we intend to monitor the damage of the single structural element. When the values of Dr. reaches high values the defects can affect the behavior of the entire system and the threshold limit is exceeded
c) Structure damage: in this case we intend to monitor the damage to the entire structural system. When the values of Da reaches high values the entire structural system needs maintenance.

The type of KPI to be used and the numerical threshold values to be set depend on the type of maintenance that the manager intends to carry out.

Limits can be set as below:

- Preventive maintenance, providing for lower limits of development of degradation and therefore interventions closer in time which prevent higher cost interventions;
- Reactive maintenance, foreseeing higher limits for the development of degradation and therefore interventions that are delayed over time but a more incisive intervention is required on an element, thus restoring its efficiency.

When the threshold limit of an element is exceeded, the platform highlights the element on the screen with a reference color (orange or red). Subsequently, an alert is sent automatically (if the exceeding of the

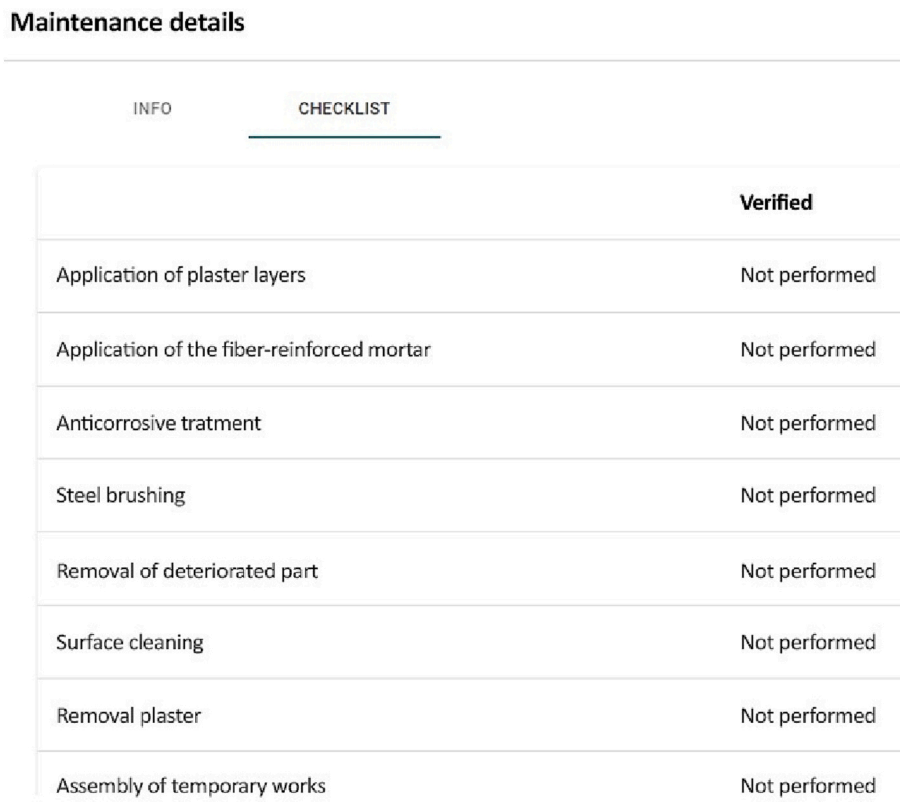


Fig. 25. Checklist for maintenance.

threshold limit is recorded through sensors or schedules) or manually (if the exceeding of the threshold limit is recorded by cameras), notifying the need to pay attention to the element that does not satisfy the acceptability threshold.

The same platform has been developed “ad hoc” to manage all the phases following the activation of the alert (UsBIM Facility). Once the alert is activated, a ticket is automatically opened in order to plan, organize and carry out targeted maintenance for the damaged element. An example of sending alerts and opening the ticket is shown below (Fig. 24):

In this case, the degradation that has been detected is the “detachment of concrete cover” correlated with the degradation “oxidation of longitudinal reinforcement”. The phases scheduled by the ticket are:

- Timing, immediate or on the first available working day, of the urgent maintenance intervention;
- The organization, which includes notification to the specialized team and the organization of the necessary resources in terms of equipment and materials;
- The execution of the maintenance, which consists in the step-by-step guide of the intervention thanks to the use of a checklist to be carried out on site for the execution of the intervention with subsequent final report that contemplates a verification and subsequent closure of the ticket and the alert.

A notification will be sent on the device of specialized workers with the date and specifications of the intervention to be carried out.

Once the team has moved to the intervention site, a checklist of operations to be carried out to resolve the alert, to complete the ticket and to re-establish the conditions of acceptability of the element will be sent (Fig. 25).

Thanks to the updates sent by the workers through their own devices, all the operations foreseen in the checklist can be monitored in real time on the centralized model. After a check by means of cameras has been performed, the ticket is closed and the color of the element that has been subject of the intervention is restored.

In this way, the viaduct model will always be kept updated on the platform and its real time conditions will always be known.

5. Discussion and conclusions

The digitization of buildings of infrastructure seems to have become increasingly essential for their care and reuse. For this reason, it is necessary to increase the knowledge about the building assets to support sustainable maintenance and conservation strategies through the development of easy-to-use resource management tools. This allows to support the decision-making process towards a conservation strategy accessible by all stakeholders.

Maintenance of existing works can be interpreted as a complex decision-making problem especially due to the limited availability of economic resources. Therefore, in decision-making processes, it becomes important to have a method that follows standard procedures that support technicians and managers.

This research aims to standardize procedures in order to optimize the management and minimize the maintenance costs of existing works.

The method is based on Building Condition Assessment (BCA) techniques integrated with Building Information Modeling (BIM) methodologies.

The result of the research consists in the application of a maintenance management procedure through the BIM modeling of two existing assets of different types in order to demonstrate the standardization of the proposed process. In particular, the first case study concerns the BIM model of the Brunelleschi’s Cloister which monitors and tracks the deterioration of the historical building, collecting and classifying various data that coexist in a model of cultural assets.

The model data is managed directly by a specially created Revit-Dynamo system that directly connects a Master database in Excel spreadsheets and the BIM model in Revit to create a “digital dossier” of the state of the art and of the design of the interventions of maintenance.

The integration between KPI related to the measurement of building condition with an emerging, automated and collaborative methodology like BIM improves BCA taking advantage from the Revit software functionalities. Besides providing a prompt strategy to evaluate building performance, this methodology motivates the implementation of BCA during facility management, since the information record becomes easier, providing a reduction of costs and a more efficient maintenance management.

The reason for using Excel spreadsheet to collect data is twofold: managers and technicians are familiar with Office packages and licence purchase costs are low. However, there are system limitations. In fact, the use of external databases, such as Excel spreadsheets or even as Access databases, connected to the BIM model through Dynamo must be located in a single server without undergoing directory changes, as this could lead to non-reading / writing. of the in-put / output information.

The second case study concerning the BIM model of a road infrastructure, in addition to retracing the same standardization process for the management of maintenance in BIM, aims to overcome the criticalities encountered in the case study of the Brunelleschi's Cloister. In fact, in this case study, a centralized information database based on IFC is proposed. This database is supported by dashboards for displaying the information collected. Furthermore, this information is updated by the data deriving from on-site monitoring, developed by means of suitable sensors, which are processed to obtain useful evidence for the decision-making process for the conduct of maintenance operations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] A.I. Che Ani, N. Mohd Tawil, S. Johar, M.Z. Abd Razak, H. Yahaya, Building condition assessment for new houses: a case study in terrace houses, Jurnal Teknologi. 70 (2014), https://doi.org/10.11113/jt.v70.2812.

[2] M.C. Dejaco, F. Re Cecconi, S. Maltese, Key performance indicators for building condition assessment, J. Build. Eng. 9 (2017) 17–28, https://doi.org/10.1016/j.jobe.2016.11.004.

[3] G. Totaro, P. Gasparoli, Sui processi di manutenzione del patrimonio costruito storico tutelato. Convenienze economiche, sviluppi occupazionali e altre esternalità positive (On the maintenance processes of the protected historical built heritage. Economic benefits, employment developments and other positive externalities), Lo Stato Dell'Arte 12 (2014) 743–750. https://www.politesi.polimi.it/bitstream/10589/116488/1/2015_gennaio_PhD_Totaro.pdf.

[4] ISO 41011:2017(en), Facility management — Vocabulary. https://www.iso.org/obp/ui/#iso:std:iso:41011:ed-1:v1:en, 2022 (accessed September 16, 2020).

[5] A. Akcamete, B. Akinci, J.H. Garrett, Potential utilization of building information models for planning maintenance activities, in: Proceedings of the International Conference on Computing in Civil and Building Engineering, 2010, pp. 151–157. https://scholar.google.com/citations?view_op=view_citation&hl=en&user=6dfQJzoAAAAJ&citation_for_view=6dfQJzoAAAAJ:UeHWp8X0CEIC.

[6] R. Marmo, M. Nicolella, F. Polverino, A. Tibaut, A methodology for a performance information model to support facility management, Sustainability. 11 (2019) 7007, https://doi.org/10.3390/su11247007.

[7] ISO 29481-1:2016(en), Building information models — Information delivery manual — Part 1: Methodology and format. https://www.iso.org/obp/ui/#iso:std:iso:29481:-1:ed-2:v1:en, 2022 (accessed January 22, 2022).

[8] D.R. Uzarski, M.N. Grussing, J.B. Clayton, Knowledge-based condition survey inspection concepts, J. Infrastruct. Syst. 13 (2007) 72–79, https://doi.org/10.1061/(ASCE)1076-0342(2007)13:1(72).

[9] B. Manganelli, Il deprezzamento degli immobili urbani: principi teorici, approcci metodologici, profili innovativi nella valutazione, (The depreciation of urban properties: theoretical principles, methodological approaches, innovative profiles in valuation), FrancoAngeli, Milano, 2011. ISBN 9788856840964.

[10] P.M. Teicholz, IFMA Foundation (Eds.), BIM for Facility Managers, John Wiley & Sons, Inc, Hoboken, New Jersey, 2013. ISBN: 978–1–118-38281-3.

[11] A. Crespo Márquez, P. Moreu de León, J.F. Gómez Fernández, C. Parra Márquez, M. López Campos, The maintenance management framework: a practical view to maintenance management, J. Qual. Maint. Eng. 15 (2009) 167–178, https://doi.org/10.1108/13552510910961110.

[12] M. Kassem, G. Kelly, N. Dawood, M. Serginson, S. Lockley, BIM in facilities management applications: a case study of a large university complex, Built Environ. Project Asset Manag. 5 (2015) 261–277, https://doi.org/10.1108/BEPAM-02-2014-0011.

[13] J.J. McArthur, A building information management (BIM) framework and supporting case study for existing building operations, maintenance and sustainability, Proc. Eng. 118 (2015) 1104–1111, https://doi.org/10.1016/j.proeng.2015.08.450.

[14] R. Volk, J. Stengel, F. Schultmann, Building Information Modeling (BIM) for existing buildings — literature review and future needs, Autom. Constr. 38 (2014) 109–127, https://doi.org/10.1016/j.autcon.2013.10.023.

[15] ISO 19650-3:2020, ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/07/51/75109.html, 2022 (accessed January 27, 2022).

[16] G. Acampa, C.M. Parisi, Cultural Heritage Management: Optimising Procedures and Maintenance Costs 29, 2022, pp. 79–102. https://siev.org/wp-content/uploads/2022/01/07_ACAMPA_PARISI_1.pdf.

[17] WARMEST Project, WARMEST EU PROJECT – loW Altitude Remote Sensing for the Monitoring of the State of Cultural hEritage Sites: Building an inTegrated Model for Maintenance. http://warmestproject.eu/, 2017.

[18] G. Acampa, C.M. Parisi, Management of maintenance costs in cultural heritage, in: Appraisal and Valuation, Springer, 2020, pp. 195–212 (ISBN 978-3-030-49579-4.).

[19] G. Acampa, M. Grasso, Heritage Evaluation: restoration plan through HBIM and MCDA, in: IOP Conference Series: Materials Science and Engineering 949, 2020, 012061, https://doi.org/10.1088/1757-899X/949/1/012061.

[20] G. Acampa, M. Grasso, Integrated Evaluation Methods to Hbim for the Management of Cultural Heritage: The Case Study of the Colonnade of Patio de Los Leones, Alhambra-Granada, 2022. https://iris.unikore.it/handle/11387/150142.

[21] V. Ferretti, M. Bottero, G. Mondini, Decision making and cultural heritage: an application of the multi-attribute value theory for the reuse of historical buildings, J. Cult. Herit. 15 (2014) 644–655, https://doi.org/10.1016/j.culher.2013.12.007.

[22] A. Oppio, M. Bottero, V. Ferretti, U. Fratesi, D. Ponzini, V. Pracchi, Giving space to multicriteria analysis for complex cultural heritage systems: the case of the castles in Valle D'Aosta Region, Italy, J. Cult. Herit. 16 (2015) 779–789, https://doi.org/10.1016/j.culher.2015.03.003.

[23] E. Piaia, F. Maietti, R. Di Giulio, O. Schippers-Trifan, A. Van Delft, S. Bruinenberg, R. Olivadese, BIM-based cultural heritage asset management tool. Innovative solution to orient the preservation and valorization of historic buildings, Int. J. Archit. Herit. (2020) 1–24, https://doi.org/10.1080/15583058.2020.1734686.

[24] A. Barontini, C. Alarcon, H.S. Sousa, D.V. Oliveira, M.G. Masciotta, M. Azenha, Development and demonstration of an HBIM framework for the preventive conservation of cultural heritage, Int. J. Architect. Heritage. (2021) 1–23, https://doi.org/10.1080/15583058.2021.1894502.

[25] R. Matos, F. Rodriguez, H. Rodrigues, A. Costa, Building condition assessment supported by building information modelling, J. Build. Eng. 38 (2021), https://doi.org/10.1016/j.jobe.2021.102186.

[26] A.J. Guillen, A. Crespo, J. Gómez, V. González-Prida, K. Kobbacy, S. Shariff, Building Information Modeling as assest Management Tool, IFAC-PapersOnLine. 49 (2016) 191–196, https://doi.org/10.1016/j.ifacol.2016.11.033.

[27] ISO - ISO 55000:2014, ISO - ISO 55000:2014 - Asset Management — Overview, Principles and Terminology. https://www.iso.org/standard/55088.html, 2022 accessed September 25, 2020.

[28] D.F. Percy, K.A. Kobbacy, Determining economical maintenance intervals, Int. J. Prod. Econ. 67 (2000) 87–94, https://doi.org/10.1016/S0925-5273(00)00013-X.

[29] S. Yacob, A.S. Ali, A.-Y.C. Peng, Building condition assessment: lesson learnt from pilot projects, MATEC Web Conf. 66 (2016) 00072, https://doi.org/10.1051/matecconf/20166600072.

[30] F. Re Cecconi, S. Maltese, M.C. Dejaco, Leveraging BIM for digital built environment asset management, Innov. Infrastruct. Solutions 2 (2017) 14, https://doi.org/10.1007/s41062-017-0061-z.

[31] S.N.F. Zuraidi, M.A. Abdul Rahman, Z.A. Akasah, The development of condition assessment for heritage building, in: E3S Web Conference 65, 2018, p. 01007, https://doi.org/10.1051/e3sconf/20186501007.

[32] M.Z.T. Anuar, N.N. Sarbini, I.S. Ibrahim, M.H. Osman, M. Ismail, M.C. Khun, A comparative of building condition assessment method used in Asia countries: a review, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2019, p. 012029. https://iopscience.iop.org/article/10.1088/1757-899X/513/1/012029/meta. https://doi.org/10.1088/1757-899X/513/1/012029.

[33] M.A.A. Rahman, A.W.N.A. Manan, Building condition assessment in school using JKR standard, Progr. Eng. Appl. Technol. 1 (2020) 39–47. https://publisher.uthm.edu.my/periodicals/index.php/peat/article/view/238.

[34] F. Faqih, T. Zayed, Defect-based building condition assessment, Build. Environ. 191 (2021), 107575, https://doi.org/10.1016/j.buildenv.2020.107575.

[35] A. Straub, Dutch standard for condition assessment of buildings, Struct. Surv. 27 (2009) 23–35, https://doi.org/10.1108/02630800910941665.

[36] S. Linggar, A. Aminullah, A. Triwiyono, Analysis of building and its components condition assessment case study of dormitory buildings, in: MATEC Web Conference 258, 2019, p. 03003, https://doi.org/10.1051/matecconf/201925803003.

[37] S. Mohd Noor, C. Shing Mei, I. Syahrizal Ibrahim, N. Nabilah Sarbini, M. Hanim Osman, N. Azeyah Khiyon, Heritage building condition assessment: a case study from Johor Bahru, Malaysia, in: IOP Conference Series: Earth Environmental

Science 220, 2019, p. 012024, https://doi.org/10.1088/1755-1315/220/1/012024. Issue 1.

[38] G.R. Abbott, J.J. Mc Duling, S. Parsons, J.C. Schoeman, Building condition assessment: a performance evaluation tool towards sustainable asset management, in: CIB World Building Congress 2007, 2007. https://www.irbnet.de/daten/iconda/CIB4748.pdf.

[39] T.T. Amasuomo, J. Atanda, G. Baird, Development of a building performance assessment and design tool for residential buildings in Nigeria, Proc. Eng. 180 (2017) 221–230, https://doi.org/10.1016/j.proeng.2017.04.181.

[40] F. Franceschini, Designing Performance Measurement Systems: Theory and Practice of Key Performance Indicators, Springer Berlin Heidelberg, New York, NY, 2018, https://doi.org/10.1007/978-3-030-01192-5.

[41] R. Marmo, F. Polverino, M. Nicolella, A. Tibaut, Building performance and maintenance information model based on IFC schema, Autom. Constr. 118 (2020), 103275, https://doi.org/10.1016/j.autcon.2020.103275.

[42] UNI EN 15341, UNI EN 15341:2019 Maintenance - Key Performance Indicators. http://store.uni.com/catalogo/uni-en-15341-2019, 2019 (accessed October 6, 2020).

[43] S. Singh Ahluwalia, A Framework for Efficient Condition Assessment of the Building Infrastructure. http://hdl.handle.net/10012/4093, 2008.

[44] F. Re Cecconi, N. Moretti, M. Claudio Dejaco, Measuring the performance of assets: a review of the facility condition index, Int. J. Strateg. Prop. Manag. 23 (2019) 187–196, https://doi.org/10.3846/ijspm.2019.7955.

[45] N. Moretti, F. Re Cecconi, A cross-domain decision support system to optimize building maintenance, Buildings. 9 (2019) 161, https://doi.org/10.3390/buildings9070161.

[46] A.A. Enshassi, F. El Shorafa, Key performance indicators for the maintenance of public hospitals buildings in the Gaza strip, Facilities. (2015), https://doi.org/10.1108/F-07-2013-0053.

[47] F.M. Leite, R.A. Volse, H.R. Roman, F.A. Saffaro, Building condition assessment: adjustments of the building performance Indicator (BPI) for university buildings in Brazil, Ambiente Construido 20 (2020) 215–230, https://doi.org/10.1590/s1678-86212020000100370.

[48] S. Moghimi, S. Mat, C.H. Lim, A. Zaharim, K. Sopian, Building energy index (BEI) in large scale hospital: case study of Malaysia, in: 4th WSEAS International Conference on Recent Reseaches in Geography Geology, Energy, Environment and Biomedicine, Corfu Island, Greece, 2011, https://doi.org/10.1007/s12053-013-9221-y.

[49] Y. Ishizuka, The degradation and prediction of service life of building component, in: Second International Conference on Durability of Building Materials and Components, September 14–16, 1981: Preprints, US Department of Commerce, National Bureau of Standards, 1981, pp. 345–352, 69. Vol. 1, No. 4, https://www.irbnet.de/daten/iconda/CIB1073.pdf.

[50] G. Acampa, M. Grasso, G. Marino, C.M. Parisi, Tourist flow management: social impact evaluation through social network analysis, Sustainability. 12 (2020) 731, https://doi.org/10.3390/su12020731.

[51] G. Acampa, G. Marino, C.M. Parisi, Social network as tool for the evaluation of sustainable urban mobility in Catania (Italy), in: C. Bevilacqua, F. Calabrò, L. Della Spina (Eds.), New Metropolitan Perspectives, Springer International Publishing, Cham, 2021, pp. 243–253, https://doi.org/10.1007/978-3-030-48279-4_23.

[52] S. Bruno, F. Fatiguso, Building conditions assessment of built heritage in historic building information modeling, Int. J. SDP. 13 (2018) 36–48, https://doi.org/10.2495/SDP-V13-N1-36-48.

[53] S. Bruno, M. De Fino, F. Fatiguso, Historic building information modelling: performance assessment for diagnosis-aided information modelling and management, Autom. Constr. 86 (2018) 256–276, https://doi.org/10.1016/j.autcon.2017.11.009.

[54] N. Bruno, R. Roncella, HBIM for conservation: a new proposal for information modeling, Remote Sens. 11 (2019) 1751, https://doi.org/10.3390/rs11151751.

[55] G. Di Pietro, F. Rinnone, C.M. Parisi, S. Caprì, G. Bianco, Status app: a mobile data collection tool for buildings adjacent to tunneling works, Buildings. 10 (2020) 7, https://doi.org/10.3390/buildings10010007.

[56] Y.-C. Lin, Y.-C. Su, Developing mobile- and BIM-based integrated visual facility maintenance management system, Sci. World J. 2013 (2013), e124249, https://doi.org/10.1155/2013/124249.

[57] Y.C. Su, Y.C. Lee, Y.C. Lin, Enhancing Maintenance Management Using Building Information Modeling in Facilities Management, in: Seoul, Korea, 2011, https://doi.org/10.22260/ISARC2011/0140.

[58] V. Villa, C. Eastman, G.M. Di Giuda, Il BIM: Guida Completa al Building Information Modeling per Committenti, Architetti, Ingegneri, Gestori Immobiliari e Imprese (Complete Guide to Building Information Modeling for Clients, Architects, Engineers, Property Managers and Companies), Hoepli, Milano, 2016. ISBN 882036705X.

[59] M.G. Masciotta, M.J. Morais, L.F. Ramos, D.V. Oliveira, L.J. Sánchez-Aparicio, D. González-Aguilera, A digital-based integrated methodology for the preventive conservation of cultural heritage: the experience of HeritageCare Project, Int. J. Archit. Herit. 15 (2021) 844–863, https://doi.org/10.1080/15583058.2019.1668985.

[60] R. Mora, L.J. Sánchez-Aparicio, M.Á. Maté-González, J. García-Álvarez, M. Sánchez-Aparicio, D. González-Aguilera, An historical building information modelling approach for the preventive conservation of historical constructions: application to the Historical Library of Salamanca, Autom. Constr. 121 (2021), 103449, https://doi.org/10.1016/j.autcon.2020.103449.

[61] L.J. Sánchez-Aparicio, M.-G. Masciotta, J. García-Alvarez, L.F. Ramos, D. V. Oliveira, J.A. Martín-Jiménez, D. González-Aguilera, P. Monteiro, Web-GIS approach to preventive conservation of heritage buildings, Autom. Constr. 118 (2020), 103304, https://doi.org/10.1016/j.autcon.2020.103304.

[62] J.H. Park, T. Nagakura, A thousand Bim: a rapid value-simulation approach to developing a BIM tool for supporting collaboration during schematic design, Int. J. Archit. Comput. 12 (2014) 47–60, https://doi.org/10.1260/1478-0771.12.1.47.

[63] M. Marzouk, M. ElSharkawy, P. Elsayed, A. Eissa, Resolving deterioration of heritage building elements using an expert system, IJBPA (2020), https://doi.org/10.1108/IJBPA-12-2019-0106 ahead-of-print.

[64] C. Oreto, S.A. Biancardo, N. Viscione, R. Veropalumbo, F. Russo, Road pavement information modeling through maintenance scenario evaluation, J. Adv. Transp. 2021 (2021), https://doi.org/10.1155/2021/8823117.

[65] C. Oreto, L. Massotti, S.A. Biancardo, R. Veropalumbo, N. Viscione, F. Russo, BIM-based pavement management tool for scheduling urban road maintenance, Infrastructures. 6 (2021) 148, https://doi.org/10.3390/infrastructures6110148.

[66] U.S. General Service Administration Public Buildings O ce of Design and Construction, GSA Building Information Modeling Guide Series: 08—GSA BIM Guide for Facility Management, General Services Administration, Washington, DC, USA, 2011. https://www.gsa.gov/real-estate/design-construction/3d4d-building-information-modeling/bim-guides/bim-guide-08-facility-management (accessed January 20, 2021).

[67] BuildingSMART Finland, Common BIM Requirements. Series 12. In Use of Models in Facility Management. https://buildingsmart.fi/en/common-bim-requirements-2012/, 2012 (accessed January 20, 2021).

[68] PAS 1192:2014, Specification for Information Management for the Operational Phase of Assets using Building Information Modelling: Incorporating Corrigendum No. 1, BSI Standards Limited, London, UK, 2014. https://bugvaorg.files.wordpress.com/2018/09/bsi_pas_1192-3_2014.pdf.

[69] J. Messner, C. Anumba, C. Dubler, S. Goodman, C. Kasprzak, R. Kreider, R. Leicht, C. Saluja, N. Zikic, BIM Project Execution Planning Guide - Version 2.2, Computer integrated Construction Research Program, Penn State. https://psu.pb.unizin.org/bimprojectexecutionplanningv2x2/, 2019 (accessed January 20, 2021).

[70] UNI 11337-4:2017, Building and Civil Engineering Works - Digital Management of the Informative Processes - Part 4: Evolution and Development Of Information within Models, Documents and Objects. http://store.uni.com/catalogo/uni-11337-4-2017?josso_back_to=http://store.uni.com/josso-security-check.php&josso_cmd=login_optional&josso_partnerapp_host=store.uni.com, 2022 (accessed March 15, 2020).

[71] Ministero delle Infrastrutture e dei Trasporti Consiglio Superiore dei Lavori Pubblici, Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti, (guidelines for risk classification and management, safety assessment and monitoring of existing bridges). https://www.mit.gov.it/sites/default/files/media/notizia/2020-05/1_Testo_Linee_Guida_ponti.pdf, 2020.

[72] M. Masciotta, L. Ramos, P. Lourenco, J. Matos, Development of Key Performance Indicators for the Structural Assessment of Heritage Buildings. https://www.ndt.net/events/EWSHM2016/app/content/Paper/363_Masciotta.pdf, 2016.

[73] J.V. Sharp, G. Ersdal, D. Galbraith, Development of Key Performance Indicators for Offshore Structural Integrity, American Society of Mechanical Engineers Digital Collection, 2009, pp. 123–130, https://doi.org/10.1115/OMAE2008-57203.