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openBIM applications in structural engineering

by

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"Crescat scientia, vita excolatur"
[Aforisma Latino]

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Ph.D. Thesis presented

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Candidate's declaration

I hereby declare that this thesis submitted to obtain the academic degree of Philosophiæ Doctor (Ph.D.) in "*Ingegneria Strutturale, Geotecnica e Rischio Sismico*" is my unaided work, that I have not used other than the sources indicated, and that all direct and indirect sources are acknowledged as references.

Parts of this dissertation have been published in international journals and/or conference articles (see list of the author's publications at the end of the thesis).

Naples, 10 March 2023

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Angelo Ciccone

Abstract

BIM is currently the methodology of reference for the digitization of the construction industry. In recent years, BIM methodologies have been adopted and applied around the world. New BIM-based workflows involve the adoption of new tools and collaborative platforms throughout the lifecycle of an asset such as a road, railway as well as a strategic facility (e.g. bridges). The open BIM approach in particular, given open data exchanges and workflows, assures significant benefits (e.g. collaboration among all professionals involved, reduction in fragmented workflows, promoting quality of outcomes, supporting decision-making processes, etc.) for the advancement of the AECO sector.

This thesis, organized in five chapters, focuses on the implementation of BIM methodologies and the adoption of the open BIM approach envisaged for structural engineering. After an Introduction section, Chapter 2 deals with the definition of a new proposal for the management of processes related to the seismic authorization procedure, within the structural design phase, where (through the adoption of the IDM/MVD approach) an MVD was defined for the production of an IFC model tailored to the purpose of seismic-authorisation permitting. New BIM processes were proposed and implemented in a case study, where IFC models represented the central core of a new delivery (i.e. via ICDD) to building authorities. Chapters 3 and 4, meanwhile, address the topic of the management of existing structures where information related not only to structural safety but also to control, maintenance, and asset management processes is managed, exchanged, and stored. In particular, Chapter 3 deals with the digitization of existing infrastructure (e.g. an existing railway line in operation) with its civil works (including bridges), and deals with a series of topics including existing conditions modeling, maintenance information management, and asset management. Following some of these topics, Chapter 4 proposes the development of a specific framework to support BIM modeling and information management activities related to the structural management of existing bridges, within the regulatory context in force in Italy. The final conclusions are addressed in Chapter 5. All these applications have thus proved how BIM, and in particular open BIM, can lead to a significant contribution to the digitization, re-conceptualization, and improvement of current processes for authorities, managing bodies, and structural engineers.

Keywords: structural engineering, building, infrastructures, BIM methodologies, open BIM.

Abstract (in lingua Italiana)

Il BIM è attualmente la metodologia di riferimento per la digitalizzazione del settore delle costruzioni. Negli ultimi anni, le metodologie BIM sono state adottate e applicate in tutto il mondo. I nuovi flussi di lavoro basati sul BIM comportano l'adozione di nuovi strumenti e piattaforme collaborative durante l'intero ciclo di vita di un asset come una strada, una ferrovia o una struttura strategica (ad esempio, un ponte). L'approccio open BIM, in particolare, considerando scambi di dati e flussi di lavoro aperti, assicura benefici significativi (ad esempio, collaborazione tra tutti i professionisti coinvolti, riduzione dei flussi di lavoro frammentati, promozione della qualità dei risultati, supporto ai processi decisionali, ecc.)

Questa tesi, organizzata in cinque capitoli, si concentra sull'implementazione delle metodologie BIM e sull'adozione dell'approccio open BIM considerato per l'ingegneria strutturale. Dopo una sezione introduttiva, il Capitolo 2 affronta la definizione di una nuova proposta per la gestione dei processi riguardanti le procedure di autorizzazione sismica, relativa alla fase di progettazione delle strutture, dove - attraverso l'adozione dell'approccio IDM/MVD - è stata definita una MVD per la produzione di un modello IFC finalizzato al rilascio dell'autorizzazione sismica. Sono stati proposti e implementati nuovi processi BIM nell'ambito di un caso di studio, dove i modelli IFC hanno rappresentato il nucleo centrale di una nuova consegna (tramite ICDD) alle autorità edilizie. I capitoli 3 e 4, invece, affrontano il tema della gestione delle strutture esistenti, quando vengono gestite, scambiate e archiviate informazioni relative non solo alla sicurezza strutturale, ma anche ai processi di controllo, manutenzione e gestione degli asset. In particolare, il Capitolo 3 si occupa della digitalizzazione delle infrastrutture esistenti (ad esempio, una linea ferroviaria in esercizio) e delle relative opere civili (compresi i ponti), affrontando una serie di argomenti tra cui la modellazione delle condizioni esistenti, la gestione delle informazioni sulla manutenzione e la gestione degli asset. In accordo ad alcuni di questi argomenti, il Capitolo 4 propone lo sviluppo di un framework specifico per supportare le attività di modellazione BIM e di gestione informativa relative alla gestione strutturale dei ponti esistenti, all'interno del contesto normativo vigente in Italia. Le conclusioni finali sono affrontate nel Capitolo 5. Tutte queste applicazioni hanno quindi dimostrato come il BIM, e in particolare l'open BIM, possano contribuire in modo significativo alla digitalizzazione, alla ri-concezione e al miglioramento dei processi attuali per le autorità, gli enti gestori e gli ingegneri strutturisti.

Parole chiave: Metodologie BIM, openBIM, ingegneria strutturale.

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Thesis Outline

I. General context

Today, Building Information Modelling (also referred to with the BIM acronym) is the methodology of reference for digitization in the construction industry. In recent years, BIM methodologies have been adopted and applied around the world. Indeed, national governments have even required their mandatory use in public projects that can involve buildings and infrastructures such as roads, railways as well as strategic structures (e.g., bridges). In the European context, Directive 2014/24/EU of the European Parliament regarding public procurement, has been an important reference for the progressive advancement of individual national codes regarding BIM methodology. For example, the United Kingdom required the use of BIM as early as 2016 in all projects, while in Italy starting with Ministerial Decree No. 560/2017, the use of BIM methodologies has been mandated on all projects by 2025. BIM-based workflows employ new collaborative tools and platforms throughout the lifecycle of an asset [1–10] and have marked a real innovation in the AECO (Architecture, Engineering, Construction, and Operation), moving on from the older CAD representation [11–13]. However, when implementing BIM, there may be implications in terms of cost and time for initial training of technicians, reduction of initial productivity, and others yet. [10,14,15]. At the same time, by using BIM methodologies, all information is centralized in a database according to well-defined rules and processes, where the "digital twin" [16–21] is conceived, built, and managed through the use of a series of technologies, tools and digital environments, representing itself as an access key to the data stored in the informative model, other applications, and platforms. Unlike closed BIM, the open BIM approach considers data exchange and workflows based on open, non-proprietary, and neutral formats that are independent of the tools and applications used. This approach provides significant advantages such as ensuring a reduction in fragmented workflows, promoting quality relative to the final deliverables, supporting decision-making processes, improving multidisciplinary collaboration among teams, and so on.

Accordingly, the work presented in this Ph.D. thesis is focused on the implementations of BIM methodologies, for the most part considering the open

BIM approach, to structural engineering for both buildings and infrastructures. These applications refer to the different phases of an asset's life cycle, from design to the management of civil works, highlighting and proving how BIM, and in particular openBIM, can lead to a significant contribution to the digitization, re-conceptualization, and improvement of current processes that characterize the AECO sector, both for clients and for structural engineers [3,4,14,15,22,23].

II. Approach and goals

This thesis proposes the development of BIM solutions and the definition of innovative processes concerning information management activities within the context of structural engineering. The proposed processes have been conceived taking into account BIM methodologies and in particular the openBIM approach, with related standards, services, and solutions. By adopting such approaches, digitalization offers an opportunity to standardize information flows about the design and management of any type of structure. A fundamental role is played by interoperability, which enables information exchange in a transparent manner through the use of open formats [11,24,25].
The research proposed in this thesis has enabled the development of a series of solutions involving the use of different tools and technologies such as BIM-authoring environments, Visual Programming tools, collaborative platforms, and so on. Clearly, the definition of specific solutions has made it possible, on one hand, to consider and involve all the actors or parties implicated in a process, and on the other hand, to consider possible links, both technological and informative, with other existing systems or applications for the management of specific data related to the context of structural engineering. Specifically, the BIM-based processes proposed here refer to specific applications related to the design phase (in particular considering seismic-authorization processes for buildings) and management phases of the asset life cycle (e.g. existing bridges). This work is mainly based on BIM implementations, considering, in particular, the adoption of the openBIM approach by investigating the use of open standards - developed and maintained by buildingSMART International (bSI) - such as the Industry Foundation Classes (IFC), the Information Delivery Manual (IDM) and the Model View Definition

(MVD), as well as others, along with further standards and services such as BIM Collaboration Format (BCF) and buildingSMART Data Dictionary (bsDD).
In regard to the practices related to seismic authorization, for instance, the author contributed to the Structural E-Permit (Str.E.Pe) research project with the Department of Structures for Engineering and Architecture (DIST) of the University of Naples Federico II. Along with the University of Naples Federico II, ACCA Software, Campania Region, the Building Authority Body of Avellino, and the Municipality of Montemarano have been involved. The Str.E.Pe. project addressed the topic of digitization (reducing and ending the need for the production of paper documentation) by adopting open BIM strategies, regarding the procedure related to the authorization phase aimed at issuing the seismic permit, which characterizes a specific phase of structural design in Italy. The author's contribution to this research project and thesis work concerns the definition of new BIM-based processes and the development of dedicated solutions (through the adoption of the IDM/MVD approach) to enable information exchange and processes based on open standards (e.g. IFC).
Furthermore, concerning the management of structures, which involves, for example, operation and maintenance activities related to civil works (bridges, buildings, etc.) along a linear infrastructure (such as roads or railways), several applications have been developed. Particular care has been given to the topic of the structural management of existing bridges and, more generally, to the topic of asset management for infrastructures. Accordingly, the author participated in research and projects that involved several stakeholders. Indeed, in the field of infrastructure, the development and application of the openBIM approach and related standards (principally Industry Foundation Classes) remain limited concerning processes in O&M (Operation and Maintenance) phases, as well as the broader context of asset management. Based on the need for new digital management of existing infrastructure (the Cancello–Benevento railway line), in addition to the assessment of its current condition and value, several activities were carried out by the author within a research team. The main goal was to systematize information by digitalizing the infrastructure to enable the assessment of possible performance gaps (compared to standards related to the manager of the national railway network) in the case of integration within the national infrastructure. In compliance with the project requirements, a digitalization strategy was designed for the definition of surveying activities and

the implementation of openBIM systems for the development of an object library and a federated digital model structured within the collaborative platform that was used, permitting management, maintenance, and subsequent financial evaluation in the broader context of asset management. The project - involving the collaboration of railway operators (RFI - Rete Ferroviaria Italiana, EAV - Ente Autonomo Volturno), a university (Department of Structures for Engineering and Architecture of the University of Naples Federico II), and a software company (ACCA Software) - enabled the implementation of innovative concepts concerning IFC (specifically with regard to the IFC4x2 version that was used at the time of the project) through the development of dedicated software solutions. The proposed solution enabled the use of digital models (also for existing bridges along the line) as access keys to survey and maintenance information (belonging to ERP platforms used by the railway operators), which was available in real-time.

In additional work on the management of existing bridges, the author focuses on the development and integration of a digital solution based principally on a framework that supports BIM modeling and information management activities, in accordance with the structural regulation in force in Italy. It does this through the use of several technologies and tools, namely BIM-authoring, a CDE platform, and visual programming, in addition to programming in Python. In addition, other developments were carried out within a specific task (regarding activities on BIM methodology implementations for bridge management) of another research project. This stemmed from an agreement between RELUIS (Network of University Laboratories of Structural Engineering in Italy) and the CSLP (Superior Council of Public Works), following the release in 2020 of the "Guidelines for Risk Classification and Management, Safety Assessment and Monitoring of Existing Bridges". With particular regard to the topic of the management of the structural safety of existing bridges, several aspects were examined in depth, including the definition of the informative models related to the structures of the existing bridges; survey of the existing condition, and mapping of degradation and damage; coding and classification of the digital model for maintenance purposes; data exchange and interoperability with systems used for structural activities concerning asset management, or public platforms for the survey and management of information relating to infrastructures (e.g. “Archivio Informatico Nazionale delle Opere Pubbliche”, abbreviated as AINOP). Thus, several scenarios belonging to the life cycle of a generic asset (whether a building or some other civil work, such as a bridge) were considered. In the field of civil engineering, specifically regarding structural engineering, BIM methodologies and particularly the open BIM approach were considered with the aim of:

1) proposing innovative processes and open BIM solutions (e.g. MVD for exporting specific IFC models, a dedicated platform where the processes take place, etc.) for the digitization of seismic permitting procedures ("autorizzazione sismica" in Italian), to support both the authorities and structural engineers in charge of designing new buildings;
2) developing a digitization strategy, based exclusively on open BIM solutions, for systematizing information concerning existing infrastructure for assessments of possible performance or infrastructural gaps. In compliance with the defined project requirements, surveying activities and implementation of openBIM solutions - for the development of an object library and a federated digital model structured within the collaborative platform being used - enabled the management, maintenance, and financial assessments under the broader context of asset management;
3) developing and integrating a digital solution based principally on the specific framework that had been developed, which supports BIM modeling and information management activities in accordance with the structural regulations in question, through the use of several technologies and tools (BIM-authoring, the CDE platform along with its functionalities, and visual programming, in addition to programming in Python). Starting from the organization of a specific BIM object library and the initial data, inserted through a custom-made input environment, it was possible to reproduce digital models of bridges under specific information requirements following the new Level of Information Need framework. Further developments permitted the management of all the required information (by AINOP) for survey and recording purposes as well.

III. Thesis organization

This thesis is organized into five chapters. **Chapter 1** deals with BIM methodologies, open BIM, and the regulatory frameworks both at the international and national levels. **Chapter 2** presents the open BIM approach considered for the structural design phase. Specifically, it focuses on the digitization of a specific process related to the seismic authorization procedure. This was achieved through the proposal of innovative BIM-based processes enabled by the open BIM solutions that had been developed (e.g. for the definition of dedicated IFC models). The chapter, therefore, deals with the adoption of the IDM/MVD approach for the development of a specific MVD for the production of IFC models for seismic-authorization permitting purposes, which represent the central core for the new digital delivery (i.e. via ICDD, Information Container Data Drop) to be deployed for the issue of the seismic permit. Successively, the proposed solution was tested on a case study (the renovation project of a school) that provides an effective workflow for innovative future delivery of necessary information to building authorities to obtain seismic authorization permits.

Chapters 3 and Chapter 4 meanwhile deal with the issues related to the management of structures in which information concerning not only structural safety but also control, maintenance, and asset management processes are managed, exchanged, and stored. In particular, **Chapter 3** deals with the digitization of an existing railway line, along with its civil works (including bridges), and covers a series of topics including existing condition modeling, maintenance information management, and asset management. **Chapter 4**, remaining in the field of the management of existing bridges, proposes the development of a specific framework that supports BIM modeling and information management activities within the structural regulation setting in force in Italy. **Chapter 5**, finally, addresses the final conclusions.

IV. Achievements and results

The work that constitutes this thesis has demonstrated considerable value both for the scientific and industrial communities. In this regard, **Chapter 2** is based on two journal articles [1,2], which were published in the *Journal of Civil*

[1] "*Structural e-permits: an openBIM, model-based procedure for permit applications pertaining to structural engineering*". Authors: Vittoria Ciotta, Angelo Ciccone, Domenico Asprone, Gaetano Manfredi, Edoardo Cosenza. Published on the "*Journal of Civil Engineering and Management*". https://doi.org/10.3846/jcem.2021.15784.

Engineering Management (JCEM). Chapter 2 is based on work related to the Str.E.Pe. research project, which won a buildingSMART® International Award in Beijing in 2019. The author would like to thank Antonio Cianciulli, Guido Cianciulli, and the ACCA Software development team for their support regarding the implementation of the proposed solution through Edilus software and the Str.E.Pe. platform.

Chapter 3 is based on an article[3] published in a special issue of the journal *Sustainability* entitled "Buildings and Infrastructures Management: Models, Strategies and Evaluation Tools". Chapter 3 is based on work related to the pilot project that was nominated among three finalists in the category "Asset Management using openBIM", which was presented by the author at the Virtual Summit 2021 of buildingSMART with the title "Asset Information Management of an existing railway infrastructure in the openBIM scenario: the Cancello-Benevento line".

Figure I – Author's presentation at the Virtual Summit of buildingSMART, a finalist project for the bSI Awards 2021, entitled "Asset Information Management of an existing railway infrastructure in the openBIM scenario: the Cancello-Benevento line" in the category "Asset Management using openBIM".

[2] "*Integration of structural information within a BIM-based environment for seismic structural e-permits*". Authors: Angelo Ciccone, Vittoria Ciotta, Domenico Asprone. Published in the "*Journal of Civil Engineering and Management*" (https://doi.org/10.3846/jcem.2023.18460).

[3] "*Application of openBIM for the Management of Existing Railway Infrastructure: Case Study of the Cancello–Benevento Railway Line*". Authors: Angelo Ciccone, Sabrina Di Stasio, Domenico Asprone, Antonio Salzano, Maurizio Nicolella. Published in the Special Issue "*Buildings and Infrastructures Management: Models Strategies and Evaluation Tools*" of the "*Sustainability*" Journal. https://doi.org/10.3390/su14042283.

The author would also like to acknowledge the two railway managing authorities, "EAV" and "RFI", for making available the documentation related to the case study (regarding the existing railway line Benevento-Cancello), which is currently in operation, and for allowing the implementation of the proposed solution on a real case. In conclusion, we would like to acknowledge "Acca Software" for their support in the technical development of the solutions targeting the goals of the pilot project.
Chapter 4 is based on the article[4] published in a special issue of *Sustainability* called "Future Prospects in Sustainable Engineering Development for Transport Infrastructures and Systems". The author would also like to acknowledge the companies "ANAS" and "Autostrade per l'Italia" for kindly providing the documentation related to the selected case studies. In addition, further developments on BIM implementations for bridge management activities were carried out as part of a research project financed by the RELUIS consortium.
Finally, mention should also be made of another study[5] in which the author participated. Specifically, an overview of applications relating to "Smart Construction" was proposed, considering different civil engineering projects (mainly focused on transport infrastructure), along with new tools and technologies such as Building Information Modeling (BIM), Internet of Things (IoT), Geographic Information System (GIS), Big Data and so on.

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[4] "*Defining a Digital Strategy in a BIM Environment to Manage Existing Reinforced Concrete Bridges in the Context of Italian Regulation*". Authors: Angelo Ciccone, Pompilio Suglia, Domenico Asprone, Antonio Salzano, Maurizio Nicolella. Published in the Special Issue "*Future Prospects in Sustainable Engineering Development for Transport Infrastructures and Systems*" of the "*Sustainability*" Journal. https://doi.org/10.3390/su141811767.

[5] "*A review on the Implementation of the BIM Methodology in the Operation Maintenance and Transport Infrastructure*". Authors: J. Jerez Cepa, R. M. Pavón, M. G. Alberti, A.Ciccone, D. Asprone. Published in the special issue "Building Information Modeling (BIM): Current Status, Application and Trends" of the "Applied Science" Journal. https://doi.org/10.3390/app13053176 .

Chapter 1

1. An overview of the BIM methodology and the open BIM approach adopted within the AECO sector.

1.1 BIM methodology as a new opportunity for the digitization of the construction industry

The digitization of the construction sector in recent years has led to various changes and improvements. It can certainly be stated that digitization can increase productivity. At the same time, high productivity in civil engineering is complicated to achieve and manage because the products to be realized are unique prototypes, often characterized by high complexity. These products, therefore, have non-linear (i.e. highly complex) relationships with each other. For instance, the design and construction of a generic building is the result of the application of technologies, systems, and disciplines that are complex and originate from different professional backgrounds. Professionals or technicians, who work together as a team to realize a specific civil work, have different skills as well as a complex level of compatibility among themselves. Full-scale prototypes (buildings and other civil works) are always designed and managed throughout their life. Construction sites are always different and the logistics associated with the building operation constitute a complicated issue, in some cases, to be managed. The construction processes are not standardized also because this sector cannot be serialized. For all the reasons stated so far, optimization goals are not achieved.

Hence, complete digitization should be deployed, in the construction sector, to overcome, even partially, some of the challenges that limit productivity in the AECO (Architecture, Engineering, Construction, and Operation) sector. In the following Figure, a comparison, in terms of work index productivity, between the construction and manufacturing sectors, underlines the trend difference between the two sectors during a specific period.

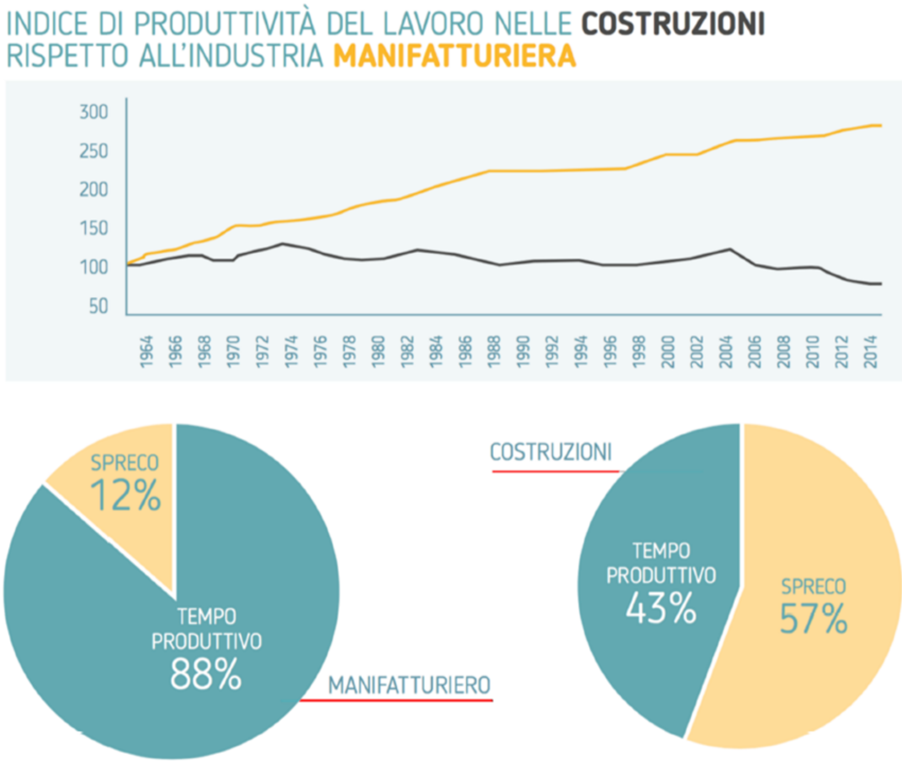


Figure 1.1 - Work productivity index for the construction industry compared to that of the manufacturing industry, from 1964 to 2014.

The construction sector, therefore, should change significantly to solve problems and critical issues that cause losses in productivity. One opportunity comes in the form of the new concept of industrial construction. This will integrate new systems and technologies based on databases, IoT (Internet of Things) systems, artificial intelligence (AI), digital methodologies that assist design and management phases (e.g. Building Information Modeling), Digital Twin technologies, off-site production, and 3D printing. Specifically, the new paradigm of BIM, using parametric and tridimensional modeling of information in a virtual environment, supports the development of a prototype (a sort of avatar of the construction) that reflects the real civil work to be built and managed successively.

In the construction industry, BIM is the methodology for managing models and information related to the design, construction, and maintenance of a project. The result of the process is a three-dimensional digital model that acts as a container of information that can provide any detail regarding any aspect of the project, supporting the decision-making process during the life cycle of the work. BIM, therefore, is not only 3D modeling but also includes other dimensions such as 4D (time), 5D (cost), 6D (facility management), 7D (sustainability), 8D (safety), 9D (lean construction), 10D (construction industrialization), and so on.

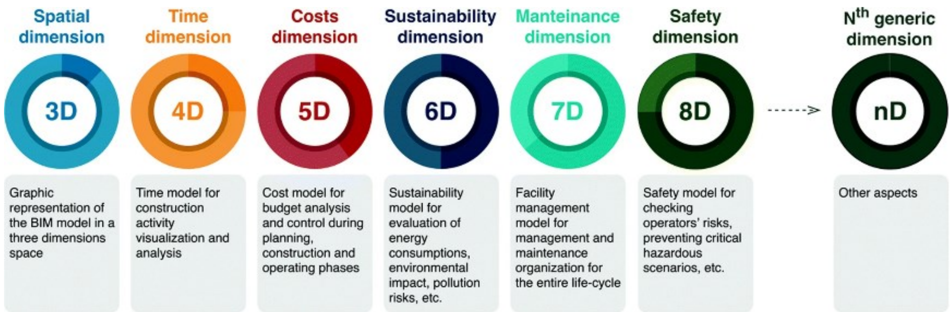


Figure 1.2 - BIM dimensions [26]

This means that any object in the BIM model contains and conveys a range of information such as geometric and physical-mechanical characteristics, installation instructions, maintenance information, etc. The BIM model contains all the information needed for the entire life of the building and provides a database that is always available as a source of information. In addition, a series of functionalities (data and process management, quantity estimations, code checking, performance monitoring, etc.) are all aspects that make BIM a highly productive technology. These new BIM methodologies make a series of activities possible, such as:

- allowing changes concerning the original BIM model, automatically updating all the deliverables linked to it (calculations, graphs, schedules, etc.). All these features speed up the design and construction process in addition to streamlining the project team's activities;
- allowing the reduction of errors and unforeseen events in the project and related construction by using specific tools that detect conflicts (e.g.

through BIM clash detection software), facilitating communication, collaboration, and information sharing among all the actors involved;

- allowing for optimized coordination and collaboration processes, working together on a digital prototype and finding and fixing all design issues before building the civil work.

Indeed, the automation of all activities (from modeling to clash detection) improves overall productivity. With the BIM approach, all information is centralized in a database according to well-defined rules and processes, where the "digital twin" is built and managed through the use of an assortment of software, tools and digital environments.

1.1.1 *Innovative technologies for supporting the new digital management of civil works*

The adoption of innovative methodologies and tools, including BIM, is undoubtedly offering new solutions for generating new processes and improving existing ones regarding the management of the built environment through the whole life cycle of civil work. These new tools enable several new opportunities including simplifying communication; automation of production processes; digitization and storage of information based on new digital environments; digital design, delivery, and management of structures; etc.

These new opportunities are enabled by the adoption of advanced technologies including collaborative platforms and cloud environments; drones or other instrumentation (e.g. laser scanners) to acquire and survey specific sites or objects; 3D printing; robotics and artificial intelligence (AI), and so on. In the AECO industry, digital technologies have also enabled new ways of working, with highly collaborative approaches, especially through the use of BIM methodologies. At the same time, new technologies are changing and improving the work of professionals and companies, achieving what is commonly known as the digital transformation of construction. Among the most advanced technologies, mostly already available in the construction industry, there are:

- **BIM tools**. The use of BIM offers better interdisciplinary collaboration, based on a virtual representation of the work (e.g. BIM model). Collaboration on the same digital model enables its simultaneous interdisciplinary evolution, simplifying the process and increasing efficiency. BIM tools also support issue-solving in the design and planning phases of a project by automating the detection of clashes and errors. This allows for the reduction of the costs associated with such changes compared to traditional processes. The development of mobile applications directly on tablets and smartphones, as well as the connection to collaborative environments, also enables greater real-time communication and the ability to work from anywhere, collecting data directly on-site more quickly and accurately. These applications may concern data collection, for example, inspections of assets, interference reporting, etc.

- **Drones**. High-resolution cameras and other installed devices can enable improved survey activities. The data collected can be used and processed to create maps, point clouds, textured meshes, and 3D or topographic models. By using this equipment, the inspection of hard-to-reach sites, such as bridges or inaccessible parts of buildings, can be carried out. They can also be used to monitor the progress of a construction site.
- **Virtual Reality**. This technology is often used to integrate BIM tools to browse and analyze complex or innovative design solutions. For example, it allows a more realistic understanding of what the project will be before it is finished, offering the opportunity to avoid making significant changes during construction.
- **3D-Printing and robotics**. This construction technology will introduce significant innovations in traditional processes related to material supply, fabrication of elements, logistics, and so on. These components or small-scale buildings can be printed on-site or transported afterward and made ready for use immediately. This speeds up and simplifies the construction process, reducing waste, and saving on transport and storage costs.

  As concerns robotics, the application to the construction sector is at its beginning, but some applications enable work on construction sites with exoskeletons and drones. These innovations aim to overcome certain issues including the lack of skilled manpower in many countries and limited human productivity. The aid of robotics can help perform tasks that can be partially performed by human operators (e.g. lifting heavy objects and positioning them in exact coordinates).

- **Digital Twin**. DT platforms can minimize trigger events, allowing a dynamic view of the project and real-time comparison of progress compared with project-defined benchmarks. These allow any variations to be managed in real-time. Drones and satellite images, as well as LiDAR-based solutions, are some of the solutions adopted for reality capture that can support the DT framework. DT allows the integration between information models and KPIs (Key Performance Index), which are monitored in real-time with the support of IoT (Internet of Things) sensors. This approach establishes a digital replica of the physical reality of civil work, enabling data to be fed into information models for automatic, real-time updates. All this leads to a more accurate decision-making process based on the real condition status.
- **Artificial Intelligence (AI).** AI can be applied to any asset lifecycle activity; indeed, early applications of AI have proven potential in terms of improving labour productivity and saving on budgets. AI and machine learning can be used to identify potential project interferences, optimize design solutions, perform automatic compliance checks of all types of code rules, etc.. Deep learning, for instance, can be adopted to predict and control costs during construction. Furthermore, AI and machine learning can be used in the field of structural engineering to assess structural damage or monitor the structural health of the building or infrastructure, to compare field conditions with previously developed projects, to detect real-time deviations from plans and consequently correct and adopt a series of predetermined scenarios and so on. . In the long term, AI and analytics have unlimited potential for application in the AECO industry. Due to the proliferation of AI in the coming years, many start-ups are already entering the construction market using new AI-centred approaches [27].

1.1.2 Definition, adoption, and implementation of BIM strategies

1.1.2.1 Origins, implementation and different interpretations of the BIM concept worldwide

An information model of civil construction consists of a digital representation of information with a defined level of detail. It generally includes information concerning the three-dimensional geometry of the related components but also relates to non-physical objects such as spaces, zones, elements of specific hierarchical-spatial project structures, and so on. Objects are also typically associated with a set of semantic information such as component type, materials, technical properties, costs, and so on.

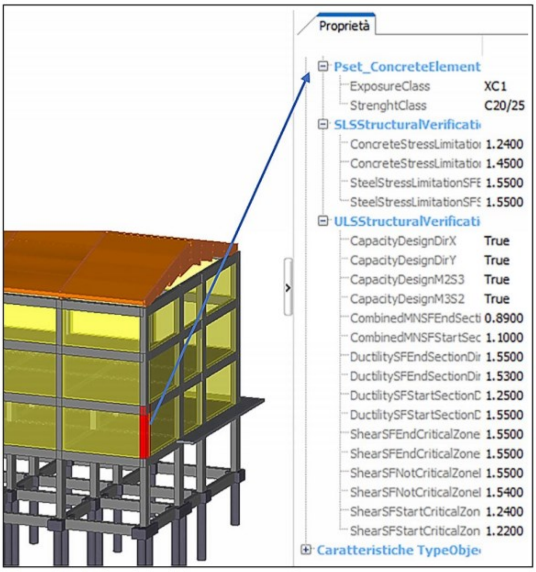


Figure 1.3 – Parameters (as IFC properties within a specific Property Set) associated with BIM objects (e.g. a generic structural column) belonging to an IFC model of a structure [1].

The term "Building Information Modeling" (BIM) refers to a process for the creation of informative models and their maintenance over time in addition to the process of using and exchanging these models during the entire life cycle of the civil work under consideration. An earlier reference to BIM originates from the 1970s [28], and the date of the first definition to around the 1990s [29]. An all-encompassing definition of its potential has been given by the National Building Information Modeling Standard (NIBS), which defines BIM as "*a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition. A basic premise of BIM is a collaboration by different stakeholders at different phases of the life-cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder*". However, the acronym BIM also stands for Building Information Modeling, even though today referring to a specific methodology for information management concerning buildings alone is completely anachronistic. Indeed, the latest developments in the buildingSMART International context are increasingly extending the deployment of such methodologies to infrastructures as well. Accordingly, taking all this into account, several meanings can be associated with the letter "M" of the BIM acronym:

- a product (Model);
- a collaboration-oriented process and outcome enabled for IT and based on open standards (Modeling);
- a requirement for the management of processes related to the life cycle of the asset (Management).

Today, the transition from traditional workflows, mostly based on 2D drawings, to those based on 3D parametric models requires significant and gradual transitions that interest internal companies and inter-company processes. The adoption of technical drawings or other types of documents has a significant disadvantage, in the design process of civil work, since related information cannot be used directly by downstream applications for any kind of structural analysis, calculation, and simulation. Mostly, they have to be re-inserted manually. This process is time-consuming and requires additional effort, often also leading to errors. This is also shown in the following Figure 1.4

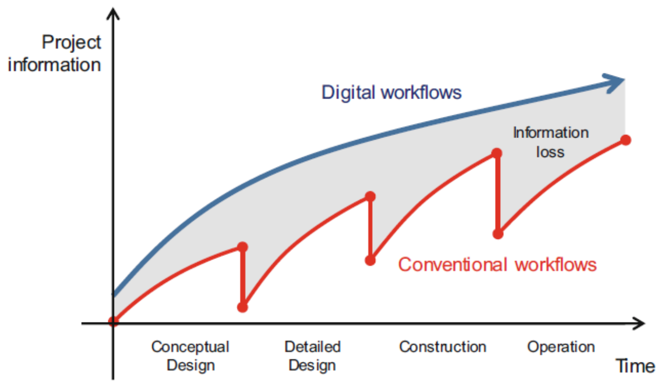


Figure 1.4 - Digital workflows compared to conventional workflows [30].

By applying the BIM methodology, BIM professionals store and exchange information using complete digital representations: information models, both for buildings and infrastructure. This approach drastically improves the coordination of design activities, the integration of information from simulations, the construction of the work, and so on. It minimizes manual data manipulation and enables the re-use of previously entered digital information.

in this way, complex and error-prone activities are avoided. The adoption of information modeling and BIM in general, therefore, leads to an increase in the productivity and quality of construction projects. Furthermore, different technological levels of BIM implementation can be considered, as shown in Figure 1.5 below.

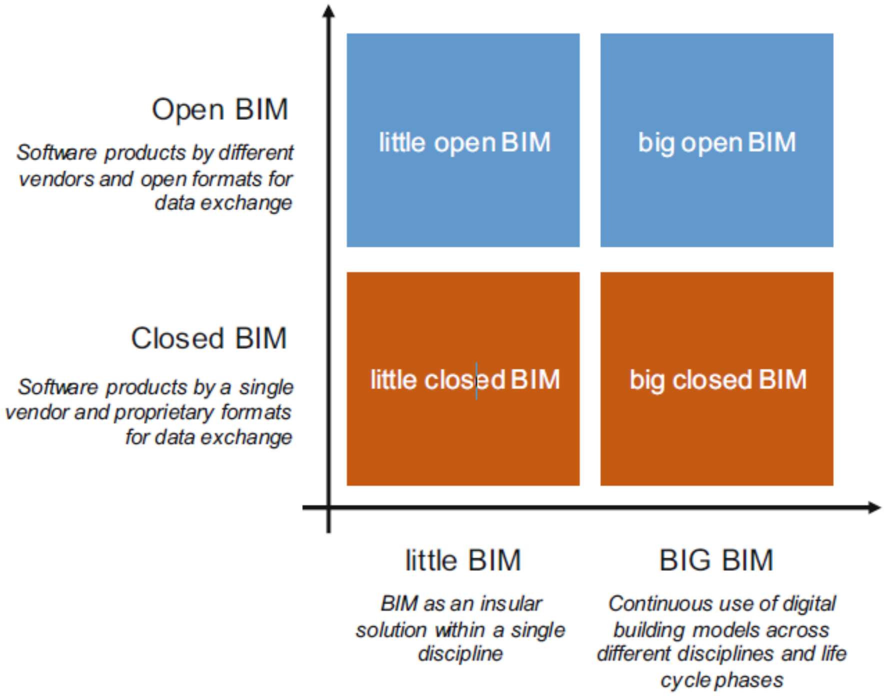


Figure 1.5 - Different interpretations of the BIM concept (i.e. "little BIM", "BIG BIM", "Closed BIM", "Open BIM") [31].

A first and simple classification is represented by the following terms [32]:

- **"little" BIM**. In this case, BIM is used for the application of a specific BIM software, by a single party, to realize a specific task regarding a specific design discipline. The realized model of the building is not used in different software and is not transferred to other stakeholders. BIM is therefore used regarding an isolated solution within a design discipline. Although this implementation still offers greater efficiency, the great potential of BIM remains unrealized because the collaboration remains paper-based.
- **"BIG" BIM**. Instead, BIG BIM provides for consistent communications based on shared informative models among involved parties over the entire

lifecycle of a structure (Fig. 1.3). The data exchange and work coordination envisage the full deployment of the developed information models, and for this, digital technologies based on servers, databases or collaborative platforms are adopted.

Another distinction is based on the technical and business nature of the BIM solution being considered:

- **closed BIM**. This implies the use of software products related to a specific vendor;
- **open BIM**. This implies the use of open and neutral data file formats to enable data exchange between products of different software providers.

Although there are software packages, available on the market, which support different needs arising from the design, construction, and operation phases of a project, there will always be a need to exchange data with other software belonging to other proprietary ecosystems. One of the few valid solutions for efficient data exchange is defined by the adoption of neutral formats. Indeed, this also has economic consequences for construction companies [33]. To overcome this and significantly improve the data exchange among software in the construction sector, the organization known as buildingSMART has the role of defining and maintaining an independent data format for the exchange of complete digital models both for buildings and infrastructure. This object-oriented data model is called Industry Foundation Classes (IFC). Although there have been several developments in recent years, the exchange of BIM data using the IFC format is still not fully effective, with data losses and misinterpretation by the different software solutions. Both the related development and implementation of the IFC format represent technical challenges, but applications in recent years have shown, involving software vendors in particular, that these issues can increasingly be resolved.

Finally, regarding the context of the maturity of BIM implementation worldwide, the construction industry is increasingly moving in the direction of establishing procedures based on information models, and introducing new technologies for that purpose. The British BIM Task Group proposed the concept of BIM maturity levels, establishing 4 levels of possible BIM implementation [34] as shown in Figure 1.6 below.

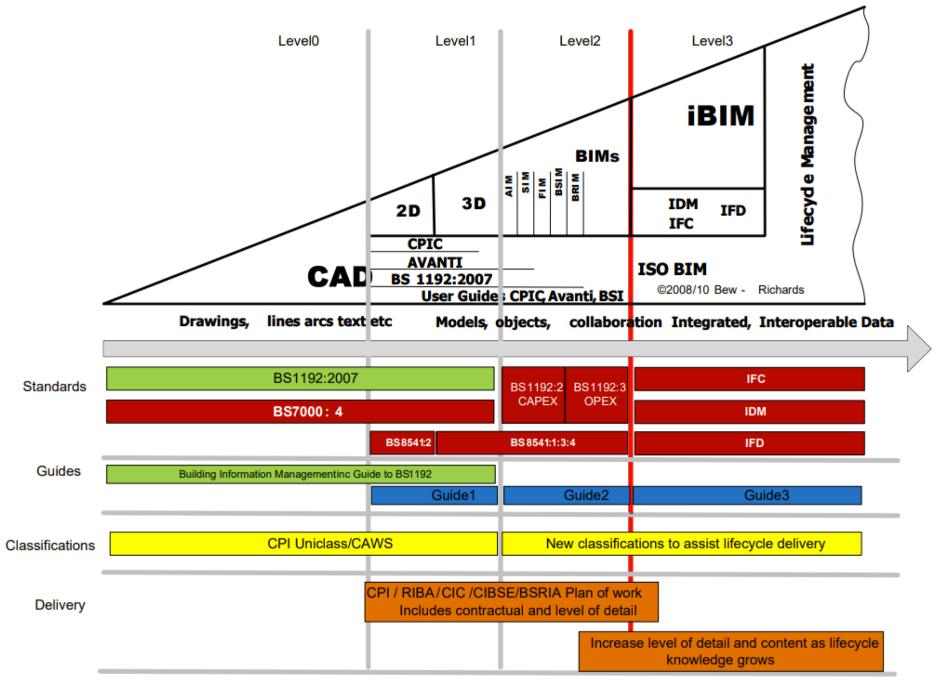


Figure 1.6 - BIM Maturity Diagram [34].

Level 0 refers to conventional work based on the processing and exchange of 2D drawings.

Level 1 refers to the partial 3D modeling of the work but, at the same time, a part of the design activity is still based on 2D drawings. In this case, data exchange still takes place via individual files without the use of collaborative platforms.

Level 2 refers to the adoption of BIM tools for the creation of disciplinary informative models. Their coherence with each other is verified by coordination procedures, involving individual models, to identify possible clashes or interferences in federated models. 2D drawings are now obtained from the BIM models. Data exchange always takes place based on files in proprietary formats, but these are managed in a Common Data Environment (CDE). A CDE can manage the status of each file, the maturity of the information contained, and the level of access provided to other actors involved in the process through formal procedures that also lead to the evolution of a file's status. The COBie standard at this level allows the transmission of alphanumeric information relevant to the operational phase concerning the work in question. Furthermore, open standards for the transmission of both geometric and semantic information are not required for the implementation level considered. Instead, proprietary formats may be used. Since 2016, the British government has imposed implementation level 2 in connection with public works projects. Several standards have been published including PAS1192-2:2013 and PAS1192-3:2014, as well as the BIM protocol.

Level 3, is based on the concept of integrated BIM, i.e. the use of ISO standards for data exchange and process definition, about the entire lifecycle and thus employing integrated digital models as well as cloud services for project data management.

With the publication of the ISO19650 series, the BIM maturity progression defined by 'levels' is replaced by a 'stages' and 'layers' scheme.

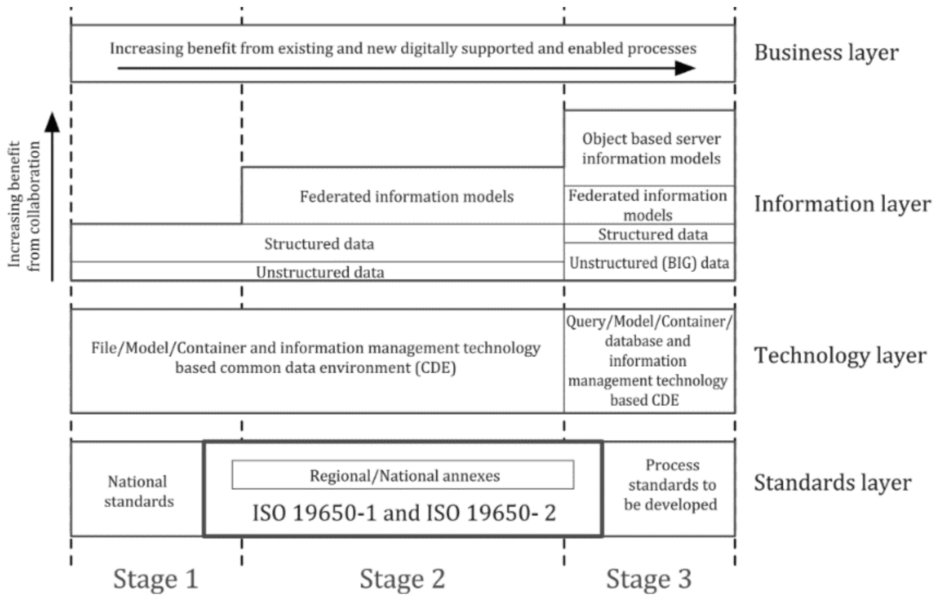


Figure 1.7 - Stages of maturity according to the ISO 19650 series.

As presented in Figure 1.7 above, there are several layers:

- a Standards Layer. Stage 1 refers to national standards, stage 2 refers to ISO 19650 standards, and stage 3 refers to standards that have yet to be developed;

- a Technology Layer. Stages 1 and 2 will be based on a common data environment based on the management of information (files or models), while Stage 3 will give direct access to the data contained in the models;
- an Information Layer, which in Stage 1 will mainly use structured and unstructured data, while Stage 2 will also introduce the concept of a federated information model. In Stage 3, the use of servers for BIM object management will be considered, and, while maintaining federated models and structured information, the concept of BIG data will need to be considered for unstructured information.

1.1.2.2 BIM adoption worldwide

In the coming years, BIM adoption will lead to an increasing number of implementations aimed at the transition of the AECO sector toward full digitization. This transition is therefore driven by the relevant regulations, standards, and guidelines developed both at the national and international levels, in most European countries as well as in America and Asia.

The USA. As mentioned earlier, the first BIM implementations occurred in the middle of the 1990s. In the same period, there was also the availability of the first versions of the open standards for data modeling (such as IFC). However, the definition of a single strategy and a national regulation valid for all confederated countries is what is missing. In fact, in these terms, BIM deployment is only based on the relationship between individual client and contractor, in different ways for each project. In addition, many federal departments or agencies have created their standards, and all these have been created independently and with no relationship to each other. This non-uniformity could also be an advantage, in the application of individual projects. The main initiative credited to a government agency occurred in 2003, when the General Services Administration (GSA) established the 3D/4D/BIM program, publishing guidelines for the gradual implementation of BIM in all major public projects [35]. Another experience concerns the "National Institute of Building Sciences" (NIBS), which aims to identify and solve potential problems that hinder the dissemination of BIM and to produce documents aimed at understanding, for example, the impacts of the adoption of standardized information models and BIM methodology in the entire construction process.

Australia. In Australia, BIM is already a widely used BIM methodology. In addition, national working groups such as the "National Specification System"

(NATSPEC), have defined documents (e.g. National BIM Guide Documents, NATSPEC BIM Scheduling guidelines) that are references for stakeholders and project digitization.

Asia. In **China**, similarly, a series of initiatives such as the "BIM Union" and the "China Industry Technology Innovation Strategic Alliance" was established, focusing on the development and diffusion of BIM in the construction sector. In **Hong Kong,** the "Hong Kong Institute of Building Information Modeling" (HKIBIM) was founded, which, together with the Construction Industry Council (CIC), aims to provide guidelines and educate BIM experts. In addition, the government has mandated the use of BIM in the design and construction phases of all public projects. **Japan, the Middle East, Dubai,** and other countries have invested in BIM-related railway and large infrastructure projects [36]. **Singapore** and **South Korea** are leaders in BIM adoption in Asia and have made it mandatory to use BIM in all public-funded projects by 2015 and 2016 [37]**.**

Europe. The European Commission has promoted the use of BIM, as a methodology for the construction of public works, in the EU Directive on Public Procurement. Following this directive, many countries are considering the introduction of BIM into their regulation. The European Commission also co-founded the "EU BIM Task Group" to bring Europe to a common approach and unify the BIM strategy. This project defined a document setting out common practices and principles for European countries, providing a general reference for the harmonization of the BIM strategy at the European level [38]. In the **United Kingdom**, the government established a "BIM Task Group" to adopt BIM maturity level 2 and target level 3 for 2020. The UK government, aiming to reduce public works costs and carbon emissions, stipulated in 2011 that public projects using BIM would become mandatory by 2016.

The Nordic countries. In Finland, the adoption of BIM is well-advanced, and relates to the entire life cycle of the built asset. Since 2001, the use of BIM models and the IFC format have been promoted through pilot projects as well as the publication of BIM documents and requirements. Driven by the needs of companies and associations, in a few years, almost 70% of projects have been managed according to the BIM approach, quickly becoming a standard. Government authorities have required BIM models in public tenders since 2007. Sweden, with very complex and large infrastructure projects (e.g. New Karolinska Solna Hospital), has also shown advances similar to Finland in the introduction of BIM. These projects have achieved, through the use of BIM, predefined goals such as increased speed and quality of construction as well as environmental sustainability, and so on. In Norway, the Norwegian Directorate of Public Construction and Property Management has directed the introduction of BIM methodology since the 2000s. Examples such as Statsbygg's BIM Handbook have been very important references. In Denmark too, since the mid-2000s several public institutions have required the BIM approach for the management of existing structures and the construction of new buildings, thus influencing the entire construction market.

Germany. Germany has worked on the introduction of BIM by adopting a bottom-up approach: starting from local organizations and working groups, a national strategy was developed and launched in 2015. The strategy is based on the implementation of several pilot projects by 2020, among them "Futurium Berlin", which is an essential reference for understanding the level of BIM diffusion and adoption in Germany.

France and Spain. In France, the "Plan Transition Numèrique dans le Bàtiment" (PTNB), launched in 2014 and completed in 2017, provided a financing plan to enable the transition of the AEC sector to the new BIM-based work methodologies, without making their use mandatory. To this end, a series of large-scale projects, infrastructure and public works was launched, in which all the potential offered by using BIM was immediately applied to specific cases. The French BIM strategy was also supported by the national project "Modélisation des INformations INteropérables pour les INfrastructures Durables" (MINnD) involving almost 60 national partners (companies, universities, etc.). Spain has rapidly directed BIM adoption with the "esBIM" strategy. Starting in 2019, the total integration of BIM into the AECO sector is expected in line with the strategy defined by the Digital Agenda for Public Administrations. Interministerial commissions on BIM have also been set up to optimize and accelerate the innovation process in this sector.

Italy. In Italy, Legislative Decree No. 50/2016 introduced BIM methodologies through "the use of specific digital methods and tools for architectural and infrastructure modeling". Further provisions such as Ministerial Decrees No. 560/2017 and No. 312/2021 introduced mandatory implementation of BIM for all public procurement by 2025, as well as further integrations and modifications. Since 2015, however, the "Ente di Normazione Italiano" (UNI) has produced voluntary technical standards on BIM.

Figure 1.8 - Worldwide adoption of BIM methodology.

In summary, the adoption of BIM differs depending on the country or continent under consideration. In Figure 1.8 above, the worldwide situation regarding BIM deployment is illustrated. Indeed, some countries such as the Nordic countries, the U.K., the U.S., and others are leading in the transition and implementation of these new BIM methodologies [39]. However, Italy too, through a series of BIM provisions, is proceeding towards a progressive digital transition in the construction sector.

1.1.2.3 *Main BIM standards and other references*

In the context of BIM methodologies, it is possible to refer to three **levels of technical standards** whose adoption is voluntary:

- **International**, represented by the activities led by the "International Organization for Standardization" (ISO);
- **European**, represented by the activities led by the "European Committee for Standardization" (CEN);

- **National**, represented by the activities led by the "Ente Nazionale Italiano di Unificazione" (UNI).

Before presenting the ISO 19650 series, a previous organic reference was represented by BS (British Standards) and PAS (Publicly Available Specification) which, in the past, acted as a guide to the implementation and application of BIM methodologies around the world. These are the following:

- **BS 1192-1:2007** - Collaborative production of architectural, engineering, and construction information – Code of practice (withdraw – ISO19650);
- **PAS 1192-2:2013** - Specification for information management for the capital/delivery phase of construction projects using building information modeling. This standard has been withdrawn due to the publication of BS EN ISO 19650-1:2018 and BS EN ISO 19650-2:2018 (withdrawn);
- **PAS 1192-3:2014** - Specification for information management for the operational phase of assets using building information modeling. This specifies requirements once the construction phase of a built asset is completed and it is in operation;
- **BS 1192-4:2014** - Fulfilling employers' information exchange requirements using COBie. This standard defines a methodology for the transfer between parties of structured information relating to facilities, including buildings and infrastructure;
- **PAS 1192-5:2015** - Specification for security-minded building information modeling, digital built environments, and smart asset management. This specifies requirements for the implementation of cyber-security-minded BIM throughout the construction process;
- **PAS 1192-6:2018** - Specification for collaborative sharing and use of structured Health and Safety information using BIM.

In the international context, a very important reference is that provided by the **ISO19650** series, which consists of the following parts:

- **ISO 19650-1:2018** Organization and digitization of information about buildings and civil engineering works, including building information modeling - Information management using building information modeling: Concepts and principles.
- **ISO 19650-2:2018** Organization and digitization of information about buildings and civil engineering works, including building information

modeling - Information management using building information modeling: Delivery phase of the assets.

- **ISO 19650-3:2020** Organization and digitization of information about buildings and civil engineering works, including building information modeling (BIM) - Information management using building information modeling - Part 3: Operational phase of the assets.
- **ISO 19650-4:2022** Organization and digitization of information about buildings and civil engineering works, including building information modeling (BIM) — Information management using building information modeling — Part 4: Information exchange.
- **ISO 19650-5:2020** Organization and digitization of information about buildings and civil engineering works, including building information modeling (BIM). Information management using building information modeling. Security-minded approach to information management.

All of these, except for ISO 19650-4, have been adopted both at the European (by CEN) and Italian (by UNI) levels to become UNI EN ISO. The following parts, briefly, cover certain topics: namely, Part 1 deals with concepts and principles of information management through BIM methodology, Part 2 deals with information management during the design phase, Part 3 deals with information management during the operation phase, Part 4 deals with information exchange; and Part 5 deals with the security-minded approach applied to information management. According to ISO 19650, several concepts are investigated:

- Project and Asset Information Model (PIM and AIM);
- Level of Information Need;
- Information requirements (OIR, AIR, PIR, EIR).
- Information process management.
- Common data environment (CDE).

Among the European-initiative standards, certainly, it may consider:

- **EN 17412-1** Building Information Modelling - Level of Information Need - Part 1: Concepts and principles

Adopted also at the national level as UNI EN 17412-1, this deals with issues related to the definition of concepts and principles concerning the Level of Information Need. After the publication of the ISO 19650 series, the UNI 11337 series will act as the national annex to ISO 19650, according to the Vienna

Agreement established between ISO and CEN organizations. The Italian Technical Committee UNI/CT 033 is currently revising and updating UNI 11337 to harmonize its contents with the new provisions introduced by ISO 19650. Currently, the UNI 11337 series comprises 12 parts, which are listed in the following Table 1.1:

Table 1.1 - UNI 11337 parts

UNI 11337 series		
Part	**Topic**	**Status**
Part 1	Concepts and principles	Under review
Part 2	Classification and identification of digital objects	Under review
Part 3	Informative attributes, product data sheets, smart CE	Under review
Part 4	LoIN and objects	Under review
Part 5	AcDat (Ambiente di condivisione dei dati)	Under review
Part 6	C.I. (Capitolato Informativo), Information Requirements	Under review
Part 7	BIM professional figures	Under review
Part 8	Information flows for the management of the project	Under development
Part 9	Construction Logbook	Under development
Part 10	Administrative check	Under development
Part 11	Data Security, blockchain	Under development
Part 12	BIM management systems	Under development

1.2 Developing and organizing information in the BIM environment

1.2.1 Geometric, Data and Process Modeling

The geometric representation of civil works is one of the most important aspects of BIM methodology. A brief overview of geometric modeling approaches is therefore a precondition for the development of BIM models, for a better understanding of the capabilities of BIM tools, and the exchange of information. The representation of physical reality by using a 3D model enables several activities including interference analysis regarding elements belonging to different disciplines, quantity estimations, generation of plans and sections, generation of mechanical or physical models for performance evaluation, and photo-realistic and rendered views of projects [40].
Accordingly, there are two approaches for generating a three-dimensional geometry of an object [41]:

- "explicit modeling" describes a volume in terms of its surface, often known as Boundary Representation (BRep), though there are other types (e.g. CSG method);
- "implicit modeling" involves a sequence of steps for describing a volume, often identified as the "procedural approach".

Boundary Representation (BRep) involves the definition of a hierarchy of boundary elements such as Body, Face, Edge, and Vertex, in order to describe the object univocally. This system of relationships, together with geometric dimensions, defines the topology of the modeled object. There are also simplified versions of BRep, such as the description of the surface of an object by defining a triangular mesh, which is often used in visualization software, for the description of ground surfaces or as input for numerical calculations and simulations.

A further implicit modeling approach is the "Constructive Solid Geometry" method (CSG), which uses predefined objects such as cubes, cylinders, or pyramids and combines them using boolean operators such as union, intersection or difference to create more complex objects. Many existing CAD and BIM systems, considering this type of logic, allow 3D objects to be generated along a path as well. A comparison is shown in the figure below:

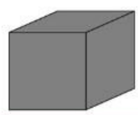
	Constructive Solid Geometry (CSG)	Boundary Representation (B-Rep)
		
Geometric Description	volumetric object	a (set of) polygon(s)
Standard Volumetric Primitive	block	surface
Operations	union, intersection, difference	connection of faces
Inner core	solid	void

Figure 1.9 - Comparison of CSG and B-Rep methods [42]

Another approach is “parametric modeling”, which allows a geometric model to be defined through constraints or parameters that lead to the development of a result that easily adapts itself to new or changing conditions. This is done by considering parameters such as geometric dimensions, relations among them or something else based on relations governed by formulations. Accordingly, this approach makes it possible to generate families of parametric objects. Examples of BIM solutions, which enable the development of these objects and related BIM models, include Tekla Structure, Nemetschek Allplan, Graphisoft ArchiCAD, and Autodesk Revit. In addition, Visual Programming Language (VPL) can support procedural and parametric design as well as data management. Examples of visual programming solutions are Dynamo and Grasshopper3D. In digital construction, VPLs are mainly used to generate information, both geometric and semantic, and to query and manage BIM models.

In the context of **data modeling**, an information model is a simplified representation of reality that allows data to be managed for the activities about the life cycle of a work. A complete data modeling of civil engineering work also implies the management of semantic data, in addition to geometric ones, such as materials, construction methods, area or space functions, maintenance activities, etc. In addition, data modeling through the definition of entities, attributes, and relations allows the conceptualization of reality on the construction under consideration through a conceptual data model. The approaches used for data modeling, which are also commonly used in BIM environments, include the Unified Modelling Language (UML), which graphically represents object-oriented models (OOM), and the Entity-Relationship (ER) approach, through the use of entities and relative relationships. The characteristic elements of a conceptual data model can include the following [41]:

- An "entity/class" is a specific data item and it can be either a physical item (e.g. beam) or a non-physical thing (e.g. space).
- An "entity type" classifies and groups entities that can have the same characteristics (e.g. shape, scope, etc.).
- An "Attribute" specifies a set of properties of an entity, where each entity differs from another for specific attribute values. Each attribute is characterized by a proper name and a relative data type. Relations indicate relationships or interdependencies among entities. Common relationships are one-to-one (1:1), one-to-many (1:N), and many-to-many (N:M).

Process modeling is an important aspect of the BIM methodology because BIM involves more than merely the creation of a 3D model. Processes allow activities to be organized or managed and project information to be shared. This is achieved by employing activities and tasks that relate to specific workflows, which enable the execution of geometric and data modeling to fulfill client requirements. The development of a workflow requires resources and an upward definition of requirements. Workflow management requires processes and structured data in addition to a specific software ecosystem. Processes can also be performed in the openBIM scenario considering open standards and services (e.g. IDM, UCM, IDS). Processes can be structured and modeled in different ways, e.g. according to the business process model and notation (BPMN). BPMN is based on basic element categories (Object Management Group, 2011), but variations are sometimes allowed. These categories are the following:

- Flow objects, representing events, activities, and gateways;
- Data, which consists of data objects, data inputs, data outputs, and data stores;
- Connection objects, which represent sequence flows, message flows, associations, and data associations;
- Swimming plans, which consist of pools and lanes;
- Artifacts, which provide information about the data required or produced in an activity.

At the same time, this BPMN notation has been chosen and used by buildingSMART for defining processes in the BIM environment.

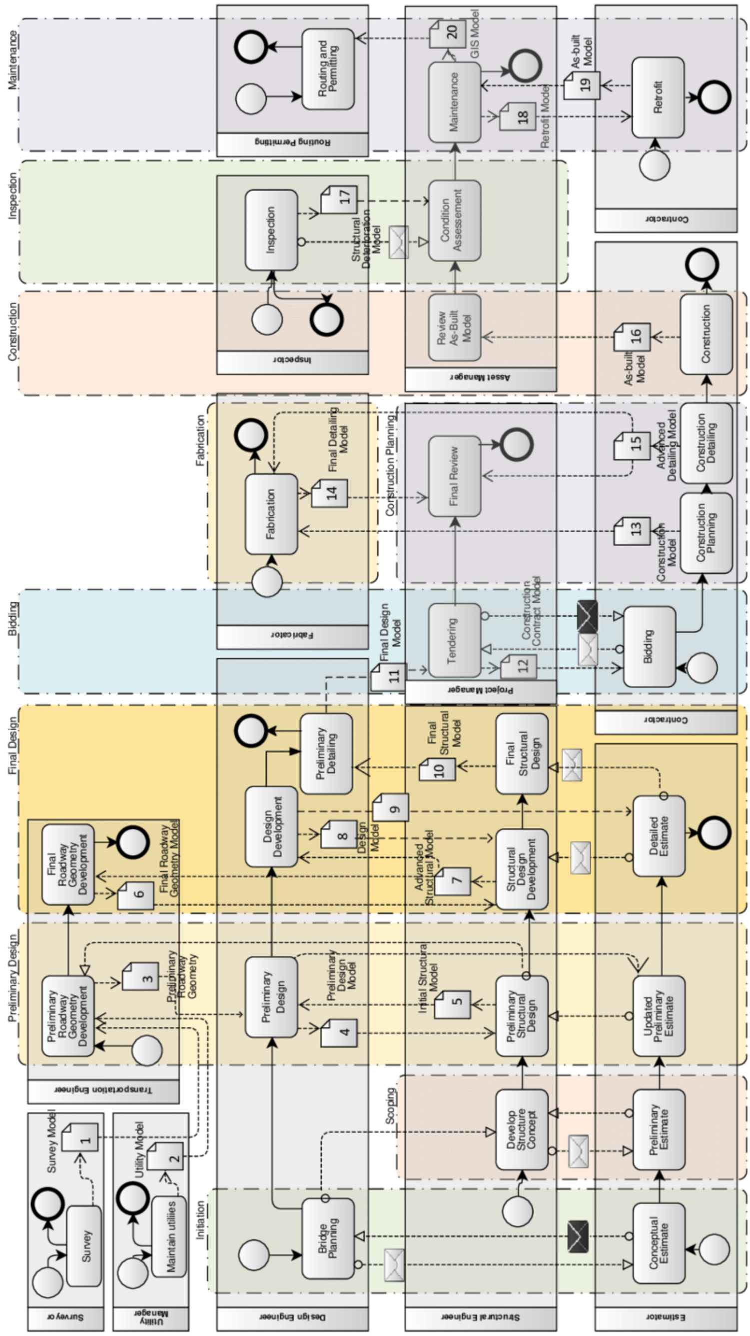
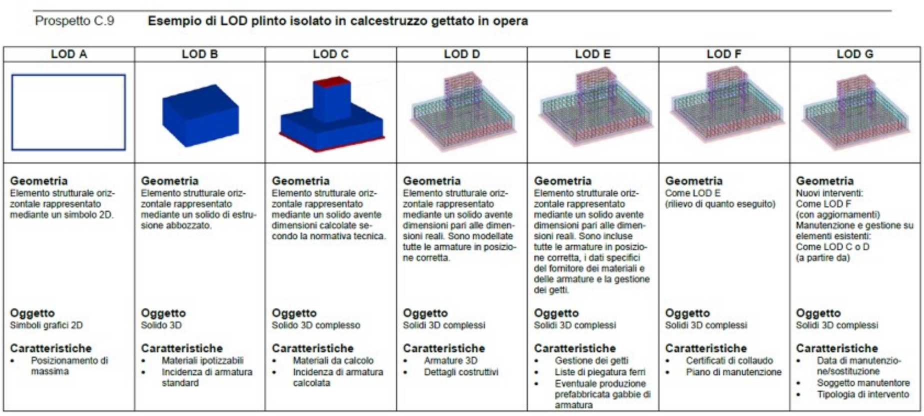


Figure 1.10 - Example of process map according to BPMN notation, developed in the context of the IFC-Bridge Project [43].

1.2.2 *Level of development: LOD and LoIN frameworks*

The concept of "Level of development" (LOD) specifies the requirements for the information to be developed in the BIM environment, according to the specific phase of reference. This is similar to the logic considered for 2D representation, in which information to be developed is related to the representation scale [41]. Specifically, LOD can be considered as the combination of the level of geometric detail (Level of Geometry - LOG) and the level of information/alphanumeric detail (Level of Information - LOI). This approach has been developed in several countries, each of which has defined its standards for the detailing of building and infrastructure components. Among the various standards, the American Institute of Architects (AIA), in collaboration with the American BIM forum, has defined the six LODs using a progressive scale from LOD 100 to LOD 500 [44,45]. However, the AIA document only provides minimal specifications regarding the LOI, since the required alphanumeric information is highly dependent on the type of project and the corresponding BIM use cases. LOD requirements are typically embedded within the Employer Information Requirements (EIR), defined by the client at the beginning of the project [41]. In the Italian framework, the LOD definition is dealt with by the UNI 11337-4:2017 standard, in which the possible LOD categories are identified by a letter, from LOD A to LOD G. The following figure represents an instance of LOD for structural elements:



Prospetto C.9 **Esempio di LOD plinto isolato in calcestruzzo gettato in opera**

LOD A	LOD B	LOD C	LOD D	LOD E	LOD F	LOD G
Geometria Elemento strutturale orizzontale rappresentato mediante un simbolo 2D.	**Geometria** Elemento strutturale orizzontale rappresentato mediante un solido di estrusione abbozzato.	**Geometria** Elemento strutturale orizzontale rappresentato mediante un solido avente dimensioni calcolate secondo la normativa tecnica.	**Geometria** Elemento strutturale orizzontale rappresentato mediante un solido avente dimensioni pari alle dimensioni reali. Sono modellate tutte le armature in posizione corretta.	**Geometria** Elemento strutturale orizzontale rappresentato mediante un solido avente dimensioni pari alle dimensioni reali. Sono incluse tutte le armature in posizione corretta, i dati specifici del fornitore dei materiali e delle armature e la gestione dei getti.	**Geometria** Come LOD E (rilievo di quanto eseguito)	**Geometria** Nuovi interventi: Come LOD F (con aggiornamenti) Manutenzione e gestione su elementi esistenti: Come LOD C o D (a partire da)
Oggetto Simboli grafici 2D	**Oggetto** Solido 3D	**Oggetto** Solido 3D complesso	**Oggetto** Solidi 3D complessi	**Oggetto** Solidi 3D complessi	**Oggetto** Solidi 3D complessi	**Oggetto** Solidi 3D complessi
Caratteristiche • Posizionamento di massima	**Caratteristiche** • Materiali ipotizzabili • Incidenza di armatura standard	**Caratteristiche** • Materiali da calcolo • Incidenza di armatura calcolata	**Caratteristiche** • Armature 3D • Dettagli costruttivi	**Caratteristiche** • Gestione dei getti • Liste di piegatura ferri • Eventuale produzione prefabbricata gabbie di armatura	**Caratteristiche** • Certificati di collaudo • Piano di manutenzione	**Caratteristiche** • Data di manutenzione/sostituzione • Soggetto manutentore • Tipologia di intervento

Figure 1.11 - Example of LOD for a structural element (in-situ concrete plinth) in accordance with UNI 11337-4

LOD scales are also proposed for historical conservation purposes due to the presence of heritage of considerable importance to be managed and digitized in Italy. Moreover, there are specifications both concerning the different disciplines (architectural, structural, MEP, etc.) and for different types of works, whether building or infrastructure.

Later, this scenario was affected by a new approach introduced by the ISO 19650 series and UNI EN 17412-1 through the definition of the "Level of Information Need" (LoIN). Unlike the existing LOD concept, the new framework (LoIN) is different since it is possible to: (i) improve the quality of information; (ii) reduce the risk of errors in interpreting requirements and checking compliance with contractual demands; and (iii) improve the effectiveness of the process by producing only the most necessary information, thus avoiding waste, redundancy or lack of information. This concept has been further investigated in a recent standard UNI EN 17412-1, also adopted in Italy, which introduces the relevant aspects (at geometric, alphanumerical, and documental levels) for information needed to define a digital model.

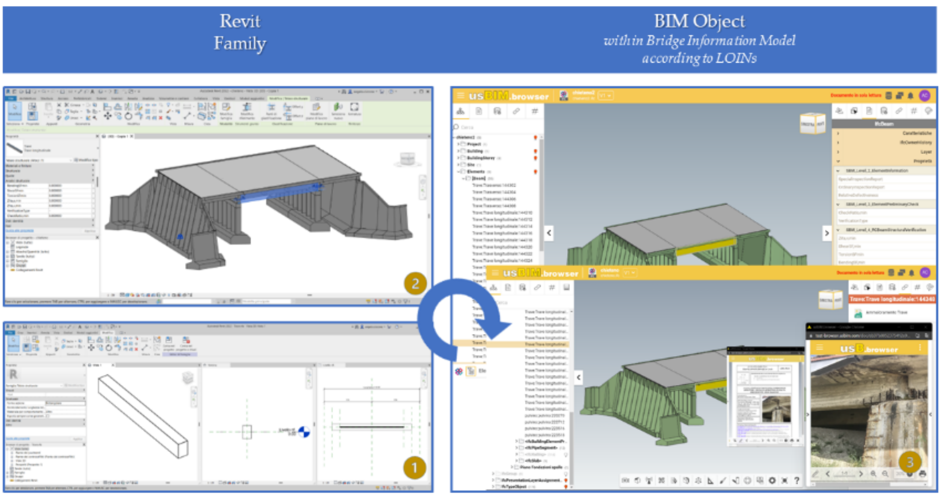


Figure 1.12 - BIM object definition (in Revit environment) and relative information enrichment for the fulfillment of the requested Level of Information Need.

Therefore, this approach provides a precise method for defining the Level of Information Need by identifying: the purpose (why), stages (when), actors involved (who), and exchange object (what). In this sense, information should be organized according to geometric, alphanumerical, and documental aspects. The adoption of this new approach is necessary to manage all information that is strictly necessary for specific use and related purposes.

1.2.3 Collaborative environments

BIM methodologies support the digital integration of the different disciplines involved in a project. To facilitate this, the availability of specific platforms, also based on open formats, is essential to ensure interdisciplinary collaboration in a single digital environment. Collaborative platforms are local or cloud-based environments that make it possible to organize workflows by defining rules and roles for each actor involved in the process under consideration. Within them, the information models, analysis models, reports, photos, schedules, and so on related to the project are organized and stored.

In the traditional approach, the professional teams, based on the different requirements defined by the client, develop a design solution that is delivered to the client utilizing graphic drawings and documents, subsequently collected in a repository (for example called "Ambiente di Condivisione di Documenti", ACDoc, according to the UNI11337-1 standard). With the introduction of BIM methodologies, the exchange and delivery of information are based mainly on BIM models, which are enriched with data that grow with the progress of the project. Following these new methods, traditional drawings can also have a secondary purpose, namely to make the information contained in information models more explicit and more usable for practitioners. All the information containers (files, models, etc.) can then be collected in a digital environment called the "Ambiente di Condivisione di Dati" (ACDat, in the UNI11337 standard) or also "Common Data Environment" (CDE, in the ISO19650 standard). Thus, a CDE enables the sharing among all professionals of individual disciplinary solutions, permitting interactions and modifications regarding an interdisciplinary federated model. This leads to an optimized design solution, unlike the traditional approach that considers practices that have reduced effectiveness and lead to errors or inefficiencies in design processes. In addition, BIM information models, stored in these environments, can be conceived as reference points for the management of all project documentation. To enable this, the platforms are equipped with functionalities and tools that allow different information to be read, visualized, and linked together to support collaboration and interoperability.

Common Data Environment. Under the current regulatory scenario, both in the national and international context, the CDE structure can be organized in different functional areas. In detail, they correspond to a specific task or working status in order not to create ambiguity among all users with different tasks and expertise.

For instance, the standard UNI11337-4 identifies four working states:

- "L0 - fase di elaborazione/aggiornamento": the information content is under processing and, therefore, still subject to changes or updates. The information content may not be made available externally to the specific working team;
- "L1 - fase di condivisione": the information content is shared between one or more disciplines, but is subject to review by other disciplines or other operators, including the client;
- "L2 - fase di pubblicazione": the information content is related to the finalization of all processes and no parties, except that responsible, can make further changes;
- "L3 – fase di archiviazione": the information content is related to a finalised process and non-active versions.

In this regard, it is possible to organize the folder structure properly, at the same time while ensuring there is no overlap among the different work areas.

Instead, according to the ISO19650 series, also based on the contents inherited from the previous British standards, a four-level structure is proposed, as shown in Figure 1.13, by following ISO 196650-1:

- "WORK IN PROGRESS" area, for the management of "Information being developed by its originator or task team, not visible to or accessible by anyone else";
- "SHARED" area, for the management of "Information approved for sharing with other appropriate task teams and delivery teams or with the appointing party";
- "PUBLISHED" area, for the management of "Information authorized for use in more detailed design, for construction or asset management";
- "ARCHIVE" area, for the management of "journal of information transactions, providing an audit trail of information container development.

In addition, ISO 19650-1 specifies that the authorized use and review of information content shared in the CDE must be carried out using metadata obtained as a result of the control, review, approval, and authorization processes.

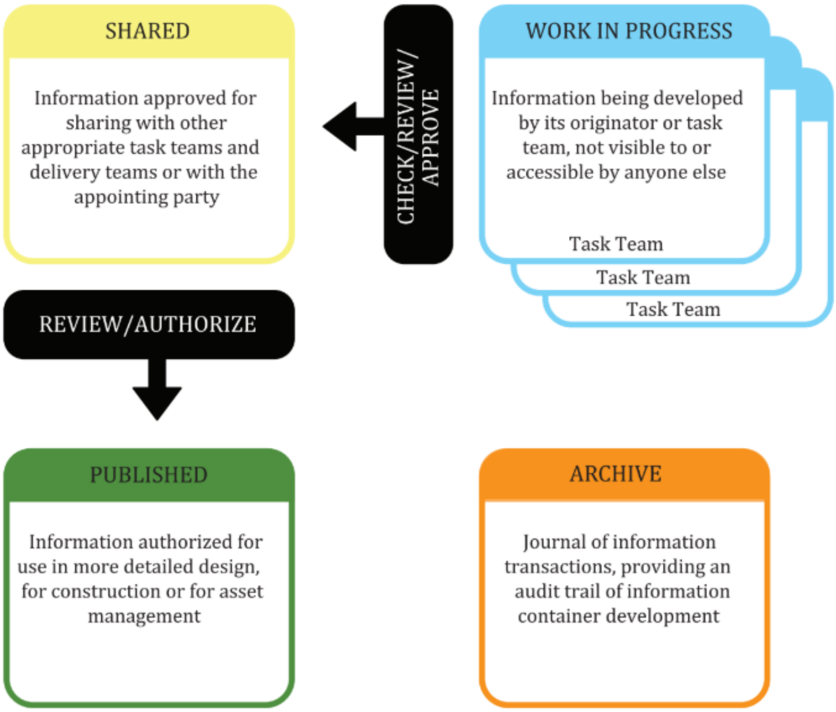


Figure 1.13 - CDE organization according to ISO 19650-1

The digital platforms mentioned so far, which make it possible to structure a CDE or ACDat, for instance, can be accessed via a browser from any device with Internet connectivity. The technological solution based on so-called "SaaS" logic (Software as a Service) makes it possible to adapt and scale the service according to project requirements. Their deployment, linked to the management of licenses on the merit of subscriptions, can provide for the customization of certain services including storage capacity, the number of users involved, etc.. At a national level, the UNI 11337 and D.M. 560 standards provide the minimum requirements that an ACDat must have in terms of accessibility for actors, traceability of the managed information, support of numerous formats (commonly open and proprietary formats), time storage, and security.

The CDE platforms on the market are numerous and they differ in the set of functionalities and tools they include, which makes them differently equipped for managing the life cycle phases of civil work, from planning to the management and maintenance phases. The following are examples of solutions on the market:

usBIM.PLATFORM. This platform is developed by Acca Software, an Italian software company with an important role in the context of open BIM. The usBIM.platform is distinguished by being one of the first platforms certified in the buildingSMART context for the use of open formats, as well as for guaranteeing interoperability with a large number of proprietary formats. In addition, it has a series of functionalities relating to task management, and data management, also regarding data from IoT sensors. The platform is user-friendly and complies with the standard requirements concerning UNI standards.

Trimble Connect. Trimble Connect is a data-sharing platform that offers collaboration tools for those involved in the design and construction phases by using a cloud environment that can be customized using proprietary or third-party plug-ins. This platform ensures compliance with security standards according to international guidelines for cybersecurity and data protection.

Autodesk BIM 360. Autodesk, a market leader in software for the AEC sector and other industries, has developed the "BIM 360" technology platform. This is one of the most widely used platforms because it guarantees integration with proprietary formats (e.g. Revit and Autocad) for design and modeling activities and with the UNI 11337 standards for the definition of an AcDat. It also can be extended with additional plug-ins to enable project management applications.

Allplan BIMplus. BIMplus is a data-sharing environment for design and coordination phases based on federated models. The platform enables the performance of activities such as model checking, clash detection, and construction simulation.

Oracle Aconex. Aconex is a CDE platform that enables collaboration and management of the different phases of the work, from design to construction, through BIM model sharing and related coordination tools. Dashboards allow the monitoring of essential activities in a single environment that provides a complete overview of the projects.

Bentley ProjectWise. ProjectWise is a platform for sharing and collaborating among multi-disciplinary teams, managing related workflows, and ensuring traceability.

Catenda Bimsync ARENA. Bimsync ARENA is a cloud-based solution for sharing information for project coordination through customized dashboards for data visualization, tracking changes, and collaboration among various project teams for resolving clashes and issues.

1.3 The openBIM approach

1.3.1 Interoperability: a key concept for open data exchanges

Interoperability can be defined as the ability to exchange data between different platforms and software, throughout the entire life cycle of the asset, fostering the integration and accessibility of design and process information to all actors involved, reducing errors, and optimizing resources. Traditionally, tools related to the AEC sector integrated poorly with each other, but today the collaborative approach promoted by BIM methodologies requires the accessibility of data in an open manner and without any technological barrier. Regarding information modeling, each BIM object contains information on several disciplines. The main challenge is to transfer this information among all the software used for the specific activities related to the project lifecycle phases. Interoperability can solve this issue. Two specific categories can be referred to as “Horizontal” and “Vertical” interoperability. Horizontal or intra-disciplinary interoperability is when applications developed by different software vendors can collaborate within a common disciplinary domain. On the other hand, vertical or inter-disciplinary interoperability is when applications, developed by the same or different vendors, can create a functional and informative link in different disciplinary domains. In addition, information exchange can take place in three different ways, independently of previous interpretations of interoperability:

- exchange of information among proprietary formats used in different disciplines or different platforms (e.g. .rvt);
- information exchange operating on proprietary transfer applications, (e.g. plug-ins developed through API);
- information exchange through open formats (e.g. IFC).

1.3.2 The openBIM scenario

The Open BIM approach is the highest expression of the concept of interoperability among all disciplines involved in the construction process. It allows for unlimited digital sharing of data and enables an effective collaboration for those involved in a specific phase of the asset lifecycle. This promotes data transfer without loss of information and fluid interaction among all professionals collaborating on the project. Indeed, Open BIM can be defined as "a universal collaborative approach during the design, construction, and management phases of civil works based on open workflows, standards, and procedures". Open BIM has several advantages:

- It fosters an open and transparent workflow that allows professionals to collaborate independently of the software;
- It defines a common language for widely shared procedures that enables industry and governments to obtain projects with transparent business purposes, service comparability, and guarantees on data quality;
- It produces durable projects involving the entire life cycle of the building, avoiding the need to replicate data with its inevitable errors;
- It enables software platform providers to participate in and compete for the development of better solutions;
- It rewards productions that are more aligned with user demands to give and obtain data directly within the BIM system through open formats.

In the AEC sector, the need for a common format for the exchange of information is very important, e.g. for those operators (e.g. clients) who require information without requiring the use of proprietary formats only, while ensuring an efficient exchange of information. This refers to a neutral, open, and standardized format for data exchange, i.e. the Industry Foundation Classes (IFC) characterized by a uniform and unique coding of both geometric and semantic information of building and infrastructure components, the relationships among them, and their properties [41]. The IFC is developed and maintained during its evolution by the buildingSMART International (bSI) organization. BuildingSMART is a non-profit organization, designed to develop and promote the Industry Foundation Classes IFC (as a neutral data model, useful to collect information related to the whole life cycle of construction) and other standards. buildingSMART develops open standards for information modeling, processes, and terms. The association has three goals: (i) to develop and maintain open international standards for BIM; (ii) to provide networking and training opportunities, with detailed specifications and guidelines; (iii) to spread buildingSMART's processes and technology to the entire built environment, throughout its lifecycle. It also has agreements with ISO, for the development of international standards, as in the case of the IFC registered as ISO 16739-1:2018 in its latest official version.

1.3.3 openBIM standards and other projects

1.3.3.1 Industry Foundation Classes

Hence, buildingSMART covers the development and maintenance of a series of standards and services related to the AECO industry.

The IFC consists of a data format with a given extension (e.g. .ifc) that allows information in three-dimensional information models to be encoded and modeled digitally. Moreover, it has certain features, which may be: (i) open, because its technical specification for encoding information has been published and consequently it can be used and implemented by everyone; (ii) neutral, because the development of the IFC format is not under the control of a specific company, corporation or organization; or (iii) interoperable, because it is currently implemented by the main BIM software and therefore allows all actors in the process to share information through a common language. ISO 16739 is defined as a standardized digital description for the built environment, which can cover buildings and civil infrastructure domains. The IFC schema is a standardized data model that logically encodes: identity and semantics (e.g. name, unique identifier), characteristics or attributes (e.g. material, thermal properties), relationships (e.g. connections and properties), objects (e.g. columns, beams, etc.), abstract concepts (e.g. performance, costs), processes (e.g. installation, operations) and people (e.g. owners, designers). Thus, the definition of both geometry and data permits the construction of an informative model which can be encoded with this data format for use in different BIM or specific tools, e.g. for data storage, model referencing, coordination, etc.

IFC can be encoded in various electronic formats, each with its advantages and complexities. The most common and official formats are the following:

- IFC-SPF is a text format defined by ISO 10303-21 and has the extension ".ifc". This is the most widely used IFC format that can be read as text.

- IFC-XML is an XML format defined by ISO 10303-28 and has the extension ".ifcXML". This format is suitable for interoperability with XML tools and the exchange of partial informative models (through the use of MVDs).
- IFC-ZIP is a compressed ZIP format consisting of a file with the extension ".ifcZIP".

For wider compatibility and size optimization regarding informative models, STEP Physical File (SPF) is used for file-based import and export procedures. Concerning the official IFC versions, these can be found on the bSI technical site (https://technical.buildingsmart.org/standards/ifc/ifc-schema-specifications/), as well as their components including HTML, EXPRESS, XSD/XML, and OWL documentation and formats. Some versions of the format itself are specified by certain ISO standards, such as the latest official version to date, IFC 2x3 (according to ISO 16739:2013) and IFC 4 (according to ISO 16739-1:2018). The latter increases support for parametric geometries, materials, structural entities, etc. At the same time, within the buildingSMART context, a new version of IFC is being developed, which includes both a geometric and semantic extension to several infrastructure domains (see Figure 1.14). This development will lead to the definition of a standard, which is currently being voted on by the ISO process.

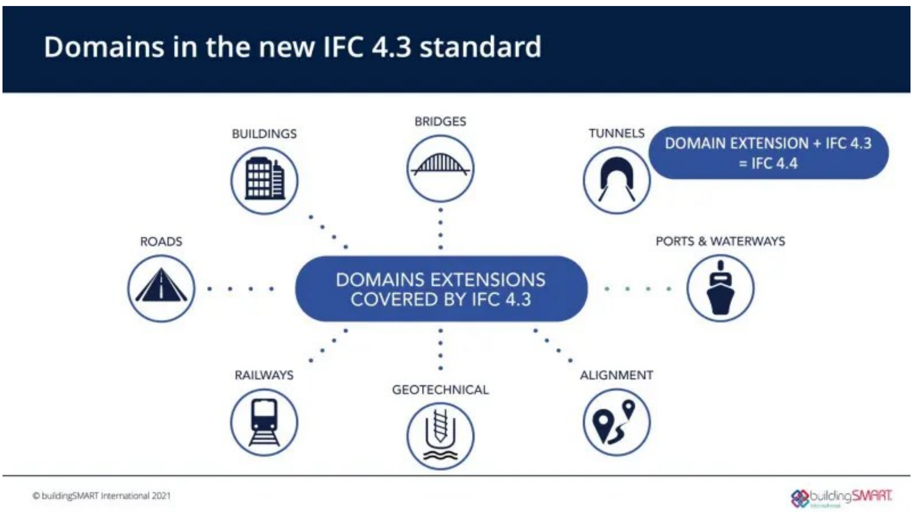
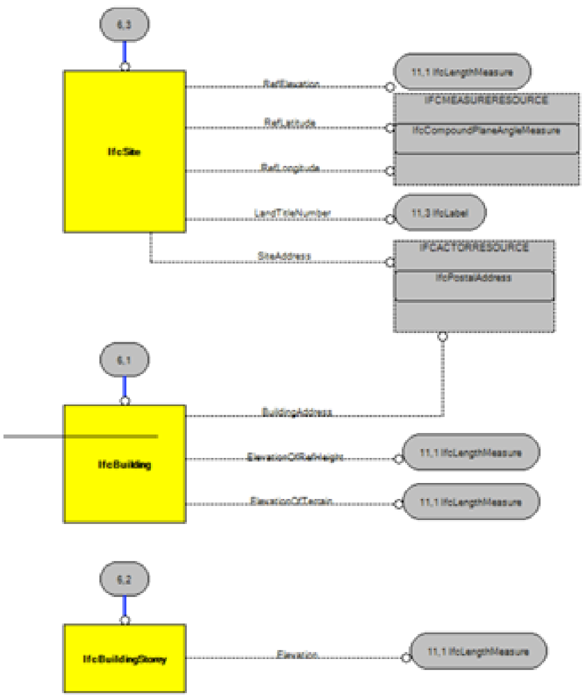


Figure 1.14 - Extension domains covered by IFC version 4.3 under development (source bSI)

Thus, the IFC format is a data model for encoding information and enabling the definition of building or infrastructure BIM models using an object-oriented approach. This data schema is defined by using two definition languages: (i) EXPRESS data definition language; and (ii) XML Schema definition language (XSD).

The EXPRESS language considers the entity (the equivalent of a class in object-oriented theory) where attributes and relationships with other entity types are defined for each entity type [41]. EXPRESS is also based on the logic of hierarchy/inheritance of concepts, allowing both direct and inverse relationships to be defined. Inheritance allows the definition of the specialized entity/class types (sub-classes, child classes) and generalized entity/class types (super-classes, parent classes). Sub-classes can inherit the attributes (properties) of associated super-classes while defining additional attributes to create a specialization of the related super-class. On the other hand, super-classes represent generalizations of associated sub-classes. As mentioned above, EXPRESS also allows data to be modeled in a graphic form, and the graphic notation language is called EXPRESS-G [41]. Examples of these two EXPRESS representations (graphical and textual type) are shown in the figure below:

a)



b)

```
#2986 = IFCSHAPEREPRESENTATION(#329, 'Axis', 'GeometricCurveSet', (#2983));
#2987 = IFCRELCONTAINEDINSPATIALSTRUCTURE('0OAYBPWPXCvAI7LTQ1IgjO', #1, $, $, (#707, #969, #1192, #1227, #1262, #1295, #1328,
#2988 = IFCBUILDINGSTOREY('1G75k_go13DAZ4vTlJ7d$W', #1, 'Piano Primo', $, $, #2991, $, $, .ELEMENT., 3.);
#2989 = IFCELEMENTQUANTITY('0_he9k4RXCyQ$fJJAMNs6g', #1, 'BaseQuantities', $, $, (#701));
#2990 = IFCRELDEFINESBYPROPERTIES('3HUz9SspD9YhUIEOAA7apR', #1, 'BaseQuantities', $, (#2988), #2989);
#2991 = IFCLOCALPLACEMENT(#259, #2995);
#2992 = IFCCARTESIANPOINT((0., 0., 3.));
#2993 = IFCDIRECTION((0., 0., 1.));
#2994 = IFCDIRECTION((1., 0., 0.));
```

Figure 1.15 - (a) Express-G representation; (b) Step Physical file syntax

Hierarchy and inheritance of concepts play a crucial role in IFC, since it defines specialization or generalization relations, defining which attributes of which classes can be inherited by other classes. The different levels are hierarchically linked to each other so that entities belonging to one level can refer to all entities belonging to lower levels (principle of gravity). Relationships between entity types or classes play an important role in describing the semantics of data models. This concept allows the creation of a hierarchical classification system (taxonomy) within a data model [41]. The IFC schema architecture is composed of four layers, each containing data schemas, as shown in Figure 1.16:

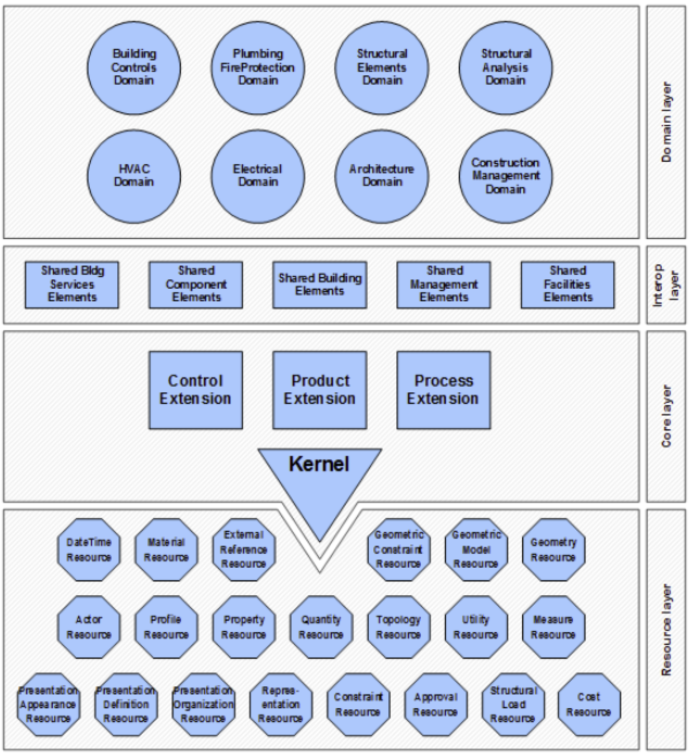


Figure 1.16 - The IFC schema architecture related to IFC version 4 ADD2 TC1.

As regards the IFC architecture layers, these are the following:

- **DOMAIN LAYER:** The highest level of the IFC schema is the most specialized. Each element contains a list of entities and enumerations specific to its domain (Architecture, Structures, etc.). They represent the last leaf nodes in the inheritance and hierarchy organization. Classes defined at this level cannot be referenced from another level or another domain-specific schema.
- **INTEROPERABILITY LAYER:** This layer includes schemas containing entity definitions that are specific to a general product, process, or resource specialization used across several disciplines. These definitions are typically used for inter-domain exchange and sharing of construction information;
- **CORE LAYER:** Here, abstract entities used and specified in other levels are defined. This level can be subdivided into two sublayers:
  - **Extension**: this specializes in the entities defined in the Kernel. In particular, it manages the entities belonging to the AEC/FM sector. It is also subdivided into Product Extension, Process Extension, and Control Extension.
  - **Kernel**: this is the sub-layer that defines the more abstract entities of the Core layer (e.g. includes abstract base classes such as IfcRoot, IfcObject, IfcProduct, IfcRelationship, etc.).
- **RESOURCE LAYER**: It represents the lowest hierarchically specialized level of the IFC schema and contains schemas that provide the basic data that can be used throughout the IFC data model. Classes, in this level, are not derived from IfcRoot and can only exist when referenced to a subclass of IfcRoot. Resource schemas include Geometry Resource (contains basic geometric elements such as points, vectors, parametric curves, and swept surfaces); Geometric Model Resource (contains all classes for describing geometric models such as IfcCsgSolid, IfcFacetBrep, IfcSweptAreaSolid); Material Resource (contains elements for describing materials); and further schemas.

1.3.3.2 Other openBIM standards and services

OpenBIM standards and services support the exchange and transfer of data among the parties involved in a project and among the applications used consistently and transparently. buildingSMART, to support interoperability in the construction sector and the widespread use of OpenBIM, is working on the development of a series of standards that support interdisciplinary communication and collaboration. Some of these are also ISO standards, due to specific agreements established between bSI and ISO. These standards refer to processes, data exchange, and terminology or dictionary as shown in the following figure:

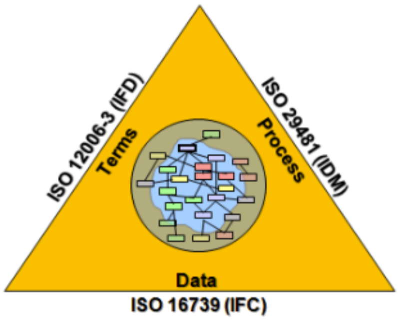


Figure 1.17 - Main reference standards in the openBIM scenario.

BuildingSMART not only defines standards but also offers a suite of online services for using standards themselves in a more effective way, as summarized in the following table:

Table 1.2 - Open BIM standards and services.

Name	Description	ISO Reference	Status
Industry Foundation Classes [IFC]	An industry-specific data model schema	ISO 16739	Completed
Model View Definition [MVD]	IFC View Filter and Data model exchange specifications	-	Completed
Information Delivery Manual [IDM]	A methodology for defining and documenting business processes and data requirements	ISO 29481 series	Completed
BIM Collaboration Format [BCF]	Model-based, software-independent communication protocols	-	Completed
Information Delivery Specification [IDS]	Exchange Information requirements in a computer-interpretable way	-	In development and under voting soon
BCF API, foundation API, Dictionaries API,	Industry-standard Application Programming	-	In development and under voting soon

and DocumentAPI	Interfaces open-CDE API family		
buildingSMART Data Dictionary [bSDD]	A standard library of general definitions of BIM objects and their attributes	ISO 12006-3 (International Framework for Dictionaries)	In the development and implementation of the Dictionaries API
Use-Case Management service [UCM]	Best Practises of use-cases	-	Completed
IFC Validation service	Service for IFC Validation activities	-	Under development

IDM (Information Delivery Manual). This is aimed at describing the processes for a given information exchange required for their execution. It specifies several aspects including defining the processes within the project lifecycle for which users require information to be exchanged; specifying the IFC capabilities required to support these processes; describing the results of process execution that can be used in further processes; identifying the actors that send and receive information within the process, along with their roles; and ensuring that definitions, specifications, and descriptions are provided in a useful and easily understood manner. ISO 29481-1:2010 and 29481-2 were developed to provide a standardized methodology for capturing and specifying processes and the flow of information during the life cycle of a facility. Generally, an IDM is composed mainly of [46]:

- Process Map (PM) consists of a sort of flow chart containing all the steps of a process and their connections preferably developed considering the Business Process Model and Notation (BPMN);
- Exchange Requirements (ER) consist of a set of information, deriving from a process and a specific actor, exchanged to satisfy an exchange requirement within a process in a particular project phase.
- Functional Parts consist of units of information, based on the IFC standard, to support the exchange requirements;
- Concepts consist of pieces of information that can be used for Functional Parts or Exchange Requirements.

The IT formalization of requirements and specifications identified by the Information Delivery Manual contributes to defining the relevant MVD, as shown in the figure below.

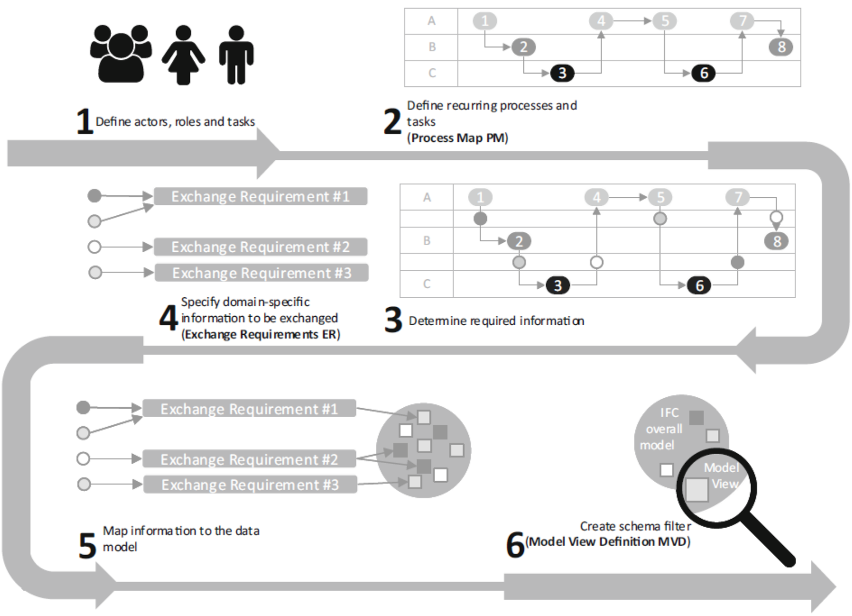


Figure 1.18 - IDM/MVD approach [41].

MVD (Model View Definition). This is an IT formalization of the specifications and requirements concerning the specific IDM. An MVD defines a subset of the IFC schema that needs to be implemented in software to fulfill the data exchange requirements of a given process or activity described in the relevant Information Delivery Manual (IDM). There are MVDs about both IFC2x3 and IFC4 versions, available in the bSI environment (https://technical.buildingsmart.org/standards/ifc/mvd/mvd-database/).

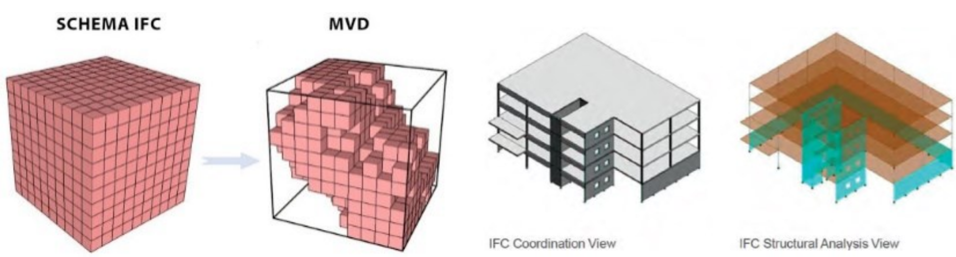


Figure 1.19 - On the left, the MVD mechanism as a subset of IFC data; on the right, examples of MVDs (IFC Coordination View and IFC Structural Analysis View) [47].

Some of them have already been accepted as international standards, while others are currently being developed through the buildingSMART standardization process. Software applications can support sending or receiving data based on the implementation of these MVDs (they must be validated by bSI to be official). However, several Model View Definitions (MVDs), developed in the context of buildingSMART International, refer to exchange specifications concerning, for example, particular versions of the IFC standard such as IFC2x3 and IFC4. These include both those accepted as international standards and those currently under development, through the buildingSMART standardization process. Clearly, MVDs are developed to support specific exchange requirements, and this defines their scope and application scenarios (e.g., with regard to structural engineering applications). In the following Table 1.3, some of the MVDs for structural engineering applications are listed:

Table 1.3 - MVDs considered for structural applications (source buildingSMART International, https://technical.buildingsmart.org/standards/ifc/mvd/mvd-database/)

MVD name	**Status**	**IFC version**	**Description**
Bridge Construction View	Draft	IFC4.2	*Build and maintain bridges*
IFC4Precast	Final	IFC4 ADD2 TC1	*Exchange of geometric information between CAD and MES systems for automated production of precast building components.*
Reference View	Final	IFC4 ADD2 TC1	*Simplified geometric and relational representation of spatial and physical components to reference model information for design coordination between architectural, structural, and building services (MEP) domains.*
Design Transfer View (DTV 1.1)	Draft	IFC4 ADD2 TC1	*Advanced geometric and relational representation of spatial and physical components to enable the transfer of model information from one tool to*

			another. Not a "round-trip" transfer, but a higher fidelity one-way transfer of data and responsibility.
Coordination View (CV 2.0)	Final	IFC2x3 TC1	*Spatial and physical components for design coordination between architectural, structural, and building services (MEP) domains.*
Basic FM Handover View	Final	IFC2x3 TC1	*Handover of model information from planning and design applications to CAFM and CMMS applications, as well as the handover of model information from construction and commissioning software to CAFM and CMMS applications.*
Structural Analysis View	Final	IFC2x3 TC1	*The structural analysis model is created in a structural design application by a structural engineer for one or many structural analysis applications.*
Architectural design to structural design	Draft	IFC 2×3	*This is not a formal bSI MVD*
Masonry Structural Design to Structural Analysis	Draft	IFC 2×3	*This is not a formal bSI MVD.*
Modular Bldgs-Arch.Design to Struc.Design	Draft	IFC 2×3	*This is not a formal bSI MVD.*
Precast Concrete Exchanges	Candidate	IFC 2×3	*This is not a formal bSI MVD.*
Structural design to structural analysis	Proposal	IFC 2×3	*This is not a formal bSI MVD.*
Structural Design to Structural Detailing(ATC-75)	Draft	IFC 2×3	*This is not a formal bSI MVD.*
Wood Structural Design to Structural Analysis	Draft	IFC 2×3	*This is not a formal bSI MVD.*
Extended coordination view	Idea	IFC 2×3	*This is not a formal bSI MVD.*

BCF (BIM Collaboration Format). This standard was created to facilitate open communications and improve IFC-based openBIM processes by using open standards to more easily identify and exchange issues, bypassing proprietary formats and complex workflows. It can contain information related to object identification (GUID); snapshots of the model area where the problem was detected; status of the problem (active, solved, or closed); person assigned to solve the problem; priority or relevance of the problem; phase to which the problem relates; and any comments. It can be used throughout the entire project life cycle, from the design phase to the management phase.

bSDD (buildingSMART Data Dictionary). This consists of a library of concepts based on the IFD standard (ISO 12006-3). The well-known bSDD encourages the development of standardized workflows to ensure the quality of data and information. For instance, BIM modelers can use the bSDD to enrich their information models, while managers use the bSDD to check the validity of BIM data. In addition, the contents of bSDD can be considered for verifying compliance, automatically finding products, extending IFC semantically, creating information delivery specifications (IDS), and much more. In addition to classification systems (Uniclass, Omniclass, etc.), project-specific, national and corporate standards can also be stored in the bSDD. Moreover, its internal structure can facilitate ISO 12006-3, ISO 23386, and Linked Data publications. The bSDD, through its many applications, can improve the quality and productivity of the data managed for a project.

IDS (Information Delivery Specification). An IDS is a computer-interpretable document that establishes the exchange requirements for information models - mainly in IFC format - defining how objects, classifications, properties, and even related valuations (derived from national or company-specific agreements, stored in bSDD or elsewhere) have to be delivered and exchanged. With this, it is possible to define the Level of Information Need, or more generally to define the information requirements for exchanging data models with additional details. The IDS leads to the validation of the IFC by the client, the modeler, and the software tools performing (automated) analyses. This leads to the use of the informative model as a legal document and it can therefore be used as a contract to provide the correct information for each use case for projects and asset management. Hence, the IDS standard is an innovative solution for more reliable model-based workflows. An example of a possible workflow based on the IDS standard is shown in the Figure below:

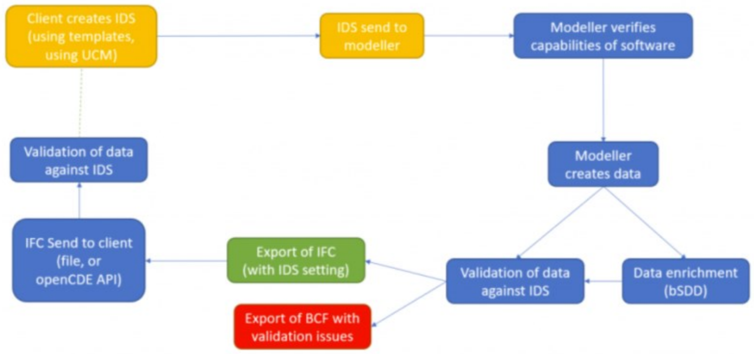


Figure 1.20 - IDS-based workflow (source buildingSMART International)

UCM (Use Case Management). This enables the acquisition and exchange of best practices related to asset lifecycle processes, making them accessible to the entire AECO industry. In order to have an effective exchange of information, it must be established according to the BIM use case. Furthermore, processes must also be established, possibly based on the IDM methodology. Collaboratively involving the respective project stakeholders, enables efficient and error-free data exchange and, by contributing to the UCM, specific experiences on the use of BIM methodology can be shared in order to pursue the overall improvement of BIM applications. The use case management service enables all buildingSMART members, companies, and associations to collaboratively develop their projects in a co-creation environment and publish their experiences on the UCM platform.

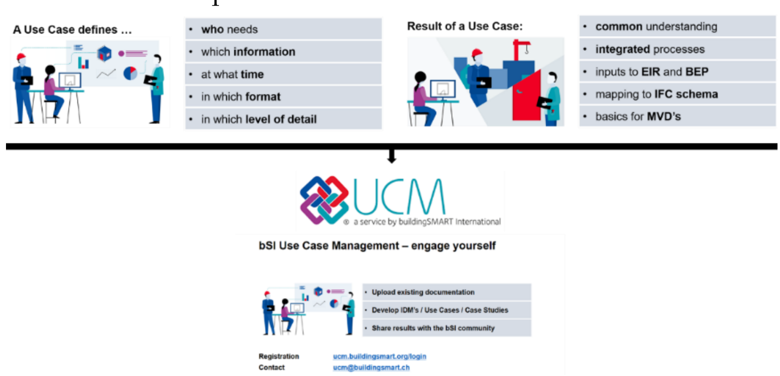


Figure 1.21 - Overview of the UCM (Use Case Management) service provided by bSI.

In conclusion, with the growing digitization of the built environment, the identification of information requirements becomes essential to handle data in the BIM environment properly. However, the specification of these requirements by users can be done by selecting the most suitable methods for the specific case [48]. Different standardized and non-standardized methods can be used to specify information requirements, including Product Data Templates (PDT), Model View Definition (mvdXML), Information Delivery Manual (IDM), Level of Information Need (abbreviated as LOIN), Data Dictionaries (ISO12006), IFC Property templates, Information Delivery Specification (IDS), Linked Data with SHACL, non-standardized textual or spreadsheet documents (.doc, .xls), proprietary solutions (e.g. Solibri), and others, such as dedicated visual programming scripts. Some studies [48] aim to highlight differences and create a synthesis - showing the aspects that are supported, partially supported, or not covered by a particular method - as defined in the following figure.

The outcomes of this research prove that no one solution covers all aspects of use-case analysis. Each method has a different purpose and should be chosen wisely in relation to its specific application. Each method plays an important role in the entire solution ecosystem but, nevertheless, tends to be improperly applied, leading to errors and limitations in the expected performances of digitization.

○ – No
◑ – Partial
● – Yes

			Fields					Value constraints				Content			Geom.		Metadata		
	Standardised	Applicability	Info. type	Data type	Unit of meas.	Description	References	Equality	Range	Enumeration	Patterns	Existence	Documents	Structure	Representation	Detailedness	Purpose	Actors	Process map
Spreadsheet	○	◑	◑	◑	◑	◑	◑	◑	○	○	○	○	○	○	○	○	◑	○	○
PDT	●	◑	◑	●	●	◑	●	○	◑	●	○	◑	○	○	○	○	◑	○	○
Data Dict.	●	○	●	●	◑	●	●	●	◑	●	◑	○	○	○	○	○	○	○	○
IDS	●	●	●	●	●	◑	◑	●	●	●	●	●	○	◑	○	○	●	◑	○
mvdXML	●	●	●	●	●	◑	○	●	●	◑	◑	◑	○	●	●	○	○	◑	○
idmXML	●	◑	◑	◑	◑	●							●		◑	◑	●	●	●
LOIN	●	◑	◑	●	●	◑	◑	○	○	●	○	○	●	◑	◑	●	●	●	○
IFC P.T.	●	◑	◑	●	●	◑	○	○	○	●	○	○	○	○	○	○	○	○	○
LD+SHACL	○	●	●	●	●	◑	●	●	●	●	●	◑	◑	●	●	○	◑	◑	○

Figure 1.22 - Information requirement aspects (supported, partially supported, or not covered) by a particular method according to a specific study [48].

1.4 BIM uses for structural engineering

Structural engineering, in the last decade, has also been affected by the implementation of BIM methodologies in both the professional and research fields. With this regard, several BIM uses can be considered for this discipline. The term "use of BIM" - which was first introduced in 2013 by Penn State University - identifies a unique task or procedure in a project that can take benefit from BIM integration in that specific process [49]. Depending on the activities related to a specific phase of the structure's life cycle, several uses may therefore be considered, such as: (i) structural analysis; (ii) optimized structural design; (iii) production of technical drawings; (iv) modeling of existing conditions; (v) risk assessment and retrofitting strategies; (vi) structural health monitoring. Each one differs according to a series of aspects, such as the use of BIM information models, task-specific workflows, information exchanges, issue solving, etc.. Different structural applications can be used, such as SAP2000, MidasGen, Edilus, MidasCivil, Robot Structural Analysis, and so on. Each of these considers different interoperability levels with a few cases of information exchange based on openBIM approaches (e.g. via IFC). At the same time, some applications [1,50–52] have implemented workflows, which consider openBIM and open-source solutions, through the use of the Python language [2,50,53,54], and specific libraries, such as IfcOpenShell [55]. Accordingly, a specific level of interoperability between BIM creation tools and structural design/analysis software is required.

Structural analysis. The phase of structural analysis is important in getting to know the behaviour of a structure. The implementation of the BIM methodology together with the open BIM approach has several benefits compared to traditional processes [1,13,50]. As regards BIM workflows, several data can be extracted directly from the BIM model in comparison to traditional procedures, in which such data are derived from drawings, diagrams, or other sources. This improves, automates and speeds up the structural design process, which is now more digital because of the use of BIM [56]. During the design phase, from an architectural concept of the work, the load-bearing structure is conceived and set up in context for the foundation soil and acting loads. Subsequently, structural engineers create a draft structural information model and then the corresponding analytical-mechanical model for structural analysis applications. If there are no detected problems - which may require bilateral changes in both architectural and structural discipline - the structural design can be verified and therefore completed. The export of an analytical model from a structural BIM model can also allow structural applications to be developed later in structural software by structural engineers [1,57,58]. After the post-processing phases, through structural software applications or specific plug-ins, the final structural design is completed following the reference structural code [59–61]. Having accomplished this, an update of the structural informative model can be envisaged, but interoperability problems - which are common between BIM-authoring software and FEM tools - may occur, leading to rework and changes [62–64]. Indeed, in the BIM environment, the practice defines an analytical-mechanical model from the relative structural BIM model with subsequent import into FEM software. Within it, certain aspects are defined including geometry, materials, constraints, loads, and so on. This exchange (BIM to FEM) can be performed by adopting various solutions involving the use of (i) proprietary format plug-ins [65,66]; (ii) openBIM standards, such as IFC file format [50,67,68]. Minor interoperability problems occur with the adoption of proprietary format plug-ins [69,70], available when BIM-authoring and FEM software belong to the same software vendor or when two different software houses collaborate to develop a common solution, sometimes even allowing "round-tripping" exchanges (concerning updating on geometry, material, etc.). Unlike plug-ins, the use of open standards (e.g. IFC) is affected by several interoperability issues because data exchanges, between BIM-authoring and structural analysis software, are affected by data loss or incorrect interpretations [68]. However, buildingSMART has dealt with the topic of interoperability, within the structural engineering scenario, through the definition of model views, such as the "Structural Analysis View". Unfortunately, its implementation has led to poor quality data exchanges due to differences in semantics, syntax, and information representation between the various structural analysis applications that are being considered [1,56]. Indeed, this model view has been implemented very rarely in the structural software on the market, which considers other MVDs such as "Coordination View" for structural applications [1,56]. Round-tripping exchanges may be necessary because the structural models produced may require further changes, due to the iterative design process, or records, as information belonging to the BIM model, of structural results obtained downstream of structural design activities.

Optimized Structural Design. In the context of structural design, the use of BIM oriented to the optimization of design choices supports both the early identification of construction issues and the comparison of different structural design solutions regarding the management of schedules, quantities, and associated costs for the work under consideration. Usually, some problems are tackled during the construction phase [71,72]. Meanwhile, unconventional structures (e.g. tall buildings, bridges, industrial plants, etc.) require highly industrialized or unique structural elements, and this implies a direct relationship with manufacturers, which can be important right from the design phase [17,73,74]. The collaborative approach, introduced by BIM methodologies, favors information and feedback sharing with manufacturers through the definition of standardized procedures based on information models. Through parametric three-dimensional representations, optimized design strategies can be defined, for example, based on the modulation of structural members to facilitate and speed up the construction process. This approach enables the early identification of issues, which could cause economic losses or delays in addition to the better management of structural assessments or updates that may occur during the design process. In addition, specific BIM tools allow specific information to be integrated into BIM objects and subsequently to export informative models in open format [1,2,75,76]. Since the BIM models consist of parametric objects, quantity estimations for structural elements can be automatically generated with related costs [77–80]. However, the optimization process, supported by BIM methodologies, is strictly dependent on the criteria adopted to define the optimal solutions obtained based on well-defined parameters. To this end, the optimization procedure should also consider a collaborative approach between the parties involved from the beginning of the project.

Production of technical drawings. The second BIM use concerns the production of drawings for a technical description of the structural aspects. To date, this use is thought of highly in professional practice. In detail, BIM methodologies bring collaborative features that traditional processes are often lacking [9,17,51,81]. A new part may also be represented through the creation of parametric libraries, consisting of BIM objects. In the structural scenario, the BIM model will consist of three-dimensional parametric objects, representing the components of a structure (such as beams, columns, walls, foundations, etc.), in addition to data and information related to different contexts (materials, loads, performance, etc.) [30,41]. Afterward, this model is often integrated with other discipline-related models to obtain federated versions. By using specific applications, activities on coordination and interference detection can be performed. Compared to traditional approaches, these activities can also be assisted by collaboration platforms that are characteristic of the BIM approach [9,51,82]. The new approach avoids time-consuming reworking, in the case of changes, because these are automatically transferred from the informative models to the design drawings [1,83]. Previously, the traditional workflow was based on the use of CAD (Computer-Aided Design) tools, which allowed modeling in a 2D environment as opposed to the new BIM tools that allow the generation of real-time virtualization of the structural system, with geometry and other information, in a 3D environment. However, regarding structural applications, detailed representations (e.g. regarding reinforcements information), generated by the informative models, still require additional time for reworking to adapt what has been obtained to the common results that project participants are used to receiving. Thus, BIM, due to its benefits (collaboration, automation in the creation of high-quality deliverables, etc.), is receiving increasing consideration in professional practice [12,13,22], and this requires the technicians involved to receive specific training.

Existing Conditions Modelling. For existing structures, a series of activities are necessary, sometimes not foreseen for new constructions, such as: (i) a knowledge phase, both from a geometric and physical-mechanical point of view (through documentation analysis, inspections, non-destructive and destructive tests, etc.); (ii) a phase of "as is" state assessments, with related structural performances; and (iii) a phase related to the design of structural retrofit strategies. For the definition of BIM models, too, there are differences between new and existing structures [13,84–87]. As regards the digitization of existing structures (buildings, bridges, etc.), the new digital process - involving BIM methodologies - can be characterized by a series of steps, including data acquisition, typical object recognition, creation of an as-is informative model, connection with a related FEM model, in addition to the capacity assessment of the structure. For example, the data acquisition phase could consider surveys using different techniques such as photogrammetry and 3D laser scanning [3,84,85,88–92]. Afterward, these acquired data (images and scans) are processed to obtain certain products such as point clouds or textured meshes [3,87,93,94]. Such products can then be imported into the BIM environment, enabling a pre-identification of BIM objects. This aspect of research can also be carried out through automatic or semi-automatic techniques [90,95,96]. This is followed by the generation of the "as-is" model and its structural analytical model (assigning data about materials, reinforcements, loads, constraints, etc.). This new approach, targeted toward the digital management of existing structures, allows a more reliable definition of the geometry, and consequently more accurate related FEMs [13,87,93]. Such workflows are especially recommended for the management of historic heritage since they allow easy digital reproduction of their details, both architectural and structural. The use also known as Historical BIM (HBIM) [97,98] can be applied to other works, such as existing bridges [42,84,90,92,93,99,100]. Hence, BIM models can also be useful as digital repositories for managing the amount of data resulting from the knowledge phase of the work and the related survey phase [2,3,13].

Risk assessment and retrofitting strategies. For seismic risk assessment purposes, BIM methodologies can collect through information models data and information used as input for such technical assessments [2,64,82,101–104] or record the relevant outcomes with the possible support of collaborative platforms as well. In this structural scenario, BIM models can also be used for recording information related to structural damage [105–110], in this way supporting cost-effective seismic mitigation strategies and extracting input data for structural analyses to obtain fragility curves, which can be summarised in specific parameters added to the BIM objects [2,64,103,106]. In addition, custom solutions, by using application programming interfaces (APIs), can be developed to automatically import information from BIM models to software that performs structural analyses and assessments. However, even considering this BIM use to support seismic risk assessments, the information exchange (based on export and/or import processes) is typically based, especially for proprietary solutions, on automated or semi-automated procedures using APIs. These languages depend on the specific solution to be communicated (BIM authoring - structural analysis tools). Information exchange could also consider solutions based on open standards such as IFC or the definition of simplified calculation procedures [64,111]. In most cases, a pre-existing BIM model of the structure itself is not even available. However, once the BIM model has been created, it represents the existing status of the structure. Its analytical-mechanical information can be exported to FEM software to perform structural verifications and capacity assessments of the structure. Typically, these results are collected in reports, drawings, and other deliverables. Some studies, therefore, propose innovative structured approaches for the creation of an informative model of an existing structure and its use for retrofitting or renovation purposes, based on the IFC standard specification [112] or implementations aimed at optimizing the retrofit strategies [64]. For the management of existing works such as bridges, other systems, and approaches can support decision-making for retrofitting and process reengineering actions [96].

Structural health monitoring. BIM tools and methodologies can also be considered for structural health monitoring (SHM). SHM makes it possible to adopt damage detection strategies, optimize maintenance strategies using a condition-based approach, assess the structural performance of existing buildings and infrastructure, and thus extend the service life of a generic structure [113–116]. In the context of SHM, BIM models can be mainly considered for the following applications: (i) for modeling and visualizing structural monitoring systems; (ii) for visualization and management of data from installed sensors; (iii) for interpretation of acquired data and process management [74]. Hence, structural information models can be also characterized by BIM objects representative of the monitoring system, e.g. sensors [18,117,118]. These may contain specific parameters such as the date and time of acquisition, sensor type, etc. In addition, information models (e.g. in IFC format) and collaborative platforms can also be considered to support the management of this type of data [113,115,119,120]. Although IFC mainly handles information with a static nature, there are also proposals in the literature to consider the IFC schema for monitoring data management and for extending the

IFC scheme itself [116,121,122]. In addition, ad hoc tools could also be developed, such as a dynamic BIM viewer that allows for dynamic and interactive monitoring of key parameters of the structural performance of a built asset [3,4,18,23,110,120]. The availability also of this type of monitoring data, managed regarding BIM models, allows us to obtain useful information for supporting decision-making processes related to renovation and maintenance works. Although BIM methodologies are currently being used in the context of monitoring, further studies and validated workflows still need to be defined to solve some challenges, including the interoperability of the different systems involved and the post-processing of the acquired raw data.

1.5 BIM adoption benefits

When technological innovations (such as those brought about by BIM) are adopted, some of the benefits associated with their implementation can affect traditional processes. Regarding the well-known MacLeamy scheme, the life-cycle costs of a project should be monitored starting from the early design stages. In traditional processes, the actual integration of all disciplines (structures, MEP, etc.) only takes place in the final steps of the design. If this happened earlier, conscious choices would be made to reduce costs and optimize schedules. In addition to the design phases, there is also the construction phase, during which many variations traditionally occur due to, for example, interference during the construction of the work to be built. According to traditional methodology, design phases are based mainly on paper drawings, which require a considerable amount of time to prepare and great effort to be modified. This makes it difficult to share information among several stakeholders, leading to many errors and redundancies. Nowadays, with the introduction of BIM technologies, the greatest efforts are made in the early stages, when it is easier to make project changes and lower costs are required to implement them. All professionals, starting from the early stages, can be involved through rapid and effective data sharing for project optimization. All this takes place based on information models, where drawings are extracted from them directly. From an engineering perspective, one of the most important contributions of BIM is the increase in productivity, especially in the production of construction documents [83,99,123]. With the philosophy of "begin with the end in mind", the technological, performance and economic aspects are clear and established right from the beginning, so that each team member can, at any time and in a collaborative manner, make changes, even of a significant nature, to the project.

In this direction, during the asset life cycle, other studies analyze the management of data and information, comparing the traditional approach with that related to BIM methodologies [30,41]. Traditional processes are fragmented for several reasons (e.g. paper-based processes, lack of interdisciplinary integration, activities carried out at different times and with different teams, etc.), and a loss of information often occurs. Instead, the support of BIM leads to a collaborative approach that establishes common goals within the work team, increasing the efficiency of the activities that are completed with less effort and greater awareness. In addition, information management is based on well-defined processes and appropriately codified information via information models, which can reduce data losses. These aspects make the BIM methodology also suitable for the management of existing civil works (e.g. facility management activities). To ensure the successful management of the projects, all parties involved in the project must be able to access and update information at any time and in any place (e.g. for inspection or maintenance operations) [3,4]. Also, openBIM can support the management of these activities [2,3,124]. Communication among designers is not the only important feature, but also communication with clients and decision-makers. Coordination based on federated BIM models enables access to all information necessary to make decisions querying the database at any time, reducing the amount of paper documentation, and avoiding related misunderstandings.

As regards leading companies, they have implemented the BIM methodology on many projects concerning buildings, roads, railways, bridges, tunnels, and industrial plants. As a result, the implementation of BIM has brought many benefits including better control in terms of planning and costs, as well as reduced risks. In most engineering companies, especially big ones, it is common to work with teams in different locations. New technologies, such as cloud servers, significantly facilitate the overall process, allowing all information to be shared through cloud environments and collaborative digital platforms.

A study carried out by McGraw Hill Construction [125] discusses the main benefits of implementing BIM in companies, such as reduced planning time, increased profits, reduced rework, collaboration across different regions, identification of conflicts before the construction phase, etc.. In general, for organizations and companies, the benefits of adopting BIM include improved internal communication, increased efficiency with associated cost reductions, and higher quality and reliability of the information produced. Further studies have examined the status of BIM adoption in-depth, highlighting BIM benefits and common barriers to BIM adoption in the AEC industry worldwide [39].

In conclusion, organizations can therefore measure their level of BIM maturity by assessing their internal processes, information flows, and the capabilities and skills of their workers. The adoption of BIM methodologies must be contextualized considering what the company strategies and objectives are, in addition to available resources and capabilities. In this way, organizations should be aware of their level of BIM maturity to set their own goals and develop a roadmap considering the BIM adoption challenges in terms of software licensing costs, training, and the recruitment of qualified professionals with the definition of new contracts and remuneration plans. Finally, BIM is an emerging technology in the AECO industry, and its adoption level varies from country to country. At the same time, it can offer numerous benefits for new digital management of asset lifecycle to all stakeholders. Nonetheless, there remain several barriers to the implementation of BIM methodologies.

Chapter 2

2. Integration of structural information within a BIM-based environment for seismic structural e-permits considering openBIM solutions.

2.1 Introduction to the application of BIM methodology for e-permitting procedures in the AEC industry

A possible development affecting the construction ecosystem is the adoption of digital building permitting (DBP). Gradually, the diffusion of innovative topics such as environmental sustainability has led authorities to consider that dematerialization alone (e.g. through PDFs) clearly cannot provide a complete approach to digitization. At the same time, the demand and management of large amounts of data also require an improvement with regard to increasingly open and dynamic data exchanges.

Thus, the digital issue of building permits, including through the support of the openBIM approach, can be one of the enabling solutions for complete digitization, especially for public administrations. Indeed, the construction sector, along with other regulated fields (health, environment, etc.), has required the adoption, by national institutions, of administrative processes that favor the digital management of the associated bureaucracy. This involves an improvement, both from a technological and professional point of view, not only of technical services but also of legislative bodies concerning the integration of the principles for standardized digitization and the resulting approval of increasingly machine-readable laws (e.g. e-laws). These issues have led to the growth in recent years of the regulatory technology sector. One of the driving factors is certainly OpenBIM. Indeed, numerous companies that manage infrastructure assets (existing roads, railways, etc.) and authorities, at various levels, are progressively adopting the standardization of information and process modeling based on the OpenBIM approach in the context of project approvals. Worldwide, building regulators have recently started to modernize their traditional systems for permit applications [126]. Their proposals consist of reducing paper-based submissions or replacing them with digital submissions of application forms, drawings, and reports containing technical information. These are known as "e-permitting" systems. Regulators and building authorities are currently considering the open BIM approach as a possible strategy to further improve their existing procedures [127]. Therefore, the use of processes based on open formats and tools (e.g. for automatic validation of their information content) would simplify and speed up operations related to permitting applications [128,129]. In the context of buildingSMART International, Regulatory Room produced a study published in 2020 that highlighted how e-submission systems and procedures were being adopted worldwide for applying for permits and approvals in the AEC sector [128]. One of the interesting topics regarded different information exchanges, related to the various phases of the building process, between Building Body Authorities (BABs) and AEC stakeholders. For supporting applications related to approvals and permits, since the early 2000s e-submission systems (or platforms) have been developed but, currently, their use is still limited. Indeed, through a study conducted within buildingSMART, only five examples were identified (shown in Table 2.1), and only one of these allowed openBIM-based proposals to be submitted.

Table 2.1. Examples of existing e-submission platforms in the AEC sector [1]

Country	Name	Year	Notes
Singapore	CORENET	2000	Accepted BIM submissions from 2010
Norway	ByggSøk	2003	-
Finland	Tekra-GIS, Lupapiste.fi	2012	-
Korea	SEUMTER	2002	-
Japan	-	2015	Introduced for small wooden houses

According to this study, a few examples considered the IFC standard (ISO 16739-1:2018) to deliver data and information through an information model. In addition, it emerged that there was a need to identify the stakeholders involved ("who"), the exchange information phases ("when"), and the related information requirements ("what data") for delivery. This report also considered the development of Process and Interaction Maps - following the Business Process Model and Notation (BPMN) - for describing exchanges with the e-submission platforms. For a gradual transition towards a BIM-based workflow, from a legal perspective, the buildingSMART study identified four stages: manual, digital, hybrid, and automated. In detail, the adoption of the IFC model and its features, e.g. through the use of properties, enables three levels of development of BIM e-submission procedures: (i) visualization - property value is not actively considered; (ii) hybrid/information flow - property value is actively adopted for code-checking activities; (iii) automated code verification - property value is used for automated code-checking purposes. To achieve this, e-Laws, i.e. machine-readable building codes, should be available.

Academic research was also interested in e-submission topics. Some authors [127] defined an e-permit reference framework as having four levels of development: traditional permit; basic e-permit; automated model-based e-permit; and fully-integrated (BIM+GIS) e-permit. This framework considers the impact of each level on the entire life-cycle of a project, i.e., from the submission of permit documentation until the O&M phases of the built asset, underlying the need for automated model-based and fully-integrated BIM+GIS e-permit applications, in addition to the adoption of openBIM standards [127]. Finally, this study suggested that implementations of open BIM-based procedures contain only a few real-world applications, none of which address the use of MVD and IDM to support structural engineering information exchanges with BABs, both in terms of workflows and information requirements. Considering this general overview of e-permitting procedures, which affects some structural engineering practices, the proposed work focuses on the adoption of open BIM to digitize and support this type of process. In particular, considering the IDM/MVD approach defined by bSI, this study aims to overcome some of the obstacles highlighted previously, for the implementation of open formats within e-permitting procedures in structural engineering.

2.1.1 Str.E.Pe. Project

The Str.E.Pe. project refers to research conducted by the Department of Structures for Engineering and Architecture (University of Naples Federico II) in collaboration with ACCA Software, Campania region, BAB of Avellino, and the Municipality of Montemarano. This project was awarded as a winner in the "Professional Research" category at the buildingSMART Awards in 2019. The project aimed to create an IFC-based approach to be implemented and adopted, in the future, in seismic authorization applications in Italy (known as "autorizzazione sismica" and mainly concerning the structural engineering sector). To be compliant with national building codes, structural engineers have to apply (e.g. regarding the design of a new building structure) for approvals and permit from the BAB, which verifies and certifies the compliance of the submitted project. Unfortunately, the traditional interaction with BABs typically consists of manual and paper-based processes involving, for example, printing out documentation, and filling out application forms and checklists. In addition, it was highlighted that BABs introduced summary checklists - that are still filled in by hand - to speed up the countercheck procedures. All this is very time-consuming. Therefore, new approaches, for instance, based on the IFC standard, could improve traditional processes in countries such as Italy, which is characterized by high levels of seismicity and accordingly by specific structural design strategies. In the context of the Str.E.Pe. project, to overcome this gap, seismic authorization practices in force in Italy were analyzed and reference regulations along with required deliverables were identified. A specific dataset was then defined for seismic authorization and related automatic code-checking rules were conceived, based on an IFC model. To this end, a specific strategy for using the IFC format was adopted with the aim of reducing the amount of data required by the authorization process. To do that, it was necessary to understand whether the IFC format supported the structural engineering domain and whether it was able to convey the information collected from the dataset developed during the previous phase. It emerged that only a few pieces of information could be conveyed by the IFC format. Therefore, possible ways to integrate information into the IFC format were considered (e.g. classes, properties, etc.) to exchange the information identified from the reference dataset. Accordingly, the development and implementation of a specific MVD were conceived, in structural software, for the export of tailor-made IFC models for e-permitting purposes as well as for the management of seismic authorization practices, according to the IFC-based approach, on a specific digital platform provided for these applications. Thus, the project led to the development of an IFC-based procedure for the digitization of the seismic authorization process.

2.1.1.1 Defining an openBIM model-based procedure for permit applications concerning structural engineering

As described previously, the Str.E.Pe. project consisted mainly of three steps, the details of which are outlined below.

Step 1. This consists of the analysis of the procedures for seismic-authorisation applications in Italy. Italy, along with other countries such as New Zealand, California (USA), and Greece, has played a significant role in the development of seismic engineering [130]. Measures such as seismic classification and the development of specific technical standards ("Norme Tecniche per le Costruzioni", currently in force in Italy) make it possible to reduce, mitigate and control the consequences of earthquakes. In Italy, technical requirements are embedded in building regulations, thus becoming mandatory prescriptions.

Regarding building permit procedures for seismic areas in Italy, there are two related categories namely a seismic deposit, which is required in areas of very low seismicity, and a seismic-authorization permit, for areas with medium or high seismicity along with other further conditions. Once the permit is obtained, the building process is allowed to move on to the construction phase. However, in the context of the Str.E.Pe. project, only permit procedures were considered (being almost the totality), in order to summarise the seismic permit application in all 20 Italian regions. Analyzing these practices, it emerged that all regions have a seismic-authorisation process where a structural engineer, commissioned by a client, requests the BAB to approve the design of the structure. Once the BAB receives the application with the required technical and administrative documents, these are checked and validated to ensure the quality of the project and compliance with building regulations. The procedure may therefore be completed and no revisions are necessary, in which case the BAB issues the seismic permit. Alternatively, the BAB may request changes or supplementary material and revisions. The results of the conducted survey showed that only 40% of Italian regions have online permitting platforms (i.e., e-permitting), although some allow for a choice between a manual paper-based process and an online version, and the remaining 60% still depend on manual processes [1]. Furthermore, 25% of regions also require applicants to fill out additional checklists and/or forms summarising the project information, which can differ according to the structure types, construction system (reinforced concrete, masonry, etc.), type of intervention (new or existing buildings), etc.. Other permit procedures, meanwhile, have a single format suitable for all cases [1]. Significantly, no region adopts seismic authorization procedures based on BIM models [1].

Step 2. In this step, the IFC format was chosen as a solution for the reduction of the deliverables required for seismic-authorisation applications. Consequently, an IFC model-based procedure was proposed to support the information exchange with BABs during seismic-authorisation applications. To achieve this, regarding the open BIM scenario, the IFC format was considered with the objective of (i) reducing the required deliverables; (ii) analyzing the IFC format regarding the structural engineering domain; and (iii) selecting the most appropriate strategy for the integration of relevant data into the format. At the same time, it was kept in mind that the IFC format is not able to replace all administrative and technical documents (e.g., application forms, etc.), but can nevertheless be deployed to reduce the required deliverables (e.g. through BIM models that can integrate structural information instead of only 2D drawings). Furthermore, documents such as technical reports, produced by software that performs analyses and verifications according to structural codes, are essential for understanding in-depth design choices. Checklists and summary forms could be replaced by an IFC model that integrates all the relevant information required. This would allow BAB engineers to use IFC viewers to explore and access the information in detail through BIM models, therefore also facilitating the understanding of structural designs, on which they could also conduct preliminary counterchecks.

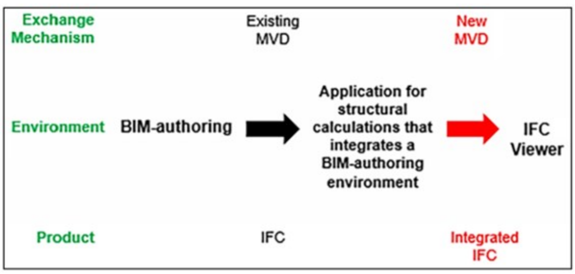


Figure 2.1 - Information flow considered for a structural e-permit process [1].

The figure above shows an example concerning the information flow to be considered for producing specific IFC models. This can be ensured through the development of a dedicated MVD. Therefore, the availability of IFC models exchanged and managed in a dedicated e-permitting platform (such as the usBIM.ePermit platform developed for the Str.E.Pe. project) promotes the definition of new workflows for all actors involved in the process (BAB officers and structural engineers). Under this new approach, IFC models are conceived as an access key for project documentation linked to the BIM objects and model itself, decisively improving current paper-based practices. Producing a tailor-made IFC model for structural e-permitting procedures would be an important achievement for the digitization of seismic-authorisation practices for structures. Accordingly, research was conducted to understand the capabilities of the IFC format (e.g. in terms of classes, attributes, and properties) for conveying selected data, for example concerning the results of structural analyses and verifications. To manage the procedures considered in the BIM environment, especially considering the open BIM approach (e.g. through the use of IFC), it was necessary to identify specific information to be considered. This was identified from the analysis of the documentation required by the examined procedures in Italy (e.g. checklists, forms, etc.). From this study, a complete dataset was developed, which satisfies the information requirements of all the Italian BABs, concerning several aspects including project description; foundation soil; design actions; design criteria and structural modeling; material properties; structural analysis methods and results; structural safety assessments of structures and foundations; and construction details [1]. To this end, generally, the IFC format covers information relating to this context through concepts defined in two data schemas within the domain layer, namely: IfcStructuralAnalysisDomain and IfcStructuralElementsDomain, respectively referring to the representation of concepts describing "planar and/or spatial structural analysis models which can be used by structural analysis applications" (source: https://technical.buildingsmart.org/standards/ifc/ifc-schema-specifications/) and the description of different types of building structural elements from foundations to other structural sub-parts. In addition, further data schemas (e.g. IfcSharedBldgElements) allow the description of real building objects such as beams, columns, walls, and other things (e.g. via the classes IfcBeam, IfcColumn, IfcWall, etc.). Unfortunately, the structure of the IFC format lacks “spaces” dedicated to a clear description of the information about structural outcomes and results. From the analysis that was conducted, it emerged that the IFC format is most appropriate for the characterization of concepts aimed at the export of an analytical-mechanical model from BIM-authoring software to FEM software [1]. This activity is supported by the mechanism of existing MVDs, such as the Structural Analysis View, with reference to the IFC 2×3 version. However, to record the results of structural assessments, IFC is not capable of conveying this type of data as well. To fill this gap, the IFC format should have specific attributes and properties for existing classes or means for new ones to be added. This would correspond to the creation of a "space" within the format for the integration of this information. So, there is a need to define an IFC-based information flow, and ensure it is enabled in structural calculation software, which also integrates BIM-authoring environments, to export the contents of structural outcomes. IFC models, exported in this manner, could be a standardized means for supporting the verification and checking processes of information required by BABs for seismic permit applications. However, semantic extension strategies for the IFC standard can be different, both static (e.g. adding new classes) and dynamic (e.g. adding properties) [131]. In the context of the Str.E.Pe. project it was decided to adopt the second approach, establishing the common content to be associated with the added and exchanged information (e.g. properties). Within the Str.E.Pe. project, one of the pursued objectives was the development of an MVD, which would then be implemented in software, which would allow the production of specific IFC models to be delivered to the BABs, with other linked documentation. Specifically, it allowed the relevant classes to be filtered and the new properties to be associated with them, to integrate specific information currently contained only in traditional documentation (reports, drawings, structural specifications, checklists, etc.). This approach, through the development of a specific MVD, will enable standardization of the information flow by allowing all software houses to implement this new MVD for producing specific IFC models for structural e-permitting applications.

Step 3. This is focused on the structural e-permit workflow. The work proposed in the context of the Str.E.Pe. project consists of the definition of new processes to be implemented in a dedicated digital platform (i.e. usBIM.epermit platform) and based on specific BIM models (in IFC format). Several exchange requirements are involved, such as permit requests, ICDD, and seismic permits. In regard to new processes implementation, the structural engineer is logged on to the dedicated platform and submits an application or form available online (first exchange requirement). Then, the IFC models and documents are delivered to the BAB via Information Container Data Drop (ICDD, second exchange requirement), defined by ISO 21597-1:2020. This is generated by the structural engineer, appointed by the client for the design of the construction, and sent to the BAB. Thus, the ICDD is conceived in the proposed process as the container of all technical information to be submitted to the BAB for design validation and the issue of the official approval document, i.e., seismic permit (third exchange requirement). In addition, the digital platform can be equipped with preliminary automated code-checking mechanisms based on the IFC model. If these activities are concluded positively then the request can progress, otherwise, changes or integrations will be requested for the structural engineer who will resubmit the related ICDD. If the preliminary countercheck is positive, the BAB engineer will carry out his checks with the support also of the functionalities offered by the digital platform that operates on the ICDD and the related IFC model. If they are positive, the authorization permit will be issued on the platform. The ICDD solution has been chosen because it is a standardized solution (ISO 21597-1:2020) for defining an information container that can be shared among several parties (e.g. BAB technician and design engineer), allowing the relative linking of IFC models, data, and related documents. The scenario in which these processes take place, as described in the process map proposed in Figure 2.9, is the collaborative platform developed for the digitization of seismic-authorization permit applications, i.e. usBIM.epermit platform. The platform allowed the BAB officials to check the compliance of the structural project with the predefined requirements. On this platform, if the automated code-check process is successful, the uploaded documentation is counterchecked using its links to the IFC model, and further checks are made on the information and data contained in the structural reports and calculations. Finally, with the issue of the seismic permit (without the need for integrations or changes) by the BAB officials and its upload onto the usBIM.ePermit platform, the process was completed.

2.2 Adoption of BIM methodologies in e-permitting procedures

As a result, the scientific community is increasingly focusing on the topic of digitizing e-permitting procedures by using BIM methods and tools. Recently, the adoption of BIM and open BIM to support e-permitting procedures for both building and construction permits has attracted considerable attention from the international scientific community. Specifically, some studies [105,126,132–134] have focused on identifying the potential that the BIM approach offers generally in reconceiving e-permitting procedures. Other authors [1,128,133,135,136] have focused principally on the potential offered by openBIM. In general, e-permitting procedures can be applied to both building permits (i.e., design permits) and construction permits (once the design phase has ended). Indeed, a recent study argues that the use of open model-based processes and automated code-checking tools could simplify and accelerate permit application practices considerably [128]. Using BIM models for e-permitting procedures essentially means transferring information about the geometry of the asset to the officers; studies [127,136] focus on the possibility of integrating GIS systems into BIM-based e-permitting procedures.

To date, research has identified two main obstacles to the implementation of the most advanced e-permitting scenarios in professional practice. The first relates to ensuring quantifiable and standardized data in BIM models, while the second considers the requirements for translating structural codes into shared machine-readable rules. To overcome the first obstacle, the availability of appropriate information in BIM models can be achieved through (i) defining clear rules for structuring BIM models in proprietary formats, as Singapore did with the .rvt format; (ii) using open formats, such as the IFC format. BuildingSMART International's Regulatory Room report [128] provides a recent snapshot of the trend in using IFC models for e-permitting. To overcome the second obstacle, it would be better, henceforth, to work and subsequently adopt regulations that can be effectively translated into machine language [60].

2.2.1 *A brief overview of the development of IDMs and MVDs from the structural engineering perspective*

The IDM/MVD approach is suggested for the development of open BIM solutions as proposed in this work. In detail, the aim of an IDM (Information Delivery Manual) is to organize activities in a structured manner and describe the data exchanged within a specific BIM process [137]. The IDM provides a framework for defining the considered exchange requirements, describing the information flows, and exchanging data between different types of applications for certain purposes. Information, organized and managed in this way, is useful to both users and software vendors for the development and subsequent implementation of an IT specification that “translates” it into an appropriate data schema. The considered data schema for information exchange is the IFC (Industry Foundation Classes). Therefore, what is defined in the IDM is necessary for the development of an IT specification, i.e., the MVD (Model View Definition), which can be implemented and supported by different types of software applications [137]. This mechanism allows IFC models to be exported following specific processes and exchanged information defined in the IDM and properly constructed to satisfy predefined exchange requirements.

Specifically, the IFC is an international standard developed by buildingSMART which can represent building elements as BIM objects with associated relationships and properties. To date, one of the most widespread IFC versions is IFC2×3, which was released in early 2006 and subsequently became an international standard. In 2013, bSI released the IFC4 version and subsequently updated it with the IFC4 ADD2 TC1 version, officially published as an international standard ISO [138]. Regarding mainly the IFC2×3 version, one of the most popular MVDs implemented in BIM-authoring applications and other software is “Coordination View”, which was developed to support the sharing of building models among different disciplines (architecture, structural engineering, MEP implants, etc.). Applications of the IDM/MVD approach may concern architectural design [139] or structural design, specifically for the assessment of interoperability in the structural domain [58]. In the same context, some authors [140] identify the IDM/MVD approach as an integrated process for the management of processes and data related to the design of wooden structures. In the case of modular buildings, the authors [141] consider different MVDs to facilitate the use of a BIM model for different design disciplines (architecture, structural engineering, manufacturing, logistics, etc.). Instead, the research carried out by the authors [18] analyzes challenges and opportunities in

the application of BIM standards to off-site constructions. The authors [142] suggest the development of IDMs and MVDs to support the planning, design, construction, and fabrication phases of PSC constructions. As regards the automatic control of information within BIM models to support structural analysis, the authors [143] propose a new method using Python and structural analysis software. Meanwhile, in the context of the collaborative and interdisciplinary design phase, and regarding data exchange for structural engineering, the authors [144] develop a specific method for the delivery of structural information. In Italy, the Structural E-Permit (Str.E.Pe.) project is the first attempt to investigate the creation and use of integrated IFC models to modernize traditional processes for applications to building authorities for seismic structural engineering approvals and permits [1]. In addition, MVD can also support checks and validation of the exchanged data. To ensure the integrity of the data and maintain a reliable data exchange environment, the authors of one study investigated the different types of rules for checking and validating data via MVD [145–148].
In conclusion, the application of the IDM/MVD approach in the field of seismic structural engineering mainly concerns the exchange of information between BIM-authoring software and tools for structural analyses and verifications. Unfortunately, there is a lack of proposals concerning the integration of information related to structural design outputs, such as the results of structural verifications and other structural information.

2.2.2 Problem statement and research scope

Therefore, considering the procedures for permit applications about structural engineering, a need emerges to integrate structural information (derived from structural design outputs and other context-related information) into new digital means (e.g., BIM models) as well as to design new digital methods to support the activities of building authorities. Generally, the BIM database provides input data for the structural design, but most of the data produced by structural designers, according to the structural codes, do not fully integrate into the BIM database along with other context-related information, especially in open BIM standard file formats such as IFC. To date, no business software solutions (i.e. structural software), which organize the data in a synthetic and optimized manner for structural e-permit processes, are available. existing software does not allow the export of tailor-made IFC models for structural e-permitting processes. One of the reasons can be found in the lack of a specific MVD that enables the production of IFC models, as a means of summarising structural data, e.g. required by the structural e-permitting context (e.g. PSets, IFC classes, etc.), and obtained downstream of structural design activities.

In the context highlighted above, it has been proposed an open BIM approach for the integration of structural information to support the activities of building authorities. Accordingly, a specific framework was developed, which led to the development of an IDM and related MVD, using the IFC schema, for the integration and exchange of the selected information within a BIM-based environment. The adopted IDM/MVD approach enabled the production of a context-related IFC model, which represents a part of the delivered ICDD solution related to seismic permitting [1], allowing the design solutions to be transferred and validated more easily (e.g. via checks and validation carried out via the e-permit platform by the BAB technicians). In addition, the considered approach was also essential to provide specific instructions and data in order to perform automatic or semi-automatic code-checking along with the opportunity to reduce the deliverables required for seismic-authorisation applications via IFC format. Accordingly, the proposed MVD was implemented in a specific software structural application (i.e. Edilus) and all the structural e-permitting procedure was tested on a selected case study (renovation project of an existing School) within a specific collaborative platform (usBIM.epermit platform). As a result, this provided an effective solution for the innovative delivery of necessary information to building authorities to secure the issue of seismic-authorization permits through these new digital processes. Accordingly, the full integration of the selected structural information into the IFC database enables an open and transparent workflow for the design and management of structural systems as well as the development of improved approval processes. This digital solution allows for achieving knowledge of the building heritage (e.g. newly built structures starting from the permit issue). Due to this new approach, it is possible to reduce the time required to issue permits compared with the traditional procedure in force in Italy so far. In conclusion, from a methodological point of view, this approach could be taken into account for any construction project (building, bridge, tunnel, etc.). However, the structures considered for this proposal refer to new R.C. buildings. New developments will certainly consist of the extension of this approach to other building construction typologies (e.g. steel, masonry, etc.) by means of new additions related to the authors' proposal.

2.3 Development of IDM/MVD for integrating structural information into a BIM environment

Thus, a new digital approach is necessary to improve and expedite seismic permitting processes. With regard to the scenario under investigation, an IDM/MVD approach has been considered for the integration of specific information within an IFC model.

Before developing the specific solution (i.e., MVD) to be implemented in the structural software considered (i.e., Edilus) that integrates a BIM environment, context-related information was established and a specific integration strategy was adopted. Accordingly the considered process (seismic authorization permitting), there is a lack of usable "structural MVDs" to convey outputs and other kinds of information using the IFC file format. This content consists of the development of an MVD that, through its implementation in structural software, can enable the export of specific IFC models following the purposes of the structural e-permitting process. In this way, the gap that was highlighted previously can be filled. Thus, the produced IFC models can meet the information requirements defined by the process in question, in addition to recording and conveying all structural information obtained downstream of the design activities and other activities related to the general context. The IFC-based approach as proposed in this study, which was successively implemented in a real case, provides a new way that enables checking and validating the required information, thereby allowing users to save time and increase productivity concerning BAB technicians' activities. The integrated IFC models produced by means of this MVD, implemented in the structural software, will be part of the delivery represented by the ICDD container, which is produced by the structural engineer in charge of the design activities of a new building. All this represents a new digital method, based on the openBIM approach, for managing and conceiving the whole structural e-permitting process [1]. Following these goals, this proposal was organized as shown in the next *Figure* 2.2; successively it will explain in detail the development phases of the proposal.

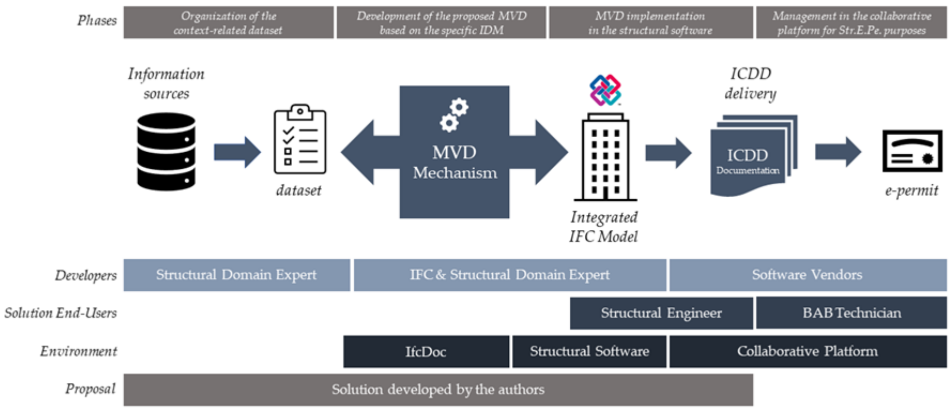


Figure 2.2 - Adoption of IDM/MVD approach for integrating structural information in the context of seismic structural e-permitting.

This study analyses and proposes the use of the IFC standard to convey and transfer information for the release of seismic-authorization permits. However, only a well-designed summary of project information should be transferred through IFC, along with the related documents that must be delivered for further investigation of a specific issue. Moreover, this approach does not eliminate technical drawings and plans, which will always be a fundamental reference for a detailed understanding of the design choices. At the same time, this approach aims to speed up the delivery of information to BABs, and their related verification, where the IFC format can be considered as a valid solution to optimize the seismic-authorisation process and synthesize large quantities of information, which are not only related to the structural context. For instance, 2D drawings could be replaced entirely by IFC models that achieve a sufficient level of development of BIM objects. Meanwhile, BAB civil engineers could use simple IFC viewers to explore the models in detail. Project documentation, such as reports and printouts, would then be consulted, if necessary, starting from synthetic information integrated into the IFC models. However, for the appropriate definition of the dataset related to the seismic-authorisation process, it is necessary to consider certain issues associated with the complexity and heterogeneity of the information that may be required by BABs. Accordingly, the requirement would be to develop an unambiguous and wide-ranging solution for information exchange. However, this is particularly difficult because the information is strictly related to three aspects: (i) the structural code of reference; (ii) the choice of structural and construction type; and (iii) the condition of the building, i.e., whether it is new construction or existing building.

In detail, about the first aspect, it should be noted that structural calculation must necessarily refer to specific structural codes which regulate, for instance, the methods and strategies of structural analysis or verification of a structure and its elements. Although there are international codes (e.g. Eurocodes), structural design activity must be compliant with relevant national codes and annexes, which are typical of each country where engineers work and design a given structure. These are characterized by numerous theoretical and practical approaches, and various ones can be considered. These are characterized by prescriptive or performance rules and specifications. The former specifies a series of requirements that must be observed step by step, both in the structural analysis and verification phases; the latter only constrains the verification result, i.e., the performance required of the structure or its components. Accordingly, the information produced in the structural verification phase changes. Therefore, the information content to be conveyed through the IFC standard is strictly linked to the nature and type of structural codes that can be considered.

The second factor may influence the information that must be considered for the integration of IFC models, which consists of the structural materials and construction technologies adopted to build the structure. It is well known that the latter refers, for example, to prefabricated, cast-in-place, or hybrid systems. At the same time, the materials with which the structural systems are built can also be different (concrete, wood, masonry, steel, mixed solutions, and so on). This involves the use of different structural verification procedures and methods depending on the material and type considered. This is addressed in an organized and systematic manner within the structural codes, with dedicated sections or chapters, also in the case of "Norme Tecniche per le Costruzioni" in force in Italy (NTC). Indeed, they deal with the different verifications to be developed, with various approaches depending on the specific case to be considered (e.g. masonry, reinforced concrete, wood, steel, and so on). Furthermore, for each scenario, regarding the construction material (e.g. R.C. buildings), it is possible to have different structural configurations (e.g. frame, wall, or mixed structures, etc.) depending on the presence of specific structural elements (e.g. column or wall elements) with specific geometric and mechanical characteristics. Therefore, in this scenario too, the result is that different sets of information are considered each time.

To conclude, the third aspect is a building's condition, which refers to the difference that exists between new and existing buildings. The former is concerned with structural design work to identify both geometric and mechanical characteristics able to withstand design actions. The latter can be characterized by assessment operations (e.g. verification of the safety conditions of the building) or structural retrofits when it is necessary to restore safety levels with interventions aimed at increasing performance in terms of strength and/or ductility. Depending on the condition, some checks and verifications may be performed according to different structural methods. In the case of a new building, the most commonly used analysis methods are linear (static or dynamic); in the case of an existing building, non-linear (static or dynamic) methods are mostly applied, since the structural capacity of the building has to be assessed. The dataset of information is therefore quite specific depending on the case in question, i.e., whether the structure is new or existing.

Accordingly, this study refers to a specific context to formalize and subsequently implement (as shown in the following) an operational solution concerning the export of IFC models integrated with the information required by the process under analysis. In particular, it has been decided to consider new design buildings in reinforced concrete, according to the structural normative context in force in Italy. The methodological approach used for the proposal is such that afterward it could be used to cover other types of buildings (steel, wood, masonry, etc.) as well. Ultimately, the final aim is to support a new digital approach in information exchange for the seismic-authorisation process, thus improving the existing (mostly paper-based) approach mainly considered so far.

2.3.1 Organization of the context-related dataset

Before considering the possible strategies to integrate the selected information in the IFC format, it is important to specify the context-related dataset to be integrated into the BIM environment. This requires a specific organization of all the information related to the contest under investigation, as proposed in Figure 2.3, specifically under the considered use case, namely the issue of a seismic-authorisation permit by the BABs [1].

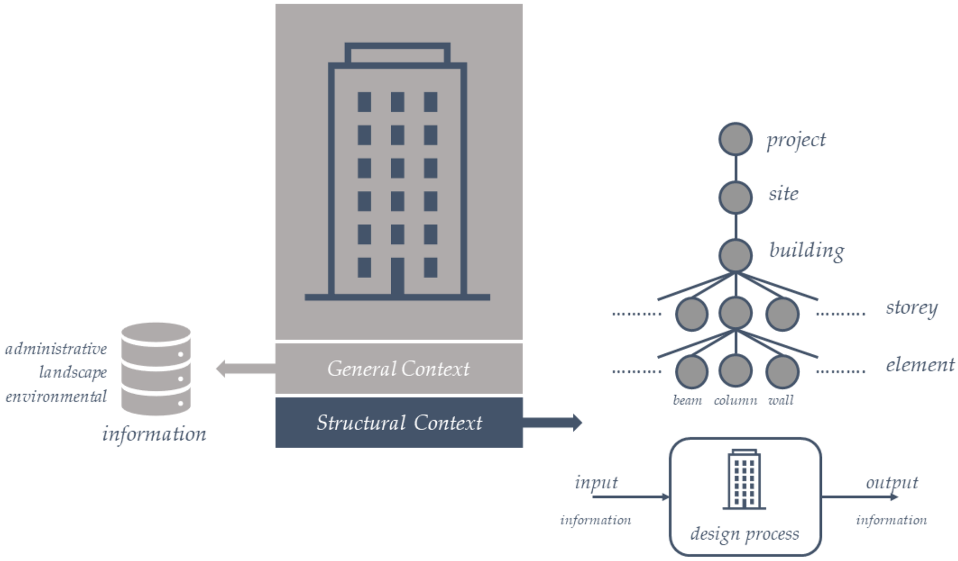


Figure 2.3 - Setting of context-related information to support integration into the BIM environment.

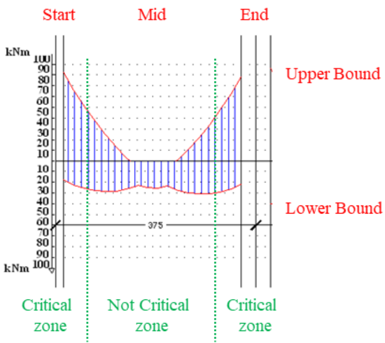
More specifically, the information can refer to two types of context: (i) the "structural context", in which the information is related to structural design; (ii) and the "general context", in which the information relates to an administrative, landscape and environmental setting. Specifically, the information related to the "structural context" is considered at the "level" of project, site, global structure; story; and structural element (i.e. beam, column, wall, foundation, etc.). Moreover, regarding each of the aforementioned levels, the information can refer to two categories: "input information", which is necessary for structural analyses and the characterization of the structure or its elements (e.g. information concerning the structural typology of the building under consideration, the type of structural element, the materials used, and more); and "output information", which is obtained after the structural analyses and the structural verifications (e.g. through Safety Factors). For example, considering structural context, at the global structure level the output information can deal with the inter-story displacements, P-Δ effects, in-plane and in-elevation regularity of the structure, and so on. On the other hand, remaining in the same context, at the structural element level, output information may be the safety factors (SFs) obtained as the ratio between capacity and demand related to the specific structural checks under consideration. In detail, SFs are the output information of structural verifications (e.g. regarding normal stress, bending, shear, etc.), and are considered for each load combination, since each combination determines a different stress demand (for different calculation sections, upper or lower section bounds, etc.). The SFs must be greater than or equal to one to comply with the code requirements, proving that the engineer has correctly designed the structural safety of the building. In addition, concerning specific cases, they also take into account conditions expressed by the capacity design strategy (e.g. demand-capacity criteria, ductility requirements, etc.) and by specific limit states (e.g. conditions on global deformability of structure and local deformability of element). For this reason, among the items of information related to the structural context at the structural element level, it has been decided for this proposal to convey SFs as output summary information. During the design activities, SFs are calculated by structural calculation software and are reported, as an output of the structural verification phase, in information containers such as tables, tabulations, and reports. However, it would be impossible to report in the IFC model all the SFs reported in these documents, and it has been therefore decided to use as synthesis parameter, for each structural verification type, both at the structural element and global structure level, the minimum SF related to all the considered combinations in the design process. If the minimum SF for a certain structural verification is greater than one, automatically all the others will also be greater than one. Therefore, this approach considers this kind of parameter (i.e., SF) because it summarizes and condenses information about the capacity and demand regarding a certain load combination. This can be used both regarding the global structure and the structural elements of which the building under consideration is composed. A detailed and in-depth investigation regarding the specific SF, with its information, can always be carried out starting from the available documentation (e.g. printouts, tables, reports, and other forms of output developed by structural engineers).

This type of approach, therefore, allows us: (i) to record a summary and easily checkable information; and (ii) to investigate, if necessary, the design choices made by the engineer in the detailed design document. In addition, the information conveyed through BIM models, which use open formats (e.g. IFC), can enable the use of quick checks, from the point of view of structural engineering, allowing the validation of the information content through sets of rules or conditions that could be easily implemented in validation software or other environments. Accordingly, the Str.E.Pe. project also proposed a preliminary countercheck considering the information related to seismic authorization within the IFC models that had been produced. In this way, by implementing possible conditionalities arising from the structural context (e.g. NTC), and considering the authorization process for these models, along with related information, the timing involved in the whole process is optimized, both in the delivery of the information, which is carried out by the design engineer and in its verification, which is done by the BAB engineer. The availability of a three-dimensional and parametric model facilitates understanding of the real complexity of the structure, and at the same time is a unique reference for the association of a series of items of information or documents to the objects and global structure (represented by BIM models and their objects), and therefore for the eventual in-depth investigation of specific situations. The setting of specific conditions ensures that the considered information is correctly recorded in the IFC models. This information, together with other information contained in the ICDD delivery, will then be validated by the BAB technicians for the release of seismic authorization. Indeed, the availability of this kind of information (for instance regarding minimum SF as a numerical value and related to each load combination to be considered about a specific limit state), allows technicians to verify in an expeditious way certain structural conditions (e.g. all SFs greater than the minimum SF and one as well), without the burden of checking them all on paper documents and number by number.

2.3.1.1 *Identification of required structural information for the seismic-authorization process*

The first step was to identify the most appropriate information to be conveyed through IFC models according to the information needs required by the (seismic) authorization process. Hence, it was decided to refer to the dataset previously developed within the Str.E.Pe. project. [1]. However, the chosen dataset refers to a specific use case, namely the seismic-authorization request mainly for new reinforced concrete structures to be built. With respect to this, much of the information that forms the dataset (i.e., the SFs) is not currently covered by the IFC standard. To integrate the information related to the dataset into the IFC model, the MVD mechanism has been chosen, considering it as an opportunity to standardize the information flow.

In particular, in addition to the choice of the IFC classes involved in the integration (e.g. IfcBeam, IfcBuilding, etc.), it was also necessary to define specific Property Sets for the association of the information content related to the dataset with the IFC classes involved in the integration. Hence, it was necessary to analyze in detail all the information in the referred dataset, which originates from several sources (i.e., simulations, structural models, printouts, reports, etc.) and refers to the structure at a global, story, and element level. It is possible to consider, for example, the case of structural beams belonging to the building structure. In the case of structural verifications, as already mentioned before, the SF synthesis parameter is used. In order to convey this information, however, it is necessary to take into account how the verifications are carried out for the element. In the example reported below (see Figure 2.4), a generic beam, belonging to a certain building frame, is shown. For this, bending moment checks were carried out, considering its longitudinal direction (for the start, mid, and end sections) and section bounds (upper or lower bounds, for each section in question). For instance, concerning shear verifications, the element was divided into three ideal zones corresponding to critical and not critical zones. In general, for all the verifications (bending, shear, torsion, and others), the lowest values of the related SF were considered among all the load combinations taken into account during the design phase. Figure 2.4 shows an example in the specific case of a structural beam. This strategy was applied for each category of structural element considered in the proposal (beam, column, wall, foundation, and others) concerning its characteristics for the structural verification phases. Each element will be characterized by the corresponding IFC class that represents it within the IFC format. For each of the categories related to the structural elements, in addition to certain aspects (e.g. geometry, material, etc.), specific PSets were developed to convey summary information about the structural outputs, obtained downstream of the structural design activities (SF and others), and specific information required by the authorization process. For example, specific PSets were developed considering a single structural element (e.g. beam) for the structural verifications for the bending moment, shear, torsion, and other aspects (e.g. ULSStructuralVerificationRCBeam), at the considered limit state (e.g. Ultimate Limit State), or concerning other items of information related to the restrictions required for a given structural element (e.g. StructuralReinforcementRestrictions).



Entity→ IfcBeam

PSet for Objects

PSet Name	Properties		
	Template	PropertyName	Value
ULSStructuralVerificationRCBeam	SingleValue	TypeOfBeam	IfcLabel
	SingleValue	BendingSFStartSectionUpperBound	IfcReal
	SingleValue	BendingSFStartSectionLowerBound	IfcReal
	SingleValue	BendingSFMidSectionUpperBound	IfcReal
	SingleValue	BendingSFMidSectionLowerBound	IfcReal
	SingleValue	BendingSFEndSectionUpperBound	IfcReal
	SingleValue	BendingSFEndSectionLowerBound	IfcReal
	SingleValue	ShearSFStartSectionCriticalZone	IfcReal
	SingleValue	ShearSFSectionNotCriticalZone	IfcReal
	SingleValue	ShearSFEndSectionCriticalZone	IfcReal
	SingleValue	CapacityDesignMS	IfcBoolean
	SingleValue	DuctilitySFStartSectionUpperBound	IfcReal
	SingleValue	DuctilitySFStartSectionLowerBound	IfcReal
	SingleValue	DuctilitySFEndSectionUpperBound	IfcReal
	SingleValue	DuctilitySFEndSectionLowerBound	IfcReal
	SingleValue	TorsionSFStartSection	IfcReal
	SingleValue	TorsionSFMidSection	IfcReal
	SingleValue	TorsionSFEndSection	IfcReal

Figure 2.4 - Example of a structural beam and proposed properties set to support the data exchange.

With regard to the global structure, other PSets were defined for the information deriving from the general context (e.g. GeneralBuildingInformation) and about the outputs related to the global structural verifications (e.g. StructuralBuildingInformation). As regards site information, for instance, regarding the IfcSite class, the PSets SoilCondition and EnvironmentalAction were proposed. This was also done for IfcProject, and all other classes covered by the proposal. An example of the above is shown in Figure 2.5. For each IFC class considered by the proposal, the information was appropriately selected and organized in tabular form. Starting from this organization, it was possible to associate certain PSets, characterized by a specific name, type, and other specification (e.g. value and description), to the IFC entities considered for the integration and development of the MVD. These classes, with related information, will then be made available in an integrated IFC model, suitable for the seismic authorization process, through the MVD mechanism proposed and integrated into the structural software. This will enable the information exchange necessary for the BABs to validate the information for the authorization process.

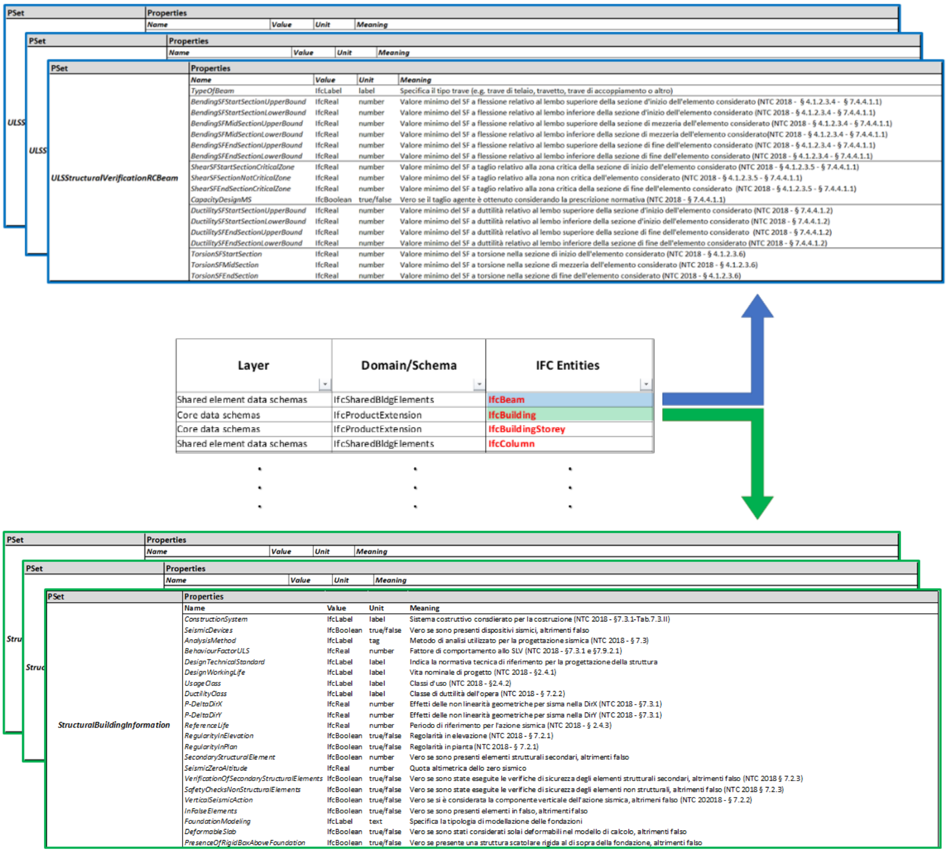


Figure 2.5 - Examples of proposed Property Sets for IfcBuilding (in blue) and IfcBeam (in green).

2.3.2 *Definition of an integration strategy in the BIM environment by means of the use of openBIM standards*

To support the information flow identified by the Str.E.Pe. project [1], it has been considered that the best-performing approach consisted of the definition of an IDM and related MVD. Starting from the definition of the process and related requirements (ERs and others), a mechanism is proposed that can successively be implemented in all structural tools that integrate BIM-authoring environments, to allow the export of a specific IFC model with classes characterized by specific PSets useful for the purposes considered. In this structural scenario, as mentioned previously, in the bSI context there are MVDs (e.g. Structural Analysis View) aimed at exporting IFC models with specific information (e.g. geometry, material, constraints, and others) useful for importing into structural software for structural analysis activities. As also highlighted before, the process of exporting information, obtained downstream of the structural calculation, has not been discussed in detail so far. As regards information exchanges in the field of structural engineering, since the IFC2x3 version with related MVDs (e.g. Coordination View, Structural Analysis View, etc.) is so far one of the most popular and widely implemented versions in the software, and includes both BIM authoring and structural calculation tools, this proposal, based on the aforementioned IDM/MVD approach, considers the IFC2x3 schema. Unfortunately, the MVDs currently certified by buildingSMART and implemented in BIM-authoring software is not able to cover information related to structural calculation outputs (https://www.buildingsmart.org/compliance/software-certification/certified-software/). Furthermore, as previously defined [1], in addition to what was stated previously, it has been shown that most of the information related to the integration context is not conveyed by the IFC standard. Therefore, the proposal deals with using and applying the IFC format in these types of processes (the issuing of seismic-authorization permits) as well. In addition, it deals with the development of a new MVD related to the process purposes under analysis (in the context of the Str.E.Pe. project) and takes as its starting point a pre-existing and consolidated MVD, namely the Coordination View (https://technical.buildingsmart.org/standards/ifc/mvd/mvd-database/), which is widely used, and also considers this concerning BIM methodologies applied to the workflows which involve structural discipline. This mechanism is very well implemented, workable, and tested with BIM-authoring software and BIM tools currently in use. Accordingly, the development of the proposed MVD started from this existing mechanism rather than creating a completely new one, optimizing time and resources. This development was also designed and successively implemented, as will be dealt with after, to show the feasibility of an operational solution in support of process needs (related to the Str.E.Pe. project). The application of this open BIM approach (IDM/MVD), using IFC format, allowed a BIM integration of specific structural information in support of BAB activities. To do that, a specific software ecosystem was considered. Firstly, regarding the technical development of MVDs, buildingSMART provided a free tool called IfcDoc (https://www.buildingsmart.org/standards/groups/ifcdoc/), which was used in this case. This tool enables the definition of the exchange requirements and the development of related MVDs. Using this tool, it is also possible to develop new proposals starting from MVDs that are already available, as happened in the case of this project. The Coordination View, in this case, was considered a starting point for the work carried out. In the context of structural analysis, the authors of another paper [56] also consider this view for developing a specific mechanism for the conversion of the IFC information models obtained from the "Coordination View" into their equivalent IFC structural models, obtained from the "Structural Analysis View". Therefore, the wide sharing in the usage and implementation of this model view in the software considered by the structural context, i.e., both BIM-authoring and structural software, justify the choice of this starting point for the development of the proposed MVD. The adoption of an approach based on IDM/MVD will allow structural calculation software, which integrates BIM-authoring environments, to produce IFC models that are properly built and targeted for the seismic-authorization process. Indeed, in the Str.E.Pe. process (see Figure 2.9), the exchange of information takes place utilizing a structural BIM model (in IFC), with the related documentation (2D drawings, reports with technical specifications, and a summary form) delivered in a single data container known as "Information Container Data Drop" (ICDD), where the links between the model and documents are also registered and stored. Therefore, considering only the structural IFC concepts related to the construction of the building (classes, relationships, and properties), only the entities concerned by the proposal are filtered, both from the physical and spatial point of view, and thus not considering some domains that are not related to the structural context (e.g. HVAC, Electrical, Construction Mgmt, etc.). Figure 2.6 shows the data schema concerned by the proposal regarding the IFC2x3 TC1 version.

After a detailed analysis of all these sources and a definition of the necessary information in relation to the authorization process, these were organized following the logic and structure of the IFC format. Specifically, a series of information items referring to the project, site, building, story, element, and so on were collected. This information was subsequently organized into properties (i.e. PropertySet and Property concept) and associated with the reference classes of the standard (respectively IfcProject, IfcSite, IfcBuilding, IfcBuildingStorey, IfcElement, and related subtypes).

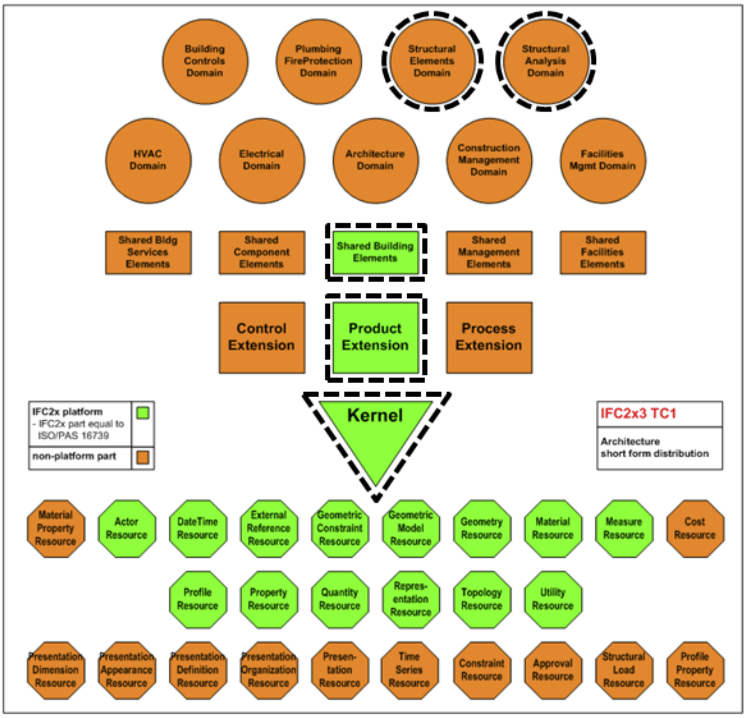


Figure 2.6 - Main data schemas involved in the proposed MVD.

The adopted mechanism was the MVD, considered a subset of the IFC schema, which needs to be implemented in software. This allows to filter of only the information of interest in terms of classes, principally, and whatever is associated considering related attributes, relationships, and properties. Consequently, user-defined Property Sets were defined. Specifically, for the related properties, both the specific type and admissible values were established to set context-related rules and subsequently to record proper information within IFC models. The dynamic approach offered by the development of specific properties (through Property Sets and Property concepts) can be considered an alternative to integration using the definition of additional IFC classes and their attributes (i.e., a static approach) [131]. An IFC model integrated in this way, through such properties and obtained by an MVD that filters only the entities of interest, would enable not only an easier validation of the information content that is digitally available but also permit improved accessibility and speedier workability of information for BAB engineers. An example of this aspect could involve the results of structural checks, historically resident in other information containers (as calculation reports, summary sheets, etc.). The proposed process, shown in Figure 2.7, will allow, through the implementation of the new Structural MVD, the production of BIM models integrated with the information required by the seismic-authorisation process. To do this, the structural software should integrate a BIM-authoring environment to allow, through the implementation of the MVD mechanism, the export of IFC models.

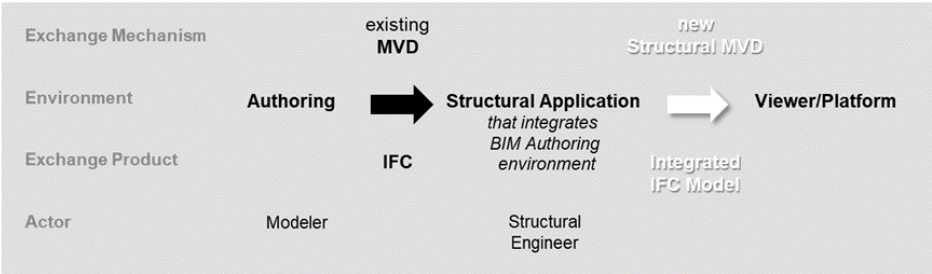


Figure 2.7 - Proposed workflow with the availability of a new MVD [1].

For the implementation of this proposal in a specific case, the software considered for the integration of the proposed MVD was Edilus, structural software certified both for IFC import (regarding the "CV 2.0" Exchange Requirement) and IFC export (regarding the "CV2.0-Struct" Exchange Requirement) and taking into account the IFC 2x3 schema, as reported by buildingSMART (considering the following link https://technical.buildingsmart.org/services/certification/ifc-certification-participants/). In collaboration with Acca Software, technical implementation and subsequent tests were carried out on a selected case study (Montemarano School). All this allowed enabling the export of IFC models from Edilus software, following context-related exchange requirements that arose through the analysis of the seismic-authorization process and the implementation of a specific mechanism (i.e., the proposed MVD) in the software in question. To conclude, other activities were carried out in collaboration with the software provider, such as automatically writing the extracted values from structural outputs (tables, reports, etc.) in certain proposed properties.

2.3.3 *Development of an IDM/MVD solution for information exchange using the IFC-schema*

Starting from the analysis of information requirements, it has been proposed the development of an IDM and its computer formalization through the definition of the MVD and its documentation. By adopting the implementation of this proposed IDM/MVD approach in structural software, the export of IFC models integrated with the structural information necessary for the seismic permitting process is enabled. In particular, the proposal is aligned with the workflow shown in Figure 2.8, where the integrated IFC models become an integral part of the ICDD container, successively delivered to the BABs, as presented in a previous study [1], considering the digital process (see Figure 2.9) developed and proposed within the Structural E-Permit project. Among the objectives of IDM is providing specifications, in a structured and organized manner, to users who decide to use the IFC format for information exchange, and offering support to those responsible for developing a software solution, based on IFC, that implements what has been proposed and organized [46]. The IDM is organized according to an architecture that involves interaction between specialists from the AEC and ICT sectors.

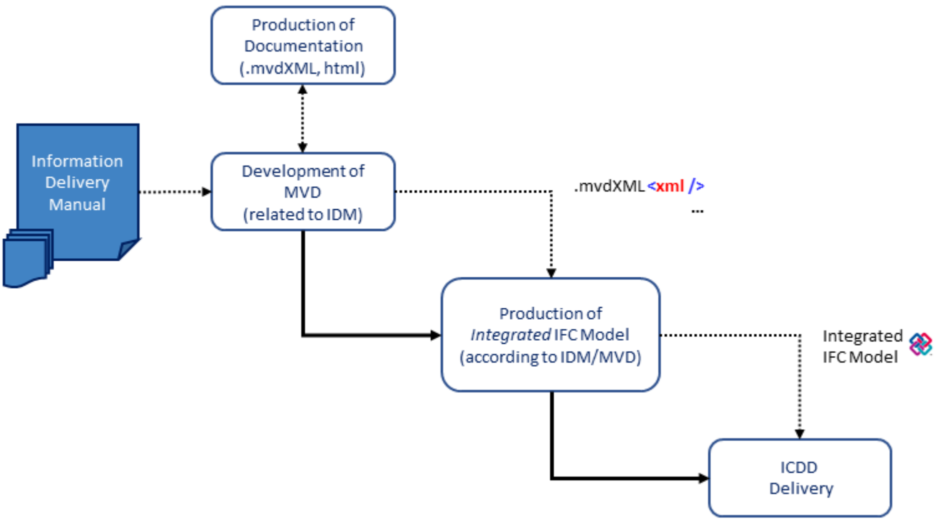


Figure 2.8 - Project workflow to define an IDM/MVD solution.

The organization of an IDM as also defined by the related ISO standards (ISO 29481-1 and ISO 29481-2), in this specific case defined to support the integration scenario in the structural context under analysis, may be composed of the following components: (i) Process Map (PM); (ii) Exchange Requirements (ER);

(iii) Functional Parts (FP); and (iv) Business Rules (BR). Concerning the integration context under analysis, the involved IFC classes should convey the relevant structural information to be stored in the BIM model and its objects. The proposed solution, therefore, fills the gap that has been identified (for the integration of the necessary information), since to date existing software does not support the information exchange in question, or the production of a specific IFC model to convey the information obtained downstream of structural design activities. Therefore, the first step in the development of the proposal is the establishment of the process through which the various professionals will be involved in the information exchange aimed at the release of seismic authorization. In this regard, one of the IDM components is the Process Map (PM), which describes the information flow established among all the actors involved in the process (i.e., in this case, regarding the exchange of structural information for seismic authorization within a BIM project). In addition, the PM identifies the role and activities of each actor and identifies the Exchange Requirements (ERs) required to support the analyzed process. An ER reproduces the information exchanged between actors and processes in a given project phase. Once the ER has been identified, to understand what information needs to be exchanged, the next step is to identify the information belonging to each ER. This will be necessary to define the Functional Parts and the relative Business Rules, considered as the technical in-depth knowledge of the IFC schema. It is known, in addition, that FPs can be used by different ERs and can also be decomposed into other FPs. As regards Business Rules, these are developed to satisfy the specific needs and conditions of a given process or activity. For the development of the above (PMs, ERs, and FPs), the relevant international standards (ISO 29481 series), guidelines or specifications should be considered [46,149] as well as technical documents related to bSI standards (https://technical.buildingsmart.org/).

Figure 2.9 depicts the process map regarding the Str.E.Pe. procedure. This is characterized by two pools and three lanes: the first and third lanes describe the operations carried out by the two professionals involved in the process – respectively, the structural engineer in charge of drawing up the documentation to apply for a seismic-authorization permit, and the technician from the BAB who is involved until the permit is issued.

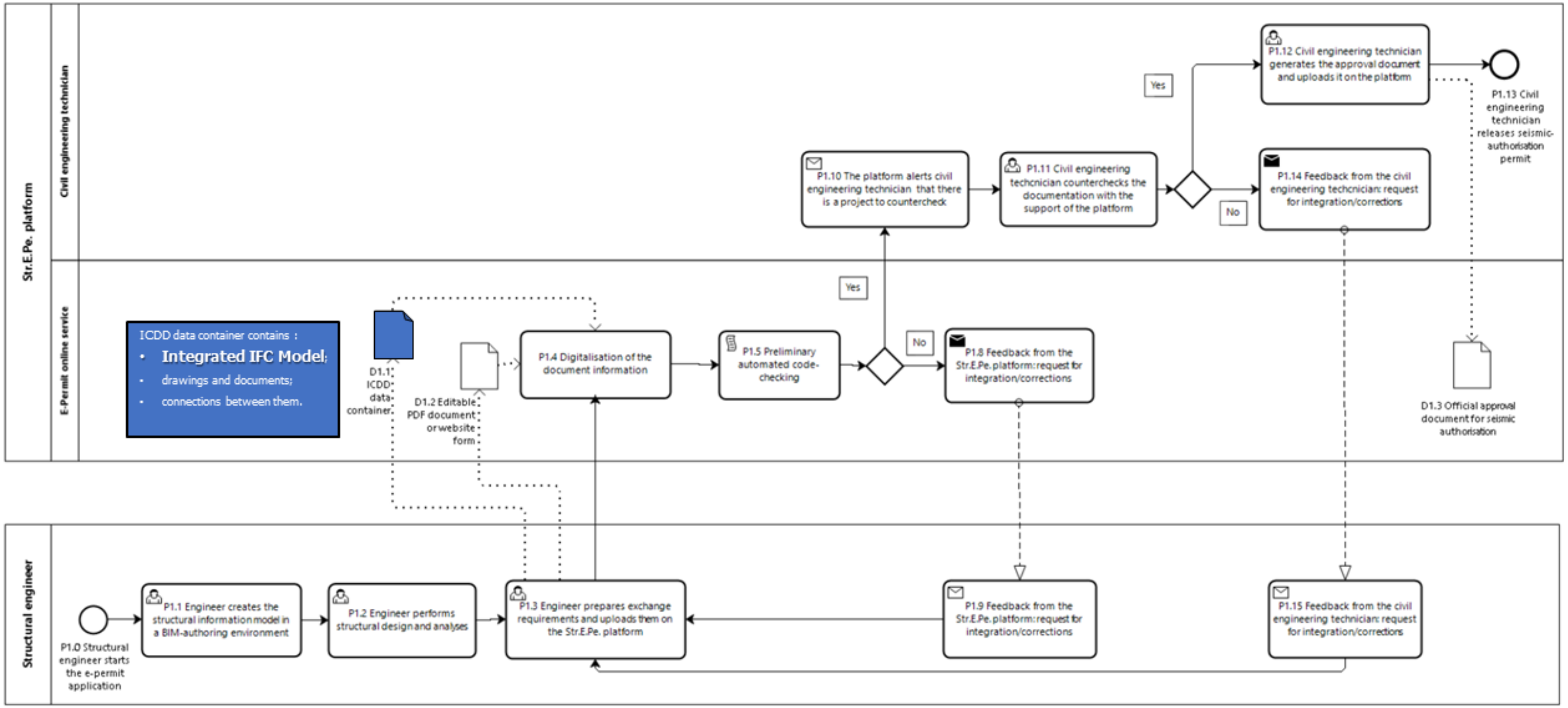


Figure 2.9 - Highlighting the contribution of the proposed solution within the Process Map related to the Str.E.Pe. project [1].

The second lane refers to operations carried out within the Str.E.Pe. platform. Specifically, the exchange requirements envisaged by the considered process are: (1) an application in an editable PDF format or an online form; (2) an ICDD comprising an IFC model, which has been integrated with property sets (PSets) describing the structural project, drawings, and technical specifications, as well as the connections between them; (3) an official approval document (i.e., a seismic-authorisation permit).

As seen in the process map, a structural engineer draws up the documentation required to apply for a seismic-authorisation permit. Then, after the design phase, he/she accesses the Str.E.Pe. platform and delivers a form (first exchange requirement), applying for a permit for his/her project, and an ICDD (second exchange requirement) that includes: a structural information model in the IFC format, 2D drawings, and descriptions of the connections between them. The Str.E.Pe. platform can then initiate a preliminary automated code-checking process which, if it ends positively, enables the application to advance; if the result is negative, the system sends an email containing feedback to the structural engineer, who is asked to review the deliverables and resubmit the ICDD. If the preliminary code-check is positive, a civil engineering technician from the relevant BAB conducts his/her counter-checks. If this counter-check ends positively, the process advances and the technician uploads an official approval document (third exchange requirement) to the platform; if the result is negative, the technician sends an email containing feedback to the structural engineer, who is asked to review the deliverables and resubmit the ICDD. It is worth noting that the ICDD is standardized according to ISO 21597-1:2020, which is a forthcoming specification for a multi-model container approach that allows the models to be interlinked and the data to be connected to external sources.

About the ER, it may contain one or more FPs, which represent a set of technical concepts with their descriptions, associated entities, and related Property Sets (IfcPropertySet). A scheme and organization of the FPs, defined and useful for information exchange, using IFC models, is shown in the figure above (i.e. Figure 2.10). This information is mainly structured according to the IFC schema.

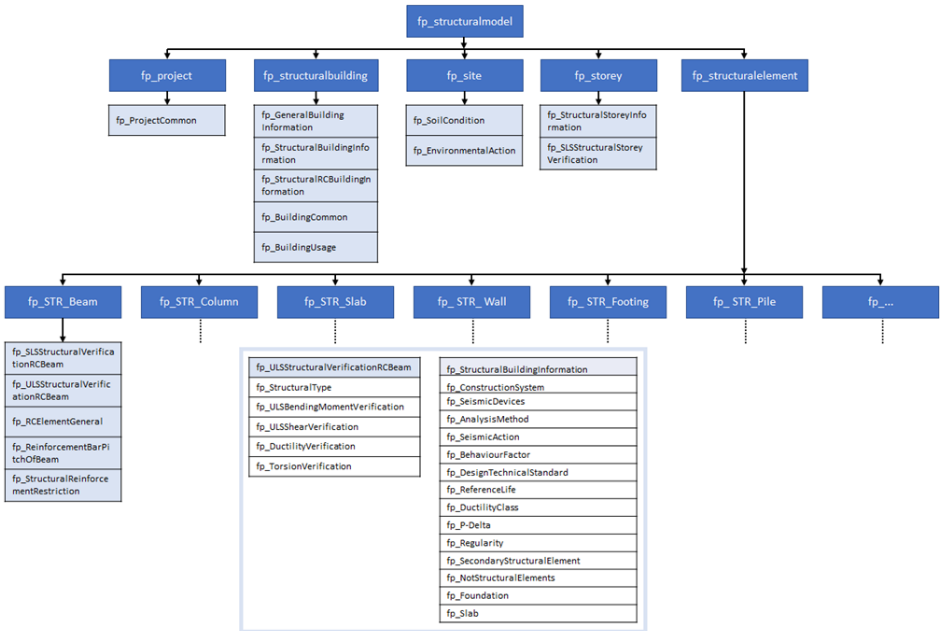


Figure 2.10 - Organization of FPs required for integrating structural information.

With each concept, several items of information are related to corresponding IFC entities, PSets, and related properties, e.g. as shown in Table 2.2. Furthermore, for information exchange, each piece of information may be mandatory (MAN), recommended (REC), optional (OPT), or not specified (NOT)).

Table 2.2 - Example of information exchanged through the organization of specific functional parts considering the IFC schema (e.g. regarding a structural beam for bending moment and shear verifications).

Information Needed	***Pset.Property/Data Type/Entity/Functional Part***	***MAN, REC, OPT, NOT***
Specify information about bending moment checks considering the ULS for structural beam *The property represents the minimum safety factor among selected load combinations, considering the "start" section and "upper" bound of a structural element (beam), related to bending moment checks for the Ultimate*	ULSStructuralVerificationRCBeam.BendingSFStartSectionUpperBound →IfcReal Applicable entity: **IfcBeam** BendingSFStartSectionUpperBound→fp_ULSBendingMoment	MAN

Limit States (ULS).	Verification	
Specify information about bending moment checks considering the ULS for structural beam *The property represents the minimum safety factor among selected load combinations, considering the "mid" section and "upper" bound of a structural element (beam), related to bending moment checks for the Ultimate Limit States (ULS).*	ULSStructuralVerificationRCBeam.BendingSFMidSectionUpperBound →IfcReal Applicable entity: **IfcBeam** BendingSFMidSectionUpperBound→fp_ULSBendingMomentVerification	MAN
Specify information about bending moment checks considering the ULS for structural beam *The property represents the minimum safety factor among selected load combinations, considering the "end" section and "upper" bound of a structural element (beam), related to bending moment checks for the Ultimate Limit States (ULS).*	ULSStructuralVerificationRCBeam.BendingSFEndSectionUpperBound → IfcReal Applicable entity: **IfcBeam** BendingSFEndSectionUpperBound→fp_ULSBendingMomentVerification	MAN
Specify information about shear checks, for elements with shear reinforcement, considering the ULS for structural beam *The property represents the minimum safety factor, considering the "critical" zone at the "start" of a structural element (beam), with shear reinforcement, related to shear checks for the Ultimate Limit States (ULS).*	ULSStructuralVerificationRCBeam.ShearSFStartSectionCriticalZone→IfcReal Applicable entity: **IfcBeam** ShearSFStartSectionCriticalZone→fp_ULSShearVerification	MAN
Specify information about shear checks, for elements with shear reinforcement, considering the ULS for structural beam *The property represents the minimum safety factor, considering the "not critical" zone of a structural element (beam) with shear reinforcement, related to shear checks for the Ultimate Limit States (ULS).*	ULSStructuralVerificationRCBeam.ShearSFSectionNotCriticalZone→IfcReal Applicable entity: **IfcBeam** ShearSFSectionNotCriticalZone → fp_ULSShearVerification	MAN
Specify information about shear checks, for elements with shear reinforcement, considering the ULS for structural beam *The property represents the minimum safety factor, considering the "critical" zone at the "end" of a structural element (beam), with shear reinforcement, related to shear checks for the Ultimate Limit States (ULS).*	ULSStructuralVerificationRCBeam.ShearSFEndSectionCriticalZone→IfcReal Applicable entity: **IfcBeam** ShearSFEndSectionCriticalZone →fp_ULSShearVerification	MAN

A PSet, therefore, includes several properties that can be associated with objects, materials, and more. About the development of the proposal (IDM/MVD), it has been noted that both the most recent IFC4 and the previous IFC2X3 schema contain only a few properties, which are not sufficient to support the whole information exchange investigated in a BIM environment. To extend the use of IFC models also to this type of process (seismic authorization), the IFC schema would need certain information integrations regarding the single object, the global structure, the site, and so on. As regards the BRs, they will define the constraints, for entities and properties, according to the needs and requirements that arise from the process in question. An example of the proposed BRs is presented in Table 2.3, which shows an example of a specification concerning the rules for information within BIM objects.

Table 2.3 - Example of specific BRs for information integration within a BIM object (e.g. ULSStructuralVerificationRCColumn for IfcColumn).

Rule ID	PSet.Property	Condition
StrEPe_RULE_01	*ULSStructuralVerificationRCColumn.CombinedMNSFStartSection*	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.CombinedMNSFEndSection	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.ShearSFStartCriticalZoneDirX	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.ShearSFEndCriticalZoneDirX	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.ShearSFNotCriticalZoneDirX	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.ShearSFStartCriticalZoneDirY	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.ShearSFEndCriticalZoneDirY	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.ShearSFNotCriticalZoneDirY	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.DuctilitySFStartSectionDirX	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.DuctilitySFStartSectionDirY	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.DuctilitySFEndSectionDirX	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.DuctilitySFEndSectionDirY	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.CapacityDesignM2S3	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.CapacityDesignM3S2	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.CapacityDesignDirX	"Exists" "AND" "≥1"
	ULSStructuralVerificationRCColumn.CapacityDesignDirY	"Exists" "AND" "≥1"

In this case, the table shows an example of rules defined for a proposed PSet, namely "ULSStructuralVerificationRCColumn" for the IfcColumn class, where, for a specific rule, a specific name, PSet with related property, condition, and value are set. This was also defined for all the information (entities and PSets) defined by the proposal.

After dealing with the development of the IDM regarding the definition of the identified needs and processes, the next step was the development of the related MVD identified as the technical specification and computer formalization of what is described in the IDM under consideration. Obviously, this work also involved software developers, who were mainly interested in the subsequent implementation of the software in question. For this purpose, it has been considered IfcDoc [150], a free tool offered by buildingSMART, for the development of the MVD related to the specifications previously described regarding the information to be integrated as defined in the related IDM. This tool allows the production of the documentation concerning the MVD, which consists of schemes, diagrams, indexes, and specifications defined by the user following the IFC schema. This tool also allows the export of the .mvdXML file for the validation of IFC data and supports software providers in the implementation of the proposed solution. The generated documentation (related to IFC entities, attributes, properties, and other concepts that were specified for the information exchange in the context under analysis) will be necessary for software developers to create a tool that allows the export of IFC models, integrated accordingly, and concerning the considered information. This is a solution for ensuring export operations in BIM applications, following information exchange requirements, to support the process considered here (seismic authorization permitting).

In the IfcDoc tool, for the development of MVD-related documentation, the user first has to load a "baseline" regarding a specific version of the IFC standard. This file represents the complete IFC schema specification (with all related documentation) and a pre-selected set of reusable MVD concept definitions.

The use of this tool, however, requires thorough knowledge of the IFC schema (regarding its ontology and semantics, principally). In an MVD, specific data requirements can be defined declaring which information, conveyed through IFC format, are necessary or not for the information exchange involved in the process. For instance, in the case of the concept of Property Sets for Objects, it is possible to define properties and associated conditions in relation to their existence, or to the allowed values, and so on. Indeed, in the following figure (see Figure 2.11) an example is shown in IfcDoc regarding the use of the

Property Template, in the case of application to a generic beam (e.g. for the IfcBeam entity), and considering the proposed property sets (e.g. ULSStructuralVerificationRCBeam, ULSStructuralVerificationRCBeam, PSet_ConcreteElementGeneral).

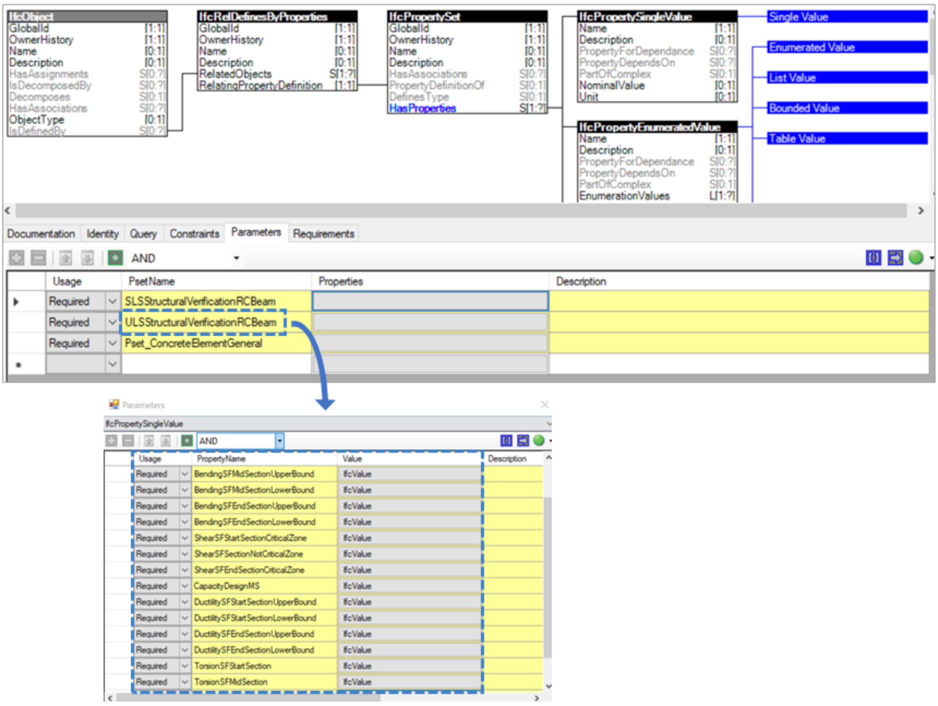


Figure 2.11 - Setting of PSet and related properties in IfcDoc for a specific entity (e.g. ULSStructuralVerificationRCBeam for IfcBeam).

The IfcDoc tool also allows users to define rules for specific entities and attributes, including the ability to define constraints and conditions of structures for specific information represented through the IFC features. This process ensures that, in a specific exchange scenario, certain entities must have specific attributes, property sets, and related specific values. This can also be considered for the production of IFC files, thus enabling the delivery of high-quality IFC files for process purposes. This was also realized in this specific case, exporting the .mvdXL file as one of the outputs generated by IfcDoc. Regarding the PSets, classes, and attributes considered by the proposed MVD, specific conditions (see Table 2.3) were successively specified through MVD development.

Once the MVD settings were completed, IfcDoc generated the HTML documentation containing the subset of IFC entities, properties, and concepts that were specified for the information exchange. In Figure 2.12 an example of HTML documentation is given, regarding the PSets developed for a beam (IfcBeam entity) and structure (IfcBuilding entity).

a)

5.4.4.43 StructuralBuildingInformation

Natural language names

Properties

buildingSMART Data Dictionary

PSD-XML

Name	Type	Description
ConstructionSystem	P_SINGLEVALUE / IfcLabel	Sistema costruttivo legato al materiale utilizzato per la costruzione (NTC 2018 - §7.3.1-Tab.7.3.II)
SeismicDevices	P_SINGLEVALUE / IfcBoolean	Vero se sono presenti dispositivi sismici, altrimenti falso
AnalysisMethod	P_SINGLEVALUE / IfcLabel	Metodo di analisi utilizzato per la progettazione sismica (NTC 2018 - § 7.3)
BehaviourFactorULS	P_SINGLEVALUE / IfcReal	Fattore di comportamento allo SLV (NTC 2018 - §7.3.1 e §7.9.2.1)
DesignTechnicalStandard	P_SINGLEVALUE / IfcText	Indica la normativa tecnica di riferimento [NTC, EC, ecc]
DesignWorkingLife	P_SINGLEVALUE / IfcLabel	Vita nominale di progetto (NTC 2018 - §2.4.1)
UsageClass	P_SINGLEVALUE / IfcLabel	Classi d'uso (NTC 2018 - §2.4.2)
DuctilityClass	P_SINGLEVALUE / IfcLabel	Classe di duttilità dell'opera (NTC 2018 - § 7.2.2)
P-DeltaDirX	P_SINGLEVALUE / IfcReal	Effetti delle non linearità geometriche per sisma nella DirX (NTC 2018 - §7.3.1)
P-DeltaDirY	P_SINGLEVALUE / IfcReal	Effetti delle non linearità geometriche per sisma nella DirY (NTC 2018 - §7.3.1)
ReferenceLife	P_SINGLEVALUE / IfcInteger	Periodo di riferimento per l'azione sismica (NTC 2018 - § 2.4.3)
RegularityInElevation	P_SINGLEVALUE / IfcBoolean	Regolarità in elevazione (NTC 2018 - § 7.2.1)
RegularityInPlan	P_SINGLEVALUE / IfcBoolean	Regolarità in pianta (NTC 2018 - § 7.2.1)
SecondaryStructuralElement	P_SINGLEVALUE / IfcBoolean	vero se sono presenti elementi strutturali secondari, altrimenti falso
SeismicZeroAltitude	P_SINGLEVALUE / IfcReal	Quota altimetrica dello zero sismico
VerificationOfSecondaryStructuralElements	P_SINGLEVALUE / IfcBoolean	Vero se sono state eseguite le verifiche di sicurezza degli elementi strutturali secondari, altrimenti falso (NTC 2018 § 7.2.3)
SafetyChecksNonStructuralElements	P_SINGLEVALUE / IfcBoolean	Vero se sono state eseguite le verifiche di sicurezza degli elementi non strutturali, altrimenti falso (NTC 2018 § 7.2.3)
VerticalSeismicAction	P_SINGLEVALUE / IfcBoolean	vero se si è considerata la componente verticale dell'azione sismica, altrimeni falso(NTC 202018 - § 7.2.2)
InFalseElements	P_SINGLEVALUE / IfcBoolean	Vero se sono presenti elementi in falso, altrimenti falso
FoundationModeling	P_SINGLEVALUE / IfcLabel	Specifica la tipologia di modellazione delle fondazioni
DeformableSlab	P_SINGLEVALUE / IfcBoolean	Vero se sono stati considerati solai deformabili nel modello di calcolo, altrimenti falso
PresenceOfRigidBoxAboveFoundation	P_SINGLEVALUE / IfcBoolean	Vero se presente una struttura scatolare rigida al disopra della fondazione, altrimenti falso

b)

6.1.5.22 ULSStructuralVerificationRCBeam

/ IfcBeam

Natural language names

Properties

buildingSMART Data Dictionary

PSD-XML

Name	Type	Description
TypeOfBeam	P_SINGLEVALUE / IfcText	Specifica il tipo trave, ovvero: trave di telaio, travetto, trave scala o trave di accoppiamento.
BendingSFStartSectionUpperBound	P_SINGLEVALUE / IfcReal	valore minimo del SF a flessione relativo al lembo superiore della sezione d'inizio dell'elemento (NTC 2018 - § 4.1.2.3.4 - § 7.4.4.1.1)
BendingSFStartSectionLowerBound	P_SINGLEVALUE / IfcReal	valore minimo del SF a flessione relativo al lembo inferiore della sezione d'inizio dell'elemento (NTC 2018 - § 4.1.2.3.4 - § 7.4.4.1.1)
BendingSFMidSectionUpperBound	P_SINGLEVALUE / IfcReal	valore minimo del SF a flessione relativo al lembo superiore della sezione di mezzeria dell'elemento (NTC 2018 - § 4.1.2.3.4 - § 7.4.4.1.1)
BendingSFMidSectionLowerBound	P_SINGLEVALUE / IfcReal	valore minimo del SF a flessione relativo al lembo inferiore della sezione di mezzeria dell'elemento (NTC 2018 - § 4.1.2.3.4 - § 7.4.4.1.1)
BendingSFEndSectionUpperBound	P_SINGLEVALUE / IfcReal	valore minimo del SF a flessione relativo al lembo superiore della sezione di fine dell'elemento (NTC 2018 - § 4.1.2.3.4 - § 7.4.4.1.1)
BendingSFEndSectionLowerBound	P_SINGLEVALUE / IfcReal	valore minimo del SF a flessione relativo al lembo inferiore della sezione di fine dell'elemento (NTC 2018 - § 4.1.2.3.4 - § 7.4.4.1.1)
ShearSFStartSectionCriticalZone	P_SINGLEVALUE / IfcReal	valore minimo del SF a taglio relativo alla zona critica della sezione di inizio dell'elemento (NTC 2018 - § 4.1.2.3.5 - § 7.4.4.1.1)
ShearSFSectionNotCriticalZone	P_SINGLEVALUE / IfcReal	valore minimo del SF a taglio relativo alla zona non critica (NTC 2018 - § 4.1.2.3.5 - § 7.4.4.1.1)
ShearSFEndSectionCriticalZone	P_SINGLEVALUE / IfcReal	valore minimo del SF a taglio relativo alla zona critica della sezione di fine dell'elemento (NTC 2018 - § 4.1.2.3.5 - § 7.4.4.1.1)
CapacityDesignMS	P_SINGLEVALUE / IfcReal	vero se il taglio agente è ottenuto dalla prescrizione normativa (NTC 2018 - § 7.4.4.1.1)
DuctilitySFStartSectionUpperBound	P_SINGLEVALUE / IfcReal	valore minimo del SF a duttilità relativo al lembo superiore della sezione d'inizio dell'elemento (NTC 2018 - § 7.4.4.1.2)
DuctilitySFStartSectionLowerBound	P_SINGLEVALUE / IfcReal	valore minimo del SF a duttilità relativo al lembo inferiore della sezione d'inizio dell'elemento (NTC 2018 - § 7.4.4.1.2)
DuctilitySFEndSectionUpperBound	P_SINGLEVALUE / IfcReal	valore minimo del SF a duttilità relativo al lembo superiore della sezione di fine dell'elemento (NTC 2018 - § 7.4.4.1.2)
DuctilitySFEndSectionLowerBound	P_SINGLEVALUE / IfcReal	valore minimo del SF a duttilità relativo al lembo inferiore della sezione di fine dell'elemento (NTC 2018 - § 7.4.4.1.2)
TorsionSFStartSection	P_SINGLEVALUE / IfcReal	valore minimo del SF a torsione nella sezione di inizio dell'elemento (NTC 2018 - § 4.1.2.3.6)
TorsionSFMidSection	P_SINGLEVALUE / IfcReal	valore minimo del SF a torsione nella sezione di mezzeria dell'elemento (NTC 2018 - § 4.1.2.3.6)
TorsionSFEndSection	P_SINGLEVALUE / IfcReal	valore minimo del SF a torsione nella sezione di fine dell'elemento (NTC 2018 - § 4.1.2.3.6)

Figure 2.12 - Example of MVD-related documentation (HTML) regarding different property sets: (a) for the IfcBuilding class; (b) for the IfcBeam class.

If structural software implemented the developed MVD, the exported IFC files would contain only the exchange requirements considered for the context investigated here, i.e., seismic authorization. This approach, considering the information exchange, establishes a series of benefits including the reduction of irrelevant information, the reduction of the time needed to acquire information from different sources, and the production of high-quality IFC models. As already mentioned, IfcDoc can generate various pieces of documentation, including .mvdXML files, which are useful for the development and implementation of the MVD [151]. Based on the requirements in question, and the information defined in the IDM, the corresponding .mvdXML file was generated. This format allows the setting of the exchange requirements concerning IFC classes, attributes, and more [152]. To also analyze, test, and validate what was produced with IfcDoc (mainly mvdXML files), XbimXplorer was used (https://docs.xbim.net/downloads/xbimxplorer.html, https://github.com/xBimTeam/XbimMvdXML). This is an open-source IFC viewer that, through a specific plugin, allows to upload of a .mvdXML file. This software, given the possible links or relationships between IFC models and views, allows simultaneous reading of an IFC and .mvdXML file. With the use of this software, the correctness of what was produced with IfcDoc was checked (based on the IFC model of the selected case study), as shown in Figure 2.13.

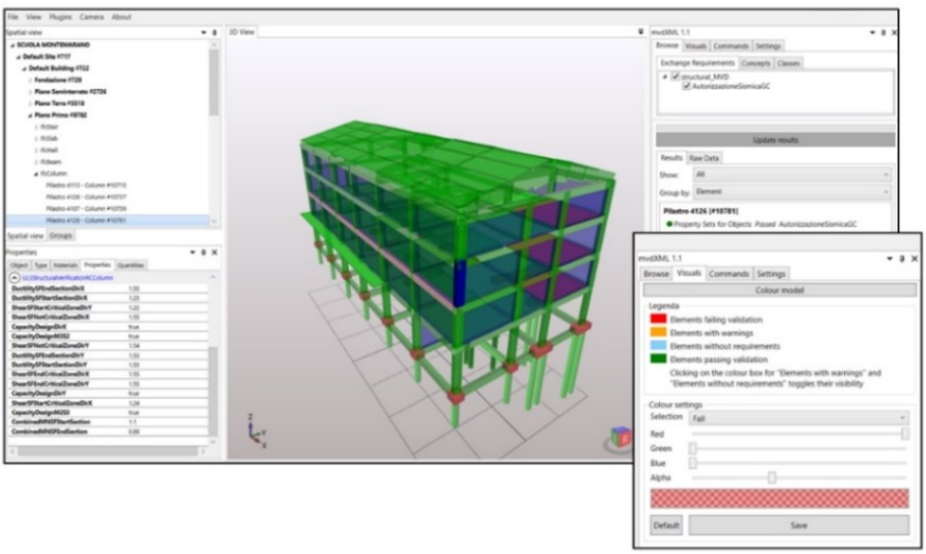


Figure 2.13 - Using XbimXplorer to check an IFC model against the developed .mvdXML file.

The requirements and conditionalities set within IfcDoc and translated into mvdXML can be visualized through the use of colored views in XBimXplorer. To do that, different values of a chosen property or the existence or non-existence of specifically required information were considered in the same model. By using color views it was possible to check the functionality of such rule sets (e.g. implementation of BRs provided by IDM). Accordingly, it was possible to visualize the results obtained (IFC classes and relative properties) more easily, and the corresponding conditionalities were expressed through the formalization of BRs. All this was brought about starting from what was defined in the IDM and later formalized in the MVD. Figure 2.13 shows the formal and visual checking of certain conditions expressed in the proposed IDM/MVD approach for a specific IFC class (e.g. IfcBeam, IfcColumn, IfcSlab, etc.). For example, the element concerned by structural verification may be verified (green), not verified (red), or not have any requirements (blue). With reference, for instance, to the structural verification expressed using SF ($SF=C/D\geq1$), applying the definition, the generic structural verification will be satisfied if it is $C\geq D$. In the case studied in Figure 2.13, the BIM objects in red had an SF of less than one, while those in green were greater than one. With this logic, as described in the previous figure, a series of tests were carried out to validate the functionality of the implemented conditions. These were developed with the aim of checking, for example, the conformity within the proposed properties of the data that had been recorded, as well as verifying the existence of the properties or PSets to which they belong. Once these tests were carried out, it proceeded to the implementation of the MVD in the software, i.e., Edilus. For this purpose, the software developers considered the documentation that had been produced. In addition, several scripts and algorithms (generated by software developers) enabled, for example, the automatic recording of values extracted from the calculation outputs, obtained downstream of the structural calculation, into the proposed properties.

2.4 Implementation of the proposed MVD in structural software for exporting IFC models for seismic structural e-permitting purposes

In order to implement what had been proposed, a real case study was considered. The entire Str.E.Pe process was applied to a school renovation project in Montemarano, Italy. This project consisted of the deconstruction of an existing building and its replacement with a new reinforced concrete structure. Figure 2.14 shows architectural BIM models for the design of the new school.

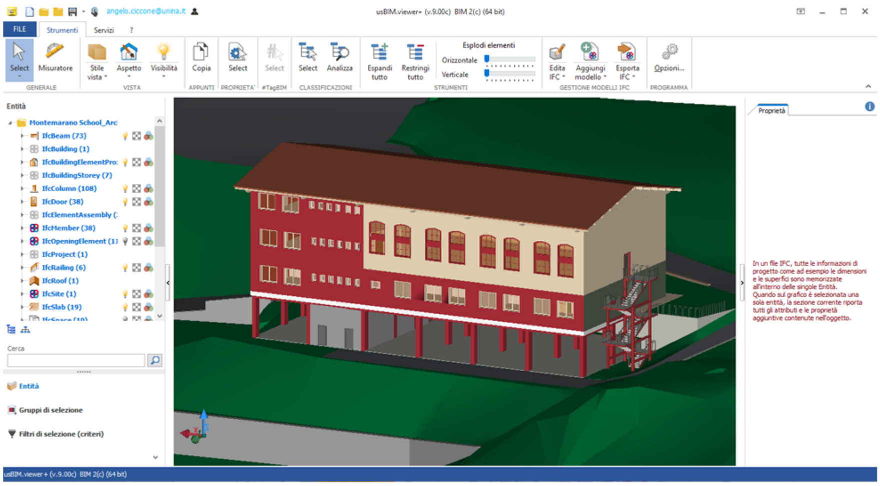


Figure 2.14 - Architectural model of Montemarano School.

For the development of the BIM structural model (see Figure 2.15), Edilus software was used, while Edificius was used to create the architectural model. Both software is produced by ACCA Software.

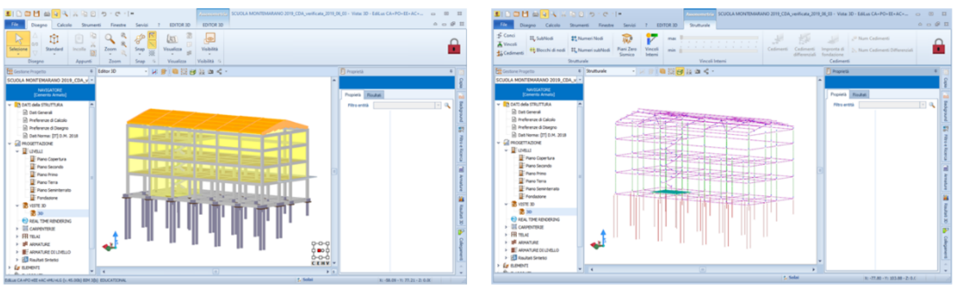


Figure 2.15 - BIM structural model (left) and structural analytical model (right) related to the case study.

Hence, in collaboration with ACCA Software, the developed MVD was implemented in the structural software (i.e. Edilus) to enable the export of IFC models (integrated with the information in question). This model will then be part of the final delivery to the BAB via ICDD before it is loaded into the collaborative platform. For the implementation of the proposed solution, the software vendor relied on all the documentation produced for the proposed MVD, obtained (mvdXML, HTML, etc.) utilizing IfcDoc and related IDMs. The structural model related to the case study, produced in Edilus, is shown in Figure 2.15. Afterward, the required information was developed according to the current structural codes (e.g. Norme Tecniche per le Costruzioni) and other standards considered for the seismic authorization process. After analytical modeling, design, and verification of the structure, Figure 2.16 shows structural outputs obtained downstream of these operations.

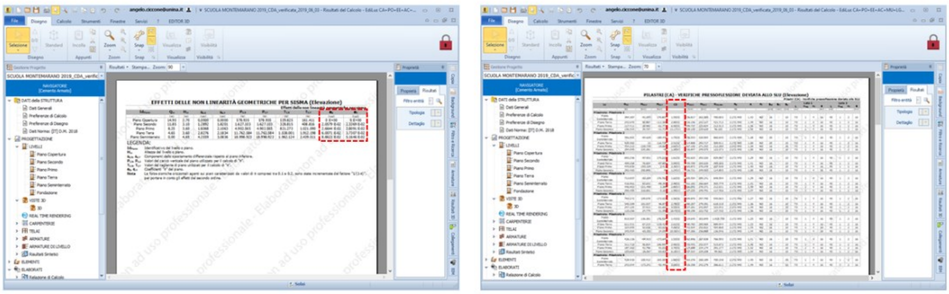


Figure 2.16 - On the left, structural checks related to global structure (e.g. P-Δ Effects) and, on the right, structural checks related to a generic column (e.g. combined bending and compression from axial force).

In the above Figure 2.17, some examples of results, obtained with reference both to the global level for the building (e.g. P-Δ Effects) and the local level for instances considering a structural column (e.g. combined bending and compression from axial force), are shown.

```
.........
#794 = IFCPROPERTYSET('1gYhLwyEj2pu93yEhD$dz1', #1, 'StructuralBuildingInformation', 'Informazioni strutturali', (#795, #796, #797, #798, #799,
#800, #801, #802, #803, #804, #805, #806, #807));
#795 = IFCPROPERTYSINGLEVALUE('ConstructionSystem', $, IFCTEXT('Cemento Armato'), $);
#796 = IFCPROPERTYSINGLEVALUE('AnalysisMethod', $, IFCTEXT('Analisi dinamica modale'), $);
#797 = IFCPROPERTYSINGLEVALUE('BehaviourFactorULS', $, IFCREAL(4.68), $);
#798 = IFCPROPERTYSINGLEVALUE('DesignTechnicalStandard', $, IFCTEXT('D.M. 17/01/2018'), $);
#799 = IFCPROPERTYSINGLEVALUE('DesignWorkingLife', $, IFCTEXT('50'), $);
#800 = IFCPROPERTYSINGLEVALUE('UsageClass', $, IFCTEXT('3'), $);
#801 = IFCPROPERTYSINGLEVALUE('DuctilityClass', $, IFCTEXT('A'), $);
#802 = IFCPROPERTYSINGLEVALUE('P-DeltaDirX', $, IFCREAL(0.), $);
#803 = IFCPROPERTYSINGLEVALUE('P-DeltaDirY', $, IFCREAL(0.), $);
#804 = IFCPROPERTYSINGLEVALUE('ReferenceLife', $, IFCREAL(75.), $);
#805 = IFCPROPERTYSINGLEVALUE('RegularityInElevation', $, IFCBOOLEAN(.F.), $);
#806 = IFCPROPERTYSINGLEVALUE('RegularityInPlan', $, IFCBOOLEAN(.F.), $);
#807 = IFCPROPERTYSINGLEVALUE('VerticalSeismicAction', $, IFCBOOLEAN(.F.), $);
#808 = IFCRELDEFINESBYPROPERTIES('103EbYs5H9Ngz2hkWHlsHv', #1, 'Object to Properties', 'Object to Properties Relation', (#731), #794);
#809 = IFCPROPERTYSET('28_R0rx_n7Mg7vP6RLy4VQ', #1, 'StructuralRCBuildingInformation', 'Informazioni strutturali Cemento Armato', (#810, #811));
#810 = IFCPROPERTYSINGLEVALUE('StructuralTypeDirX', $, IFCTEXT('A telaio, miste equivalenti a telaio'), $);
#811 = IFCPROPERTYSINGLEVALUE('StructuralTypeDirY', $, IFCTEXT('A telaio, miste equivalenti a telaio'), $);
#812 = IFCRELDEFINESBYPROPERTIES('093CKc4pz05xYYVMasAoOH', #1, 'Object to Properties', 'Object to Properties Relation', (#731), #809);
#813 = IFCLOCALPLACEMENT(#727, #816);
```

Figure 2.17 - An extract of the IFC file related to specific PSets (for IfcBuilding class)

In the images, the results employing synthetic parameters (e.g. SF) are also shown. Such information will then be necessary for enriching the IFC model for export. Through scripts elaborated by the software providers, this information will be processed (e.g. considering for each verification the minimum value of the SF for all combinations) and the related values will be automatically written in the identified properties. The software developers accordingly implemented what had been proposed in this study for exporting the integrated IFC model with the information required by the process in question. This implementation also made it possible to set everything automatically through the management of the IFC concepts required by the information exchange, and the organization of the proposed PSets (associated with the IFC classes concerned by integration) with related values obtained from the outputs (e.g. printouts or technical reports) exported by the structural software. Through the export procedure in Edilus, as shown in the previous Figure 2.17, it will then be possible to generate the required PSets, with the corresponding properties valorized, regarding the IFC classes. Figure 2.18 shows the available selection of the implemented MVD in the software used for experimentation, i.e., Edilus, among available MVDs.

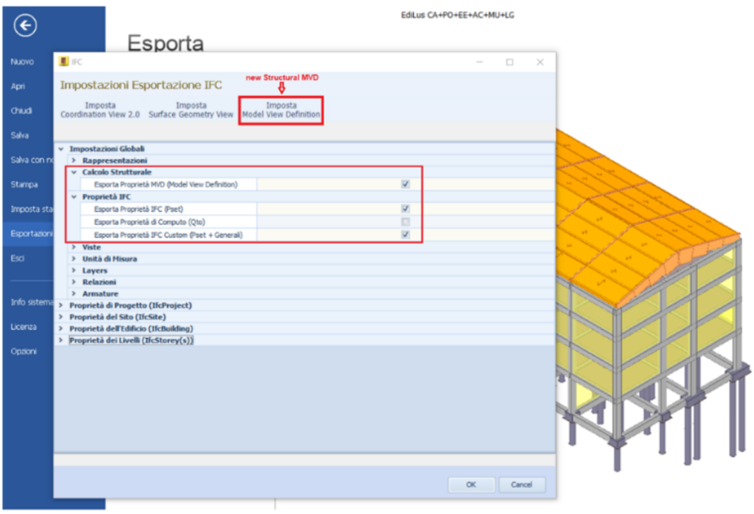


Figure 2.18 - Selection of a new structural MVD to export IFC files with specifications about the proposed PSets.

In addition, it should be noted that before the implementation of the proposed MVD, not all the required information - whether upstream or downstream of the structural calculations - was available in the IFC models exported by Edilus. To overcome these limitations too, it has been proposed, to software developers, of integrating into Edilus (e.g. through the definition of additional windows in existing sections in Edilus) context and process-related information that had previously been unavailable. This allowed the integration in the exported IFC model of all the necessary information according to the exchange requirements (described and formalized in the IDM/MVD proposal for the authorization process). The availability of a three-dimensional model in open format (IFC), integrated with the information required for seismic permitting, allows BABs technicians to avoid time-consuming verification and control activities of the information content previously performed manually, mainly through paper-based documents. The IFC model will be part of the delivery via ICDD (Information Container Data Drop), resulting in a structured reference with smart links to other file types such as technical drawings and design reports. Therefore, the solution proposed here considers the platform developed within the Structural e-Permit project to support the exchange of structural engineering information, in IFC format, for the issuing of seismic permits (see Figure 2.19). The platform thus has supported the digitization of the seismic authorization process in the field of structural engineering, addressing the need for a specific solution. In addition, the IDM/MVD approach provided the opportunity to build IFC models tailored to the purposes of the process in question.

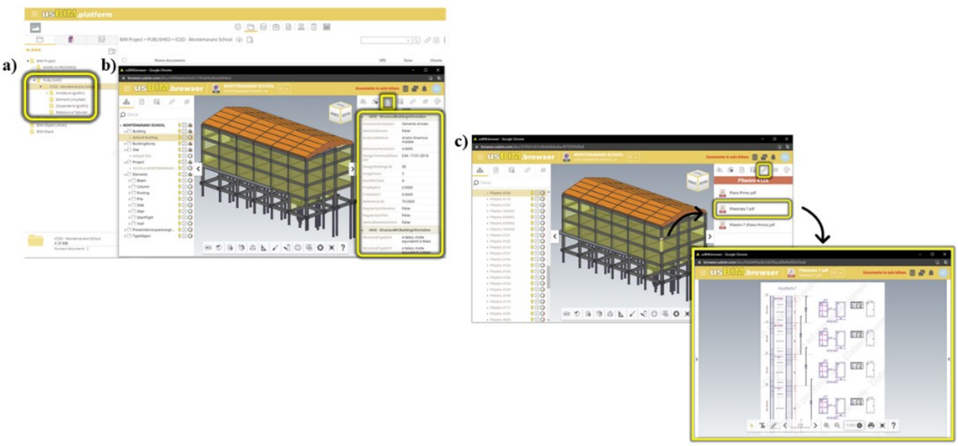


Figure 2.19 - a) ICDD file in CDE environment; b) Integrated IFC model, based on a proposed new structural MVD, belonging to the ICDD container with other files and links; c) Linking of object-related documents (structural drawings, reports, etc.).

Finally, among the various advantages that come with the adoption of the IDM/MVD approach, there are the following: the possibility of visualizing and managing information in other BIM environments or tools as well; the possibility of using a single environment (collaborative platform) on which to organize information exchange with BABs technicians; and the availability of an IFC model as a reference for the control and checking activities related to information content.

2.5 Discussion

The proposal to adopt an IDM/MVD approach for seismic authorization permitting enables, within a process based on BIM methodologies and tools, information exchange between the structural engineer (who requires the permit for the building) and the BABs technicians (who release the seismic permit), based on IFC models adequately integrated with process-related information. Given what has been analyzed previously, in addition to what was already defined in previous work [1], here it considers that the principal information required by the seismic permitting process is significantly lacking within the IFC format. This limits the application of the IFC format to these types of processes. Accordingly, it would like to see an improvement to the existing IFC schema so that it can provide more support for processes involving structural engineering. The adoption of an IDM/MVD approach favors and promotes the use of IFC models for seismic authorization processes as well. However, given the current gaps in the IFC standard about the structural domain, integration of the specific information content for seismic permitting was necessary. Specifically, information was defined at the project, site, structure, story, and element levels. These are referred both to requirements provided by the codes (in this case NTC 2018) and to the specific purpose of structural seismic e-permitting. This information, especially when referring to structural verifications, is synthetic and for this reason representative of the worst conditions (minimum safety factor, SFmin) among all possible combinations of actions provided by the structural codes. In addition, the fully digital approach proposed here allows one to acquire detailed information easily, which the engineer can investigate if necessary. Indeed, the use of ICDD allows delivering IFC models which are linked to the technical documentation, consisting of reports, tables, and drawings, so that, for example, the technician will find the specific details of the load combination from which the SF originates in the design report, or he will find detailed information relating to the reinforcements in the technical drawings. Therefore, to convey the information, about 200 properties were arranged according to the sources mentioned before. The selected information is associated at each level of the spatial organization, starting from the context of the project (IfcProject), site (IfcSite), structure (IfcBuilding), story (IfcBuildingStorey), and element (IfcBuildingElement considered as a supertype of some entities such as IfcBeam, IfcColumn, IfcWall, IfcFooting, etc.). The benefit of adopting the IDM/MVD approach for seismic permit applications and implementing the related MVD in structural software that integrates a BIM environment, consists, mainly, of making information available to BABs technicians through a parametric three-dimensional model in an IFC open format. This enables the use of e-permitting platforms that integrate simple IFC viewers, and are thus independent of proprietary formats. Moreover, among the potential e-permitting platform functionalities it may also consider the validation of the delivered information content and, consequently, the availability of reliable information from a geographic point of view as well. Once the BABs operators have validated the information content regarding the IFC models, the latter can represent an information archive that can be considered as a reference for further updates (for instance related to structural retrofit interventions or other structural assessments). With this study, preliminary validation is also addressed in a BIM environment, regarding the IFC models delivered to the BABs for seismic permit applications. Moreover, the MVD also allows for standardizing the information flow related to the seismic permit application and allows the production of tailored IFC models for process purposes. At the same time, it should be specified that, in an MVD-based approach, implementation of the proposed MVD in the considered software is necessary. As shown previously, regarding the case study, the proposed MVD was subsequently implemented in Edilus through the collaboration of the software vendor ACCA Software. The integration of different skills and knowledge was fundamental to establishing and organizing an operational information flow that was stable and under the purposes defined by Str.E.Pe. Over time, the application of the MVD-based approach led to different MVDs that were not interoperable with each other. This has caused several scenarios in which, for example, the software that supported a certain MVD could not automatically ensure the support of another MVD. In addition, to implement a generic MVD, software vendors have to spend resources to update or extend the computer codes within their software tools. Due to these issues, buildingSMART has recently begun to define a new approach where there will be several MVDs, each used for multiple use cases. This will be done regarding the new IFC standard specification (e.g. IFC4x3 or IFC5).

Hence, the main challenges, regarding the implementation of the proposed IDM/MVD approach, concerned: (i) the development of specific information requirements (e.g. for the building structural types under consideration) about the proposal (e.g. PSets and their properties); (ii) the development of the components of the IDM along with the implementation in IfcDoc for obtaining the MVD documentation; (iii) the technical implementation of the MVD, e.g. through .mvdXL files, in the specific software (this enabled to export from the software considered, i.e. Edilus, the IFC models consistent with the identified use case); (iv) testing phases regarding the validity of the exportation of IFC models relevant for the seismic authorization; (v) testing phases for the simulation of considered processes in the proposed str.e.pe. platform; education and training, on the proposed openBIM processes, for all the actors involved in the seismic structural e-permit (e.g. BAB technicians and civil engineers).

In conclusion, the adoption of openBIM led, through the use of open formats (e.g. IFC), to save management costs of software licenses; to preventing information from being obsolete or ineffective, producing durable projects with a standardized language and exchange of information; better compliance with deadlines about the information exchanged; to avoid workflow fragmentation, thus improving collaboration and communication among all actors involved in the process, therefore, providing the right information at the right time to the right people.

2.6 Conclusion

This study, therefore, proposes the use of the IDM/MVD approach for the management of information, in the context of structural engineering, on the results of building design activities and structural e-permitting processes, to allow the automatic export of information, mainly through IFC models (via

ICDD), supporting seismic permitting processes. Here, it is found that the integration of investigated structural information, in the IFC format, is a topic that is not well addressed in research. Therefore, here it first suggests a detailed analysis of the information to be integrated within BIM models. An integration framework through the selected information has been provided, which has required the definition of about 200 properties, in addition to those already existing in the considered IFC schema, useful for the purposes of the proposal in the analyzed context. The proposed IDM/MVD approach enables the information exchange required for seismic permitting in a BIM environment. It provides useful implementation insights for software vendors to develop a BIM tool capable of exporting an IFC model for the specific purpose of seismic permitting. At the same time, the implementation of the IDM/MVD approach will allow the exchange of structural information, possibly among applications or tools developed by different software companies. Accordingly, this will extend the use of open BIM to seismic-authorisation processes. The collaboration with ACCA Software allowed the production of the first implementation of the proposed solution, demonstrating its full feasibility. Here, the main benefits of this approach were: the availability of information directly from the open format IFC model; accordingly, the use of information independent of the software being used; and a new manner of reading, checking, and validating information digitally to support BABs activities.

In conclusion, here it has been proposed, for the first time in a research setting, the adoption of an IFC-based solution for the seismic permitting process, and in support of this provide an example of implementation. However, the proposed solution refers only to new designs of reinforced concrete buildings. Future developments will certainly extend the IDM/MVD approach to other structural typologies involving other construction materials (masonry, wood, steel, etc.). This operation will require only a quantitative effort for the extension of the proposed framework to other IFC classes and relative PSets. At the same time, as regards buildingSMART, the development of new standards such as the buildingSMART Data Dictionary (bSDD, https://www.buildingsmart.org/users/services/buildingsmart-data-dictionary/) and Information Delivery Specification (IDS, https://technical.buildingsmart.org/projects/information-delivery-specification-ids/) will have to be considered. Indeed to overcome the limitations of the MVD-based approach, buildingSMART is working on the development of the IDS, closely connected to the IFC standard, for the definition of interpretable computer exchange requirements depending on specific use cases. This standard, intended as a possible computer-interpretable specification, defines the exchange requirements related to the exchange information model (in IFC format). These new opportunities (bSDD, IDS) can provide further updates and extensions, allowing further developments in the open BIM scenario. Technological developments are therefore necessary to improve further what has been proposed so far concerning the new openBIM standards mentioned above. In this regard, the solution seems to be interesting, given that it considers, for instance, the future contribution of bSDD; this could be a chance to standardize the information content (e.g. properties) conveyed through the use of the information model. Finally, the integrated IFC model, which is obtained through the implementation of the proposal (IDM/MVD), could be useful to other "structural use-cases" under consideration, besides that related to the process considered here, i.e., seismic authorization. At the same time, this proposed solution will allow BABs to avoid time-consuming activities and optimize resources due to this new opportunity for digital management and the use of information through the application of open BIM in the context of structural engineering.

Chapter 3

3. Application of openBIM for the management of existing railway infrastructure: the case study of the Cancello–Benevento railway line.

3.1 Introduction

BIM methodologies, when applied to infrastructure (Infrastructure Building Information Modeling, I-BIM), can offer information management digitally, and therefore in a more effective manner and also of use with large-scale infrastructural assets. As is well known, it has been shown that these methodologies can be successfully applied principally in design phases, with considerable advantages in terms of cost reduction and improved management of both material and professional resources. At the same time, the availability and management of information relating to the entire lifecycle of an infrastructural asset may prove to be the innovative element, particularly from a strategic perspective, for infrastructure managers. Infrastructure (e.g., roads or railways), in the context of the application of BIM methodologies, involves the management of component modeling concepts in line with the development of a characteristic alignment of a given linear infrastructure, unlike modeling of assets related to the construction sector (e.g., buildings). One of the obstacles to the application of BIM methodologies to transport infrastructure is the limited availability of libraries of complex infrastructure objects, in terms of geometry, as well as other aspects. Obviously, in addition to geometric problems (e.g., the difficulty of geometric parameterization of components), there is the need to define which characteristics or information need to be recorded or associated with the model and its components in relation to a given lifecycle phase. For instance, some information may be necessary to guarantee the connection and integration of BIM methodologies with other company systems, for example, in the case of the management, operation, and maintenance of an infrastructural asset coordinated by a managing body or owner. When producing individual models considering the concept of Model Uses [14], the relative requirements can be considered about the connection with ERP (Enterprise Resource Planning) systems, for example, or to those of FM (Facility Management). Interoperability is therefore necessary when applying BIM methodologies, especially in the interdisciplinary management of information. In support of this, openBIM and related standards (e.g., Industry Foundation Classes (IFC)) are the key elements for the exchange of information. Accordingly, they are also crucial in the scenario under investigation. Following a recent ministerial decree and its updated version (Ministerial Decrees No. 560 of 2017 and No. 312 of 2021), the Italian government has made the use of digital tools and methods mandatory in the design and construction of public works and outlined six bands for the categories of the amount of work and related mandatory time thresholds (from 2019 to 2025). Furthermore, the possible application of BIM methodologies is also specified in the case of existing assets. These methodologies will thus be used to create digital avatars from the planning to management phases of a building or civil infrastructure. The pilot project presented here was developed to create a federated digital model of the entire railway infrastructure in question and was aimed primarily at managing information, for O&M phases and the wider context of Asset Management, through the use of openBIM, in which the IFC (Industry Foundation Classes) format played a key role. Specifically, an as-yet unofficial version (IFC4x2) was considered for certain concepts related to linear infrastructures, such as alignment (i.e., IfcAlignment) and other aspects (e.g., IfcLinearPlacement), and this allowed to develop the proposed solution through openBIM. Subsequent management of the federated digital model took place through the use of a collaborative platform (i.e., usBIM.platform), which made it possible to manage the large quantity of available data (models, point clouds, textured meshes, documents, etc.). To date, this is the only BIM management platform that is IFC-certified (regarding the IFC import process) by buildingSMART International. This approach allowed considering the most useful information to record, within the digital models and through the use of the collaborative environment functionalities, about the operation and maintenance practices of railway infrastructure. The collaboration environment allowed to structure of the data-sharing environment (AcDat), which is equivalent to the Common Data Environment (CDE) for UNI 11337 (UNI, the Italian national standardization body) series, in force in Italy and in line with the international reference, namely ISO 19650 (ISO, the International Organization for Standardization). This environment, constructed on the aforementioned platform, enabled the interdisciplinary management of information through a series of functions offered in addition to the possibilities made available by the models (e.g., PropertySets). This allowed rationalizing activities and information for centralized and referenced management on interoperable models of the railway infrastructure and related information (e.g., documents), also in the wider context of asset management. The digitalization of existing infrastructure begins with the survey of key elements of railway infrastructure (e.g., railway superstructure, electric traction, and signaling) and related assets (e.g., stations, bridges, viaducts, and tunnels) along the entire railway line in question. This is accomplished through the use of drones and an autonomous railway vehicle equipped with instruments, including laser scanners, GPS, and an inertial platform. The survey of the entire linear infrastructure was carried out by collecting various kinds of information (geometry, structural conditions, etc.), which were subsequently integrated into a single collaborative environment for the management and maintenance of the infrastructure.

In summary, this project focused on the application of BIM methodologies to the management of operational transport infrastructure (namely railways) and used the Cancello–Benevento line as a case study. This project was one of three finalists at the 2021 buildingSMART Awards in the "Asset Management using openBIM" category and was presented at the Virtual Summit 2021 under the title: "Asset Information Management of existing railway infrastructure in openBIM: the Cancello–Benevento line".

3.1.1 An overview of openBIM applications for the management of railway infrastructures

Over the years, BIM has played a role of fundamental importance because of its potential in O&M activities in the construction sector: it can provide three-dimensional representations that are functional in specific analyses and makes it possible to access information in real-time [73,153]. The implementation and application of BIM methodologies have undoubted advantages insofar as they improve collaboration among a project's teams and make it possible to have information models of both buildings and infrastructural assets as a reference, which is useful in O&M. Furthermore, BIM also represents a new paradigm in the world of AEC (architecture, engineering, and construction) [131,154,155]. In the same context, a study [12] demonstrates, through the application of BIM to four case studies (two hotels, a higher education facility, and a campus multipurpose facility), how the use of BIM methodologies can lead to a reduction in time and costs. Meanwhile, the development of BIM definitions and the application of BIM methodologies in the construction sector were studied [156–158]. As shown by research [159], in the case of applying BIM methodologies to the development of a railway link between a port station and an existing railway line, these can bring significant benefits to the entire project in terms of the resources employed. Such methodologies can therefore provide various fields - those associated with railways in particular - with an additional and innovative tool to face various design challenges. The use of BIM in the railway sector may have several advantages, such as promoting greater collaboration, saving resources (in terms of costs, time, etc.), and limiting possible risks and project errors due to improved communication between all actors involved [160]. Certainly, BIM has been widely applied in the design phases of railways [159–165]. Furthermore, BIM methodologies can be applied to facility management to gain efficiencies in management. Another study [166], through question-based surveys, has analyzed the application of BIM to urban rail transit to assess its diffusion and effectiveness when applied to the O&M phases. Here, for the purposes of information exchange, since interoperability is a fundamental requirement, open BIM provides increasingly indispensable support for interdisciplinary collaboration.

OpenBIM is a management process for collaborative projects that improves the benefits of BIM by ensuring the accessibility, management, and sustainability of digital data. Furthermore, it facilitates interoperability between the various entities involved with a given project during its lifecycle, and this is key to digital transformation in the construction sector, made possible through the use of open standards (e.g., IFC) that give flexibility to the choice of which software each stakeholder should adopt [167]. For instance, BIM methodologies can be used for the management of O&M phases in motorway tunnels [168], even though its application in the field of road infrastructure remains limited. Indeed, the versions of IFC currently under development will extend it semantically and geometrically to domains relating to transport infrastructure, both road and rail. To that effect, buildingSMART work is being carried out on both the RAIL and ROAD domains for their relative extensions. Concerning the semantic extension of information relating to O&M (in reference to IFC), the application of openBIM has considerable advantages (compared to closedBIM), as it makes possible the analysis of and compliance with the relevant requirements, principally by using an appropriately integrated IFC model, as has been shown in a case study involving its application to a motorway in Morocco [167]. Remaining in the motorway sector, some researchers [169] have proposed, based on a case study they analyze, that the IFC standard should be extended to support the digitalization of various entities and their characteristic information, with particular attention to asset management, allowing a transition from bidimensional management of information (e.g., paper-based) to digital management (e.g., BIM model-based), which would make it possible to monitor and manage the lifecycle of the asset more efficiently. Meanwhile, a study focuses on the challenges and prospects of the application of Asset Management principles to highway maintenance, underlining that some applications remain ineffective and that major efforts are still required in the management of the assets, although the presence of guidelines and other standards (e.g., ISO550000) could certainly help to achieve higher maturity levels in this context [23]. There are also examples concerning the definition of IFC-based semantic and geometric BIM-modeling approaches applied to pilot projects in railway infrastructure [170]. In O&M, these activities play a fundamental role; for instance, in the reproduction of the existing conditions of the asset that requires digitalization. However, BIM was developed based on story organization, typical of a generic building, and therefore it presents many limitations and issues with respect to alignment-based concepts regarding transport infrastructure (e.g., railways and roads) [171]. Through the use of photogrammetric techniques, beginning with point clouds, and considering the IFC standard, a solution that involves generating the alignment of the railway infrastructure from the data obtained from the survey (point clouds, etc.) was proposed [172]. Currently, however, the applications of open BIM, especially about the O&M phases in the case of the railway sector, are limited. BIM methodologies may also be applied to manage operation and maintenance information [73,166,167,173–175], particularly in the context of railway infrastructures [166,174,176]. In addition, a study [164] has proposed a method for the realization of BIM models based on the IFC standard for certain components (e.g., railway tracks), and the management of the information relating to those models using concepts such as alignment and classification codes (e.g., for the association of IFC entities with railway components); they have also demonstrated how this methodology can reduce the time associated with maintenance operations. The application of BIM methodologies to the O&M phases favors more reliable performance in projects involving railway transit due to the use of virtual representations of physical reality, along with the integration of information from various contexts. A case study of the implementation of BIM in the management of the handover phase of a railway transport project was presented in China, identifying suitable technologies and the best solutions to highlight the potential of BIM when applied to the management of O&M activities [163].

Road infrastructure has similar needs. The IFC standards developed by buildingSMART ensure greater interoperability between all the entities involved in each project. In this regard, some researchers [177] explore the implementation of BIM and the application of open standards (e.g., IFC) in the case of road infrastructure, while highlighting the central role played by the collaboration between academia and industry in getting the most out of BIM in transport infrastructure. Infrastructure such as roads, railways, bridges, and tunnels are indispensable to the economy of a city since they facilitate the movement of people, goods, and services. At the same time, however, depending on their location, they can be subject to catastrophic events such as fires, floods, and storms, causing damage or various other problems. For this reason, a research proposal [178] highlights the need for a new form of digital management (Digital Engineering) to optimize the acquisition, processing, and visualization of data for Information Asset Management (IAM), and to that end, proposes a Technology Integrated Matrix (TIM) that will collect data for subsequent processing, thereby exploiting digital technologies, and BIM, in particular, to obtain information and resources relating to a project most quickly and conveniently possible.

Regarding the O&M of the railway infrastructure, another important concept is intelligent monitoring, which, through artificial intelligence (AI) algorithms, allows the process of large amounts of data and detection characteristics that are unobserved when using more traditional approaches. Through this approach, more reliable, long-lasting, and cost-effective infrastructure is obtained than in the case of traditional management. Despite this, many professionals, including those in the railway sector, continue to fail to grasp the real opportunities and potential offered by the application of machine learning (ML), for instance, or big data analysis [174,179]. In conclusion, in applying openBIM, as stated above, the integration of the domain dedicated to railways (i.e., RAIL Domain) within an IFC version that is also intended for infrastructure (most likely IFC4x3) will enable greater development and availability of solutions concerning management phases and, to a lesser extent, design phases. These additions, in the context of railway infrastructure and buildingSMART, refer to the work developed as part of the IFCRail project. Various international stakeholders have collaborated on this project, eager to meet the sector's challenges, develop better practices in the workplace, and provide open standards in updated versions to meet the needs of interoperability. All of this will enable the wider diffusion of open BIM in the management phases of infrastructure and make possible evaluations and assessments as part of asset management.

3.1.2 Project activities goals

This pilot project stems from the need of Rete Ferroviaria Italiana (RFI, managing body of Italy's national railway infrastructure) to take over the management of the Cancello–Benevento railway line, which is now managed by Ente Autonomo Volturno (EAV, regional transport operator in Campania). Transfer of management was considered to be a priority objective by representatives from the two companies, in order to modernize and increase traffic along the line, which is currently underperforming. To achieve this, the relevant section of the railway must comply with RFI standards. In particular, the project tested the application of BIM methodologies and involved various actors from different groups and entities in a single collaborative process of asset management. Two railway managing authorities (EAV and RFI), a software company (ACCA Software), and a university (University of Naples Federico II) collaborated on the project. The objective was to provide support to the two railway companies involved, in the context of a possible assessment of the performance related to railway infrastructure and the transfer of the infrastructure management from EAV to RFI. Accordingly, the principal goal was to systematize all relevant information by digitalizing the infrastructure to allow, subsequently, the assessment of any gaps in performance or of the availability of technological systems necessary for the transition to take place. It was, therefore, necessary to digitalize all the information available, especially that concerning the assessment of the infrastructure's capabilities and its compliance with RFI standards. Along with proper standards within the RFI context, also a series of systems and platforms, which are used by RFI for the management of infrastructure assets so far, have been considered. Specifically, the InRete2000 system is a platform that allows technicians to manage the objects registered within the related database with specific census data and standard specifications of the asset in question. Another existing system used by RFI, which is dedicated to the management of existing bridges, is the DOMUS system. This is a system that provides the information needed to plan the maintenance and control of the bridge assets, taking into account structural, operational, and economic factors. To facilitate operators that carry out visual inspections of bridges, a Defect Catalogue is provided through which the operator can define the location, magnitude, and extension of deterioration and damage unambiguously and comprehensively.

However, the use of openBIM, in particular the IFC standard, provided a unique opportunity in the context of infrastructure digitalization, for dealing with two use cases characteristic of the project. The first is asset management (AM), whereby the actual value of the infrastructure is established by considering its management activities, contributing to the maintenance and operation of technological systems and related elements. Over time, these must be maintained, updated, and managed to satisfy both the owner and users, guaranteeing both the value and efficiency of the asset. All these activities will produce information that can be recorded in a complete database (for example, through the use of information models). The digitalization of the infrastructure, in this particular case, made it possible to evaluate the quantification of the various systems that made up the railway infrastructure itself, and therefore the availability of information that could potentially support the management of the specific infrastructure in terms of value and efficiency. The second use that has been considered case was the maintenance management of railway infrastructure, regarding the Maintenance and Repair Information (MRI) use case, in which information regarding the maintenance and repair elements of the infrastructure are collected and stored. Hence, the possibility that the BIM information model (in the IFC format) could be key to accessing maintenance management systems (e.g., ERP systems), or the management of ordinary and extraordinary infrastructure maintenance, allowing a series of optimizations of processes necessary for maintenance management. In this scenario, the development of libraries of BIM objects also played an important role; these may be the simplest approach for collecting information according to predefined requirements. Furthermore, starting from the data acquired by means of surveying activities, the Existing Conditions Modeling (ECM) use case was also considered, a process that made it possible to develop a digital model of the existing conditions of a specific infrastructure, in this case, the Cancello–Benevento railway line. Useful information, above all that regarding infrastructure management, as mentioned above, was associated with this, and could be continually updated and collected. The results obtained by the project with respect to both the primary objective (assessing the compliance of the railway infrastructure with RFI standards) and other goals (management and maintenance of the railway infrastructural asset) were very positive, and both companies, EAV and RFI, have learned fundamental lessons, particularly regarding possible future scenarios involving the use of digital systems and new technologies (based principally on openBIM), which can certainly optimize the management processes of railway infrastructure in both companies.

3.2 A digital strategy for managing existing railway infrastructure considering the openBIM approach

The project activities related to the digitalization of railway infrastructure to find a solution consistent with the information managed by the various company systems with regard to asset management and railway maintenance and operation. Accordingly, a management proposal was developed that takes into account different platforms, software, and systems for maintenance management. The final federated digital model, developed following specific requirements, will be used by the managing body, which will update the relevant information to implement, in an operational manner, the proposal of infrastructure management through the usage of a BIM environment.

3.2.1 Setting of specific information requirements

To achieve these objectives, the requirements defined in the "Capitolato Informativo" (C.I.) and its Annexes are considered, as shown in Figure 3.1.

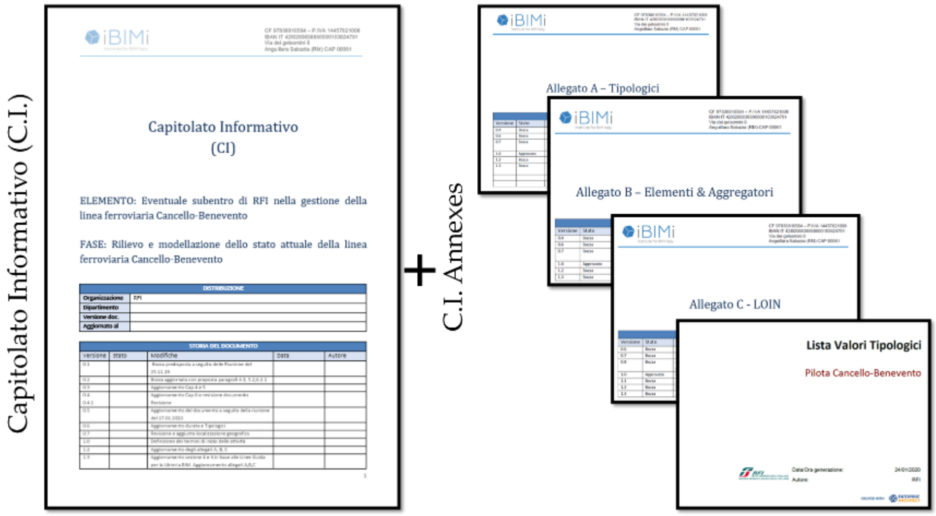
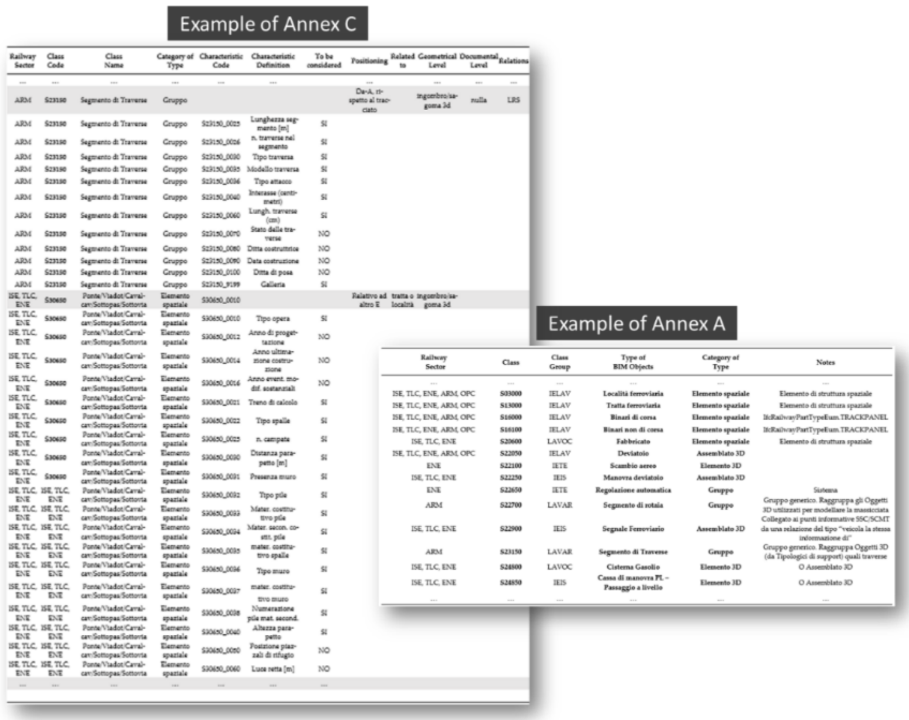


Figure 3.1 – "Capitolato Informativo" and related annexes

The C.I. is a document prepared by the client that defines the project's information management requirements. In general, it is divided into sections, including an introduction, normative references, a technical section, and a management section. This document was introduced in Italy by the Italian UNI 11337 series, which regulates aspects of the digital management of construction information processes through BIM methodologies. An international equivalent to the C.I. is the Employer Information Requirement (EIR), relating to the ISO 19650 series. In this document (i.e., C.I.), project activities, along with BIM requirements relating to the digitalization of the railway infrastructure in question, are described. These documents are the starting point for the development of the entire digital strategy supporting the digitalization of the railway line for the purposes that have been set out, as well as for the related modeling activities and integrated management of information and processes relating to the managing entities in question (RFI, EAV), about asset management.

The C.I. comes with several Annexes. Annex A contains the list of the different typologies of BIM objects that are considered. These are necessary for defining an object library and constructing a digital model of the infrastructural asset for its management in a BIM environment. In the definition phases of the C.I., around 90 types are identified. As shown in Figure 3.2, Annex A defines the specialization (or railway sector) to which each of them belongs (Railway Superstructure, CivilWorks, Electric Traction, Telecommunications, and Signaling), the corresponding class of the maintenance management system (for example S03000 for "railway location"), the corresponding BIM modeling concept (Element, 3D Assembled, Group, etc.) to be subsequently translated into IFC (respectively: IfcElement, IfcElementAssembly, IfcGroup, etc.), possible notes, and so on.



Example of Annex C

Railway Sector	Class Code	Class Name	Category of Type	Characteristic Code	Characteristic Definition	To be considered	Positioning	Related to	Geometrical Level	Documental Level	Relations
...	...	...	...	...	...		...		...	...	...
ARM	S23150	Segmento di Traverse	Gruppo				Da-A, rispetto al tracciato		ingombro/sagoma 3d	nulla	LRS
ARM	S23150	Segmento di Traverse	Gruppo	S23150_0025	Lunghezza segmento [m]	SI					
ARM	S23150	Segmento di Traverse	Gruppo	S23150_0026	n. traverse nel segmento	SI					
ARM	S23150	Segmento di Traverse	Gruppo	S23150_0030	Tipo traversa	SI					
ARM	S23150	Segmento di Traverse	Gruppo	S23150_0035	Modello traversa	SI					
ARM	S23150	Segmento di Traverse	Gruppo	S23150_0036	Tipo attacco	SI					
ARM	S23150	Segmento di Traverse	Gruppo	S23150_0040	Interasse (centimetri)	SI					
ARM	S23150	Segmento di Traverse	Gruppo	S23150_0060	Lungh. traverse (cm)	SI					
ARM	S23150	Segmento di Traverse	Gruppo	S23150_0070	Stato delle traverse	NO					
ARM	S23150	Segmento di Traverse	Gruppo	S23150_0080	Ditta costruttrice	NO					
ARM	S23150	Segmento di Traverse	Gruppo	S23150_0090	Data costruzione	NO					
ARM	S23150	Segmento di Traverse	Gruppo	S23150_0100	Ditta di posa	NO					
ARM	S23150	Segmento di Traverse	Gruppo	S23150_9199	Galleria	SI					
ISE, TLC, ENE	S30650	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0010			Relativo ad altro E	tratta o località	ingombro/sagoma 3d		
ISE, TLC, ENE	S30650	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0010	Tipo opera	SI					
ISE, TLC, ENE	S30650	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0012	Anno di progettazione	NO					
ISE, TLC, ENE	S30650	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0014	Anno ultimazione costruzione	NO					
ISE, TLC, ENE	S30650	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0016	Anno event. modif. sostanziali	NO					
ISE, TLC, ENE	S30650	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0021	Treno di calcolo	SI					
ISE, TLC, ENE	S30650	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0022	Tipo spalle	SI					
ISE, TLC, ENE	S30650	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0025	n. campate	SI					
ISE, TLC, ENE	S30650	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0030	Distanza parapetto [m]	SI					
ISE, TLC, ENE	S30650	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0031	Presenza muro	SI					
ISE, TLC, ENE	ISE, TLC, ENE	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0032	Tipo pile	SI					
ISE, TLC, ENE	ISE, TLC, ENE	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0033	Mater. costruttivo pile	SI					
ISE, TLC, ENE	ISE, TLC, ENE	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0034	Mater. secon. costr. pile	SI					
ISE, TLC, ENE	ISE, TLC, ENE	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0035	mater. costruttivo spalle	SI					
ISE, TLC, ENE	ISE, TLC, ENE	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0036	Tipo muro	SI					
ISE, TLC, ENE	ISE, TLC, ENE	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0037	mater. costruttivo muro	SI					
ISE, TLC, ENE	ISE, TLC, ENE	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0038	Numerazione pile mat. second.	SI					
ISE, TLC, ENE	ISE, TLC, ENE	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0040	Altezza parapetto	SI					
ISE, TLC, ENE	ISE, TLC, ENE	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0050	Posizione piazzali di rifugio	NO					
ISE, TLC, ENE	ISE, TLC, ENE	Ponte/Viadot/Cavalcav/Sottopas/Sottovia	Elemento spaziale	S30650_0060	Luce retta [m]	NO					
...	...	...	...	...	...	...					

Example of Annex A

Railway Sector	Class	Class Group	Type of BIM Objects	Category of Type	Notes
...	...	...	...	...	...
ISE, TLC, ENE, ARM, OPC	S03000	IELAV	Località ferroviaria	Elemento spaziale	Elemento di struttura spaziale
ISE, TLC, ENE, ARM, OPC	S13000	IELAV	Tratta ferroviaria	Elemento spaziale	Elemento di struttura spaziale
ISE, TLC, ENE, ARM, OPC	S16000	IELAV	Binari di corsa	Elemento spaziale	IfcRailwayPartTypeEum.TRACKPANEL
ISE, TLC, ENE, ARM, OPC	S16100	IELAV	Binari non di corsa	Elemento spaziale	IfcRailwayPartTypeEum.TRACKPANEL
ISE, TLC, ENE	S20600	LAVOC	Fabbricato	Elemento spaziale	Elemento di struttura spaziale
ISE, TLC, ENE, ARM, OPC	S22050	IELAV	Deviatoio	Assemblato 3D	
ENE	S22100	IETE	Scambio aereo	Elemento 3D	
ISE, TLC, ENE	S22250	IEIS	Manovra deviatoio	Assemblato 3D	
ENE	S22650	IETE	Regolazione automatica	Gruppo	Sistema
ARM	S22700	LAVAR	Segmento di rotaia	Gruppo	Gruppo generico. Raggruppa gli Oggetti 3D utilizzati per modellare la massicciata
ISE, TLC, ENE	S22900	IEIS	Segnale Ferroviario	Assemblato 3D	Collegato ai punti informative SSC/SCMT da una relazione del tipo "veicola la stessa informazione di"
ARM	S23150	LAVAR	Segmento di Traverse	Gruppo	Gruppo generico. Raggruppa Oggetti 3D (da Tipologici di support) quali traverse
ISE, TLC, ENE	S24800	LAVOC	Cisterna Gasolio	Elemento 3D	O Assemblato 3D
ISE, TLC, ENE	S24850	IEIS	Cassa di manovra PL – Passaggio a livello	Elemento 3D	O Assemblato 3D
...	...	...	...	...	...

Figure 3.2 - Example of C.I. Annexes.

Annex B, on the other hand, concerns the coding of those typologies through the knowledge and location of the assets and all external elements related to the railway infrastructure, which are fundamental for the management of financial investment in safety, maintenance, and so on. The assets themselves concern the components that make up the railway (the track, signal, etc.), whereas the external assets are owned by third parties, and generally consist of overpasses, crossing points of overhead lines, and elements that involve the territorial conditions that may affect the infrastructure, such as landslide slopes and areas of possible flooding. All these things are cataloged and located in the InRete2000 system, a platform that allows technicians to manage the objects registered within the related database with specific census data and standard specifications of the asset in question. It is used by the RFI partner on the project for the management of activities, including but not limited to, maintenance. Assets are characterized by a unique code (called the Sede Tecnica) that allows the association and connection of position, function, or process, and which is used to represent a system, a part of it, or a collection of logically groupable pieces of rail equipment. The levels of the codes of the census structure allow hierarchical identification of the composition and structure of individual pieces of rail equipment as they undergo various processes (e.g., maintenance). These Sedi Tecniche, which are geographically localized objects, are used for the census of assets according to a census reference structure, which, below each initial level, presents a tree structure with a hierarchy that can reach up to the seventh level of association. Knowledge of this structure must begin from the analysis of the second levels, which identify significantly relevant subsystems or parts of the infrastructure. The levels below the second represent objects that can be logically grouped below them. Some Sedi Tecniche function as "containers" of similar underlying objects, whereas others function as "aggregators" of several different objects. Annex C defines the requirements given the specific LOIN (Level of Information Need, following EU UNI 17412-1), with geometric specifications, such as positioning, as well as other information regarding the evaluation of certain expected specifications (see Figure 3.2). Meanwhile, Annex D contains the rules and admissible values for the specifications related to the context and the maintenance management systems (e.g., InRete2000) analyzed for each type of asset. In defining the requirements, it also took into account the system used by EAV (i.e., LINFE), the other partner on the project, to maintain the railway infrastructure, as well as the management of entities relating to the railway infrastructure. Similar to the InRete2000 system defined above, LINFE offers a complete overview of the infrastructure assets related to railway superstructure, electric traction, telecommunications, and others, managing each of them through a series of digital data sheets containing individual data, maintenance data, georeferences, and other links to documents. The modeled BIM objects were consequently created in accordance with these requirements from geometric, informative, and documentation perspectives. The C.I. with its related annexes was considered an essential reference for BIM modeling and information management activities in the context under analysis. The information requirements regarding the BIM objects, and therefore the BIM models as well, were met, following the definition of the specific Level of Information Need, by deciding on an appropriate digital strategy that exploits the openBIM approach and related standards (e.g., IFC). The capabilities offered by BIM models, in an open format, allowed to satisfy these requirements (e.g., Level of Information Need), for instance through the development of specific PSets associated with the IFC classes considered for the digitalization of the railway infrastructure.

3.2.2 Organization of survey activities

The project activities took into account the extension of the entire railway infrastructure (around 47 km) in trying to define a methodological approach concerning the construction of the BIM object library, and above all, the definition of the digital infrastructural model concerning the development of the geometric, information (e.g., PropertySet), and documentation (technical documentation, diagrams, layouts, and more) components of required LOINs, for the management of operations and maintenance in the broader context of asset management. The railway infrastructure, which is currently in operation, is characterized by technical complexity due to its numerous components. Drones and an autonomous survey vehicle were used for survey activities. To carry out these activities, it was considered how railway traffic impacts the line, weather conditions (rain and wind), and accessibility to surveyed sites. The university (Federico II), through a multidisciplinary research team, dealt principally with the survey phases and used various instruments, including drones, specifically a DJI Mavic 2 Enterprise Dual. This is an easily transportable instrument, extremely light, and equipped with a high-resolution camera stabilized by a three-axis gimbal that provides digital and mechanical cushioning of the framing. Taking into account flight autonomy (around 30 min) and maximum speed (around 70 km/h), each flight was planned and defined for a given asset (areas and buildings related to railway stations and bridges) and radio-controlled from the ground (via a DJI Smart Controller). From these surveys, point clouds and textured meshes were initially obtained for the various stations, certain bridges, and viaducts. This information was used to construct the BIM object typologies and BIM information models, as well as to enrich the final federated digital model in a collaborative platform. Due to the availability of an autonomous railway vehicle (belonging to an exterior contractor appointed by the railway operator to survey track infrastructure) that was equipped with specific instrumentation (a laser scanner, GPS, and an inertial platform, among other things), it was possible to acquire videos and photos, create point clouds, and more, along the entire line (see Figure 3.3).

(**a**) (**b**)

Figure 3.3 - Surveying equipment engaged for existing condition acquisition of railway line: (a) drones; (b) autonomous railway vehicle.

This innovative system is dedicated to rail systems: its wide range of tools is placed on a single vehicle, giving a mobile rail-mapping system that involves various detection technologies, including laser scanners, georadar, thermo-graphic imaging, and a high-speed/resolution digital camera. It allows to carry out the continuous activity (average speed 15–30 km/h), acquiring information in terms of point clouds, photos, etc. These can be post-processed to obtain, as in the present case, the alignment of the infrastructure (e.g., 3D polyline), including information about the geometry of the railway track and sections, as well as other information. All the collected data were integrated into a single collaborative environment for the management and maintenance of the infrastructure.

3.2.3 Stages of the proposed digital approach

Digital management of the entire railway infrastructure allowed to development of BIM-based procedures for the maintenance and management phases of the railway line, which were realized by means of BIM modeling of existing conditions and the integrated management of information in the context under analysis. The digitalization strategy, shown in Figure 3.4 - Definition of a digitalization strategy for existing railway infrastructure., was proposed accordingly.

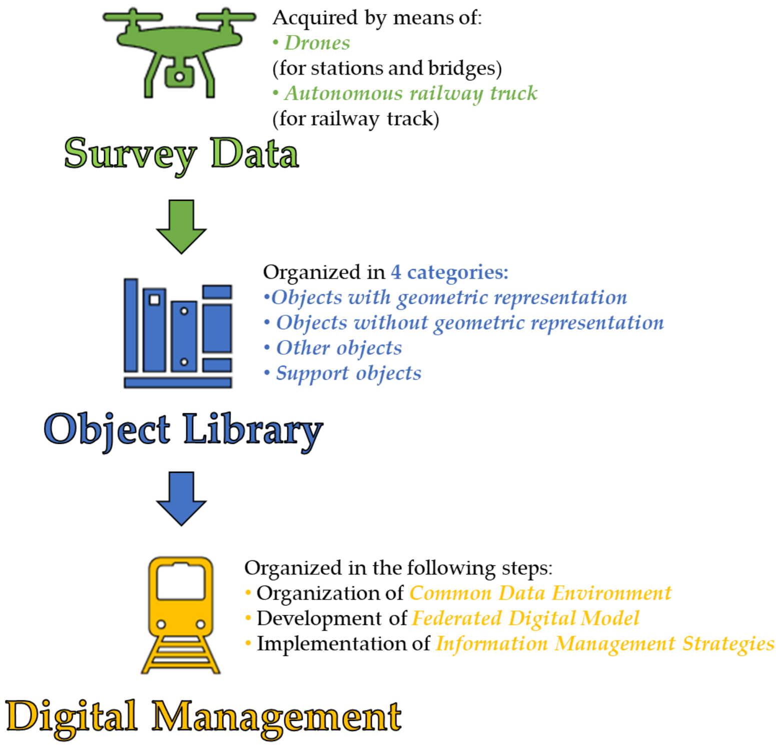


Figure 3.4 - Definition of a digitalization strategy for existing railway infrastructure.

The methodology and technical solution (developed in collaboration with ACCA Software) adopted for the construction and management of the proposed digital solution (federated BIM model) for the existing railway (around 47 km) involved the use of IFC4x2, the latest version of IFC available at the time the project activities were carried out. In this version, reference was made to the concept of alignment of linear infrastructure (IfcAlignment) and positioning of objects along the infrastructure alignment (IfcLinearPlacement). At the same time, it should be specified that regarding the concept of alignment, information is not yet completely available to the user, i.e., utilizing the BIM software currently available on the market. Therefore, to offer an operational solution to the railway company responsible for the line, but based nonetheless on the innovative concepts outlined above, and to make this alignment information available to the stakeholders, a "fictitious" model relating to alignment was created. This model is characterized by horizontal and vertical geometry and consists of specific segments with associated and defined PropertySets that convey information about the geometric path that is both planimetric (e.g., curve radius, slopes, etc.) and altimetric (e.g., levels, superelevation, etc.). For the realization of the library, various BIM object typologies (corresponding to 3D elements, groups, assemblies, etc.) were digitally reproduced, which were typical of the railway infrastructure in question, and following the information requirements that had been requested and specified (in terms of geometry, information, and documentation) in the Annexes to the C.I. Surveys and other information were then used to define a BIM objects library, in other words, generic entities represented through BIM objects. These were produced considering the use of open formats (IFC, CSV, etc.). This was proposed with the aim of allowing the owner or manager of the infrastructure to choose from among the many kinds of software that support these types of formats, without being limited to any one of them. The development of typologies (i.e., BIM objects) also involved the definition of four categories: (i) typologies with geometry; (ii) typologies without geometry; (iii) other typologies; and (iv) support typologies. The first category is characterized by a specific geometry with related information (such as PropertySet) and documents by following the requirements of the C.I. Annexes. The second category, meanwhile, does not have a reference geometry, but only takes into consideration the appropriate information, namely, PropertySet and its related properties, associated with aggregations, zones, systems, and so on, developed according to the logic or practices of maintenance and asset management following the requirements of the C.I. Annexes. The third category concerns elements that are not considered by the C.I. and its Annexes, but which have to be considered for the development of the whole digital model of the infrastructure. Finally, the support typologies are simple graphic models used to support the creation of the typologies in the previous categories. Specifically, two types of properties (associated with type object and related occurrence) were associated with each BIM object. The type object properties are covered by Annex D to the C.I., and also regard other requirements or procedures relating to the managing entity (e.g., RFI), which include various specifications associated with the elements in the model. For instance, in relation to the typology "sleeper segment", properties will refer to the type of sleeper, the number of sleepers, sleeper length, and so on. Meanwhile, the instance (or occurrence) properties are associated with all occurrences of BIM objects within the BIM model. They report information relating to the census codes of the given asset following the various maintenance management systems in question. This code refers to the generic asset that has been registered, and which has to be maintained. Some of the codes relating to the reference structure are given in Annex B and are subsequently evaluated following the logic provided by the maintenance management system (e.g., LO1336-BC-BC01-DEV for a specific BIM object related to "railway switch" typology). The PropertySets proposed here have been developed to transmit information and create a correspondence with the maintenance management systems (InRete2000 for RFI and LINFE for EAV). This information constitutes a sort of "information bridge or link" between the ERP systems used for maintenance management. With the approach taken in the future by openCDEs, it may be possible to automate the updating of values taken directly from the designated systems (e.g., ERP platforms) concerning the properties defined within the BIM models and related objects. An example of these properties, regarding the "railway signal" typology, is given in Table 3.1 and Table 3.2. So far, as the construction of the digital model of the infrastructure is concerned, individual disciplinary models were developed (railway superstructure, civil engineering works, signaling, etc.), as well as sub-models (such as rails, sleepers, etc.) and other subdivisions following the census and maintenance logics, and aimed at defining information management strategies.

In sum, this project is an application of openBIM to the O&M (operation and maintenance) phases of the railway asset lifecycle. In this scenario, the proposed solution was implemented in a real case of an existing operational railway. Successively, this application also allowed making important considerations in the context of asset management, evaluating the real financial and operational value of infrastructure to define possible investments necessary to make the infrastructure compliant with RFI standards. All this was supported by the creation of a specific CDE organized into several folders, each of which was given specific permissions and workflows. This CDE, created within the collaborative environment used for the project (usBIM.platform), was where the owner of the railway and all the other participants in the project could collaborate through the use of workflows organized to keep track of overall progress with the allotted time, following the process map shown in Figure 3.5.

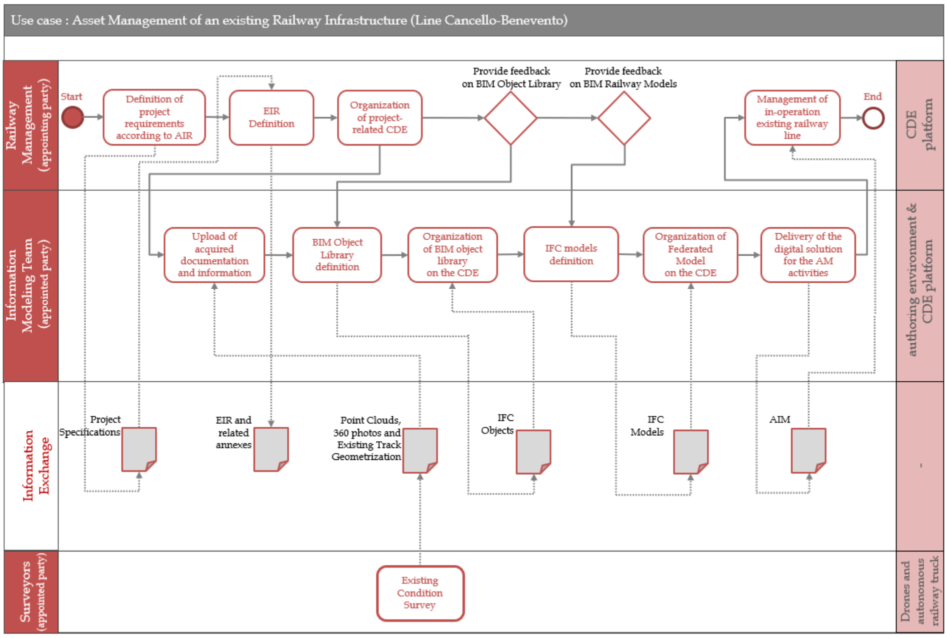


Figure 3.5 - Process map related to the pilot project activities

In order to capture existing conditions, the railway infrastructure manager commissioned various actors (among them the University of Naples and an outside contractor) to survey the railway, as well as some bridges, tunnels, and stations belonging to it. As anticipated, this allowed obtaining a series of images, point clouds, and textured meshes, among other things. One of the outputs of the survey phase was the geometrization of the railway track. This was loaded into the CDE environment, and this information, which related to the track and other assets along the line, provided the input for the BIM modelers to realize BIM models and create the library of BIM objects. For each object, a specific geometric representation was provided, along with other information requested by the railway specialists, and was transmitted via properties, for example. The object library was subsequently uploaded to the CDE as well, with the goal of being reused for future projects. This, together with the geometrization of the existing track, gave the inputs for the modeling of the railway line using a specific tool developed for the project (i.e., usBIM.IFCinfra). The IfcAlignment and IfcLinearPlacement concepts, which are typical of the linear infrastructure domain, were used to create the alignment and position of the railway objects (e.g., signals) along it. The models approved by the railway specialists were subsequently uploaded to the CDE along with the point clouds, 360-degree photos, and all relevant documentation (technical reports, maintenance forms, layouts, etc.), to obtain a single federation of all available information referenced in the IFC models. In addition, the various typologies were associated, as anticipated, with properties that play a central role in asset management and integration with the existing maintenance management systems of the railway owner (e.g., ERP platforms). Finally, the results of the project gave the input for the (real) management workflows of the existing railway infrastructure. The railway owner was therefore able to test the accuracy of the modeling activities that had been obtained from surveys and the geometrization of the track; just as important, however, was that an entire process had been developed for carrying out the project activities. Various actors with specific skills collaborated to achieve the project objectives. The railway experts, appointed by the railway operator, defined the requirements and levels of information necessary for the various assets under consideration. The BIM modelers, meanwhile, used tools and technologies for infrastructure modeling and considered concepts such as IfcAlignment for modeling the railway track, IfcLinearPlacement for positioning objects along the track, and IfcSweptAreaSolid to extrude solids along the railway track. The BIM modelers also complied with the requirements and relevant LOIN.

3.2.4 Software ecosystem considered for project activities

A specific solution was developed to support the project activities in collaboration with the software provider (ACCA Software). It was possible to build the digital model of the railway structure by modeling the BIM object typologies with BIM-authoring software (e.g., Edificius). Specifically, a non-commercial version (in development yet), related to infrastructure BIM modeling, was used. This had been made available by the software provider for the purposes of the project. Its integration with other tools (e.g., Blender and SketchUp) was also exploited for the geometric modeling of complex parts. Furthermore, it emerged during the project that BIM-authoring tools alone are insufficient for managing all the information relating to the railway infrastructure (approximately 47 km). Consequently, it was necessary to use collaborative platforms for the integrated and federated management of all BIM models and other information relating to the infrastructure. This solution can also be applied operationally to other existing railway lines managed by the railway operator. To address and manage the complexity of these activities, it was developed, in collaboration with ACCA Software (a company active in the development of openBIM-related software), a solution that was tailor-made for the aims of the project. This consisted of the creation of usBIM.IFCinfra. This tool made it possible to manage the modeling of infrastructure (railway superstructure, electric traction, etc.) by providing as input (through the development of databases, such as Excel sheets) information relating to the railway infrastructure (e.g., positions of elements such as poles, ports, and signals), as shown in Figure 3.6.

Punto	Progressiva	Posizione PALO	PALO	BRACCIO	MENSOLA	Osservazioni	Nuvola	Abbassar	Regolazione	Nome TIPOLOGICO SKP
112	5504,29	DX	M	B2/A1-B1	Singola + Singola	B doppia + AB singola	49		Sì	Palo M__Mensola Singola + Singola__Braccio B2/A1-B1
114	5553,32	DX	M	A2/A1-B1	Singola + Doppia	A doppia + AB singola	50	-0,10	Sì	Palo M__Mensola Singola + Doppia__Braccio A2/A1-B1
117	5592,30	DX	M	B2/B1	Singola + Singola	B doppia + B singola	50	-0,10		Palo M__Mensola Singola + Singola__Braccio B2/B1
119	5642,08	DX	M	A2/A1-A1	Singola + Tripla	A doppia + AA singola	51	-0,10		Palo M__Mensola Singola + Tripla__Braccio A2/A1-A1
121	5695,28	DX	M	B2/B1	Singola + Singola	B doppia + B singola	51	-0,10		Palo M__Mensola Singola + Singola__Braccio B2/B1
123	5737,04	DX	M	A2/B1	Singola + Singola	A doppia + B singola	52	-0,10		Palo M__Mensola Singola + Singola__Braccio A2/B1
125	5772,19	SX	M	A2-B1	Doppia		52			Palo M__Mensola Doppia__Braccio A2-B1
186	8093,58	DX	M	B1-A2	Doppia	A singola + B doppia	76	-0,01		Palo M__Mensola Doppia__Braccio B1-A2
188	8141,62	SX	M	B1/A2-B1	Singola + Doppia	B singola + A doppia + B singola	76	-0,10		Palo M__Mensola Singola + Doppia__Braccio B1/A2-B1
190	8199,51	SX	M	A1/B2-B1	Singola + Doppia	A singola + B doppia + B singola	77	-0,10		Palo M__Mensola Singola + Doppia__Braccio A1/B2-B1
192	8258,58	SX	M	A1-B1/A2-A1	Doppia + Doppia	AB singola + A doppia + A singola	77	-0,10		Palo M__Mensola Doppia + Doppia__Braccio A1-B1/A2-A1
194	8312,32	SX	M	A1-A1/B2-B1	Doppia + Doppia	AA singola + B doppia + B singola	78	-0,10		Palo M__Mensola Doppia + Doppia__Braccio A1-A1/B2-B1
198	8357,78	SX	M	B1-B1/A2-B1	Doppia + Doppia	BB singola + A doppia + B singola	78			Palo M__Mensola Doppia + Doppia__Braccio B1-B1/A2-B1
199	8395,18	SX	M	A1-B1-A1-B2	Doppia	ABA singola + B doppia	79			Palo M__Mensola Doppia__Braccio A1-B1-A1-B2
494	20343,03	SX	M	A3-A3-B4	Doppia	A [C] + A[C] + B [c]	198	-0,05		Palo M__Mensola Doppia__Braccio A3-A3-B4
496	20385,03	DX	M	A3/B4	Singola + Singola	A [C] + B [c]	198	-0,10		Palo M__Mensola Singola + Singola__Braccio A3/B4
498	20427,34	DX	M	B4/B4	Singola + Singola	B [c] + B [c]	199	-0,10		Palo M__Mensola Singola + Singola__Braccio B4/B4
501	20487,46	DX	M	A3/A3	Singola + Singola	A [C] + A [C]	199	0,05		Palo M__Mensola Singola + Singola__Braccio A3/A3
503	20547,44	DX	M	B4/A3	Singola + Singola	B [c] + A [C]	200	-0,10		Palo M__Mensola Singola + Singola__Braccio B4/A3
504	20607,45	DX	M	A3/B4	Singola + Singola	A [C] + B [c]	201	-0,05		Palo M__Mensola Singola + Singola__Braccio A3/B4
506	20647,46	SX	M	A3-A3-B4	Doppia	A [C] + A[C] + B [c]	201	-0,05		Palo M__Mensola Doppia__Braccio A3-A3-B4
616	25844,47	SX	M	A2-A1-B1	Doppia	A doppia + AB singola	253			Palo M__Mensola Doppia__Braccio A2-A1-B1
618	25889,61	SX	M	B2-B1	Tripla	B doppia + B singola	254			Palo M__Mensola Tripla__Braccio B2-B1
620	25934,59	SX	M	A2-A2	Tripla	Doppia forca	254			Palo M__Mensola Tripla__Braccio A2-A2
622	25984,57	SX	M	B2-B1	Tripla	B doppia + B singola	254			Palo M__Mensola Tripla__Braccio B2-B1
623	26034,53	SX	M	A2-A1	Tripla	A doppia + A singola	255			Palo M__Mensola Tripla__Braccio A2-A1
624	26084,38	SX	M	B2-B1	Tripla	B doppia + B singola	255			Palo M__Mensola Tripla__Braccio B2-B1
625	26124,44	SX	M	B2-B1	Doppia	B doppia + B singola	256			Palo M__Mensola Doppia__Braccio B2-B1
694	29164,88	DX	M	A2/A1-B1	Singola + Singola	A doppia + AB singola	286	-0,20		Palo M__Mensola Singola + Singola__Braccio A2/A1-B1
696	29207,97	DX	M	B2/B1-B1	Singola + Doppia	B doppia + BB singola	287	-0,10		Palo M__Mensola Singola + Doppia__Braccio B2/B1-B1
698	29251,34	DX	M	A2/A1-B1	Singola + Tripla	A doppia + AB singola	287	-0,10		Palo M__Mensola Singola + Tripla__Braccio A2/A1-B1
700	29295,45	DX	M	B2/B1-B1	Singola + Tripla	B doppia + BB singola	288	-0,10		Palo M__Mensola Singola + Tripla__Braccio B2/B1-B1

Figure 3.6 - Example of input (e.g. Excel sheets) for modeling activities related to the positioning of some BIM objects (e.g. poles).

The tool that was created thus made it possible to produce a state-of-the-art model based on the modeling techniques of the IFC specifications, such as the use of alignment and the positioning of various BIM objects along the line. This tool implements IfcLinearPlacement, which defines the positioning and direction of the axes of the coordinate system for objects by referring to a curve, for instance, IfcAlignmentCurve. The implementation of IfcLinearPlacement ensures that the positioning of objects along the railway line (IfcAlignment) is organized, with the reference information given in terms of kilometers and the relative offsets of the objects in question. More precisely, a positioning function was used, using specific algorithms, in which each object was characterized by three pieces of information: longitudinal distance, vertical offset, and lateral distance from this. Indeed, based on specific inputs (e.g., Excel datasheets) characterized by specific information (e.g., kilometers, vertical, and horizontal offsets, orientation, and object type), these algorithms allowed us—among other things—to automate the positioning along the infrastructure alignment of specific and recurring BIM objects, such as poles and railway signals, thereby avoiding the manual positioning of single objects within a single BIM model. The various BIM objects (occurrences of the objects proposed by the library) were positioned accordingly.

Table 3.1 - Example of defined type object properties concerning the "railway signal" typology.

PSet Name	Property Name	Property IFC Type
Caratteristiche_S22900	Tipo segnale	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Costruttore segnale	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	n. luci	IfcPropertySingleValueIfcInteger
Caratteristiche_S22900	Funzione del segnale	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Ripetitore di partenza	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Segnale sussidiario partenza	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Indicatore alto di partenza	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Segnale attenzione	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	n. indicatori bassi di partenza	IfcPropertySingleValueIfcInteger
Caratteristiche_S22900	Prima ctg. Con avv. Accoppiato	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Posa segnale	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Galleria	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Visibilità segnale	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Aspetti	IfcPropertySingleValueIfcText
Caratteristiche_S22900	Permissività	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Installazione segnale	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Segnale di avvio	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Segnale di avanzamento	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Segnale prosecuz. Itinerario	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Lettera A	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Lettera C	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Lettera D	IfcPropertySingleValueIfcLabel

Caratteristiche_S22900	Lettera T	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Lettera P	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Indicatore di direzione	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Rappel	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Tabella triangolare	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Freccia indicatrice	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	Tavole di orientamento	IfcPropertySingleValueIfcLabel
Caratteristiche_S22900	n. segnali ausiliari luminosi	IfcPropertySingleValueIfcInteger
DatiBase	Codice SeTe provvisorio	IfcPropertySingleValueIfcText
DatiBase	Codice SeTe definitivo	IfcPropertySingleValueIfcText
DatiBase	Inizio progressiva km	IfcPropertySingleValueIfcText
DatiBase	Fine progressiva km	IfcPropertySingleValueIfcText
S22900_DatiTipologico	ID	IfcPropertySingleValueIfcText
S22900_DatiTipologico	Nome	IfcPropertySingleValueIfcText
S22900_DatiTipologico	Nome in inglese	IfcPropertySingleValueIfcText
S22900_Tipo1_DatiTipologico	ID	IfcPropertySingleValueIfcText
S22900_Tipo1_DatiTipologico	Nome	IfcPropertySingleValueIfcText

Table 3.2 - Example of defined occurrence properties with regard to the "railway signal" typology.

PSet Name	Property Name	Property IFC Type
SistemaGestioneManutenzione	IDLinfe	IfcPropertySingleValueIfcText
SistemaGestioneManutenzione	CodiceCensimentoInRete	IfcPropertySingleValueIfcText

The alignment that was obtained (also in landXML format) and the object library were useful inputs for the BIM modeling phases of both the components and the railway infrastructure. Using the survey data that had been obtained (such as point clouds), tags or flags were defined to highlight the specific coordinates relating to the positioning of a given object. The BIM models of the infrastructure were created in accordance with a modeling plan developed for the project (e.g., a subdivision of the line into about 21 IFC models). For the modeling of some infrastructural components (such as rails, ballast, and tunnels), another important concept was IfcSweptAreaSolid, which could be used to extrude the profiles of the elements considered along the alignment through its implementation in usBIM.infra. Once the individual IFC models of the planned infrastructural parts had been obtained—with these created starting from the alignment as a common reference, which was previously uploaded to the used software—they were then uploaded to usBIM.platform (the collaborative platform for the management and coordination of project workflows), where they were federated together with point clouds, 360-degree photos, textured meshes, and all other information (alphanumeric and documentary) available. Thus, a single federation of the railway infrastructure model was produced to ensure the secure storage of information and avoid its dispersion over time. Examples of digital management, selected from the federation in question, and regarding certain stations, overpasses, tunnels, and railway superstructures along the line, are given in Figure 3.7.

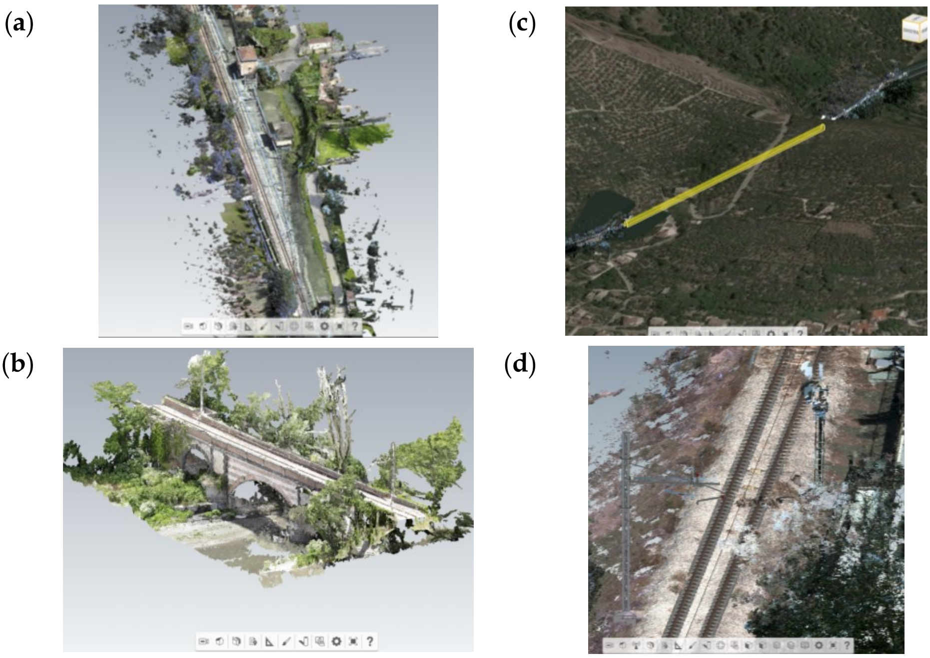


Figure 3.7 - Examples of digital management of the railway infrastructure in question (Cancello–Benevento line) for (a) stations; (b) bridges (c) tunnels; and (d) railway superstructure along the line.

The various IFC models that were created, regarding the various disciplines being considered, and associated with PropertySets useful for the management of maintenance, make possible connections and correspondence between the elements to be maintained, which is managed through a maintenance management system (e.g., InRete2000 or LINFE). This solution, which began with a survey of existing conditions, can be used for the operation and management of maintenance, or financial evaluations in the wider context of asset management. Since the BIM objects proposed by the library are obtained beginning with an analysis of the specific needs of the given context, the related properties also have the purpose of providing information as a part of asset management, and integrating maintenance management systems (e.g., ERP platforms). This information will then be handled by railway specialists in the relevant maintenance sector. The solution was conceived entirely in openBIM, and thus involves the use of open formats and procedures (principally based on IFC). The software ecosystem is described in Figure 3.8. At the same time, other software and tools were used (e.g. Revit). In addition, the project involved the use of the semantics (e.g., classes) offered by the version used, namely IFC4x2, the latest available at the time of the project. This has obviously limits and deficiencies, mainly from a semantics point of view, which will certainly be improved by the next IFC version (probably IFC4x3), which will also integrate the developments made in the IfcRAIL project. This will enable more accurate IFC mapping of various railway elements (rail equipment, electric traction, signals, etc.), as well as specifications of the spatial structures most relevant to infrastructure.

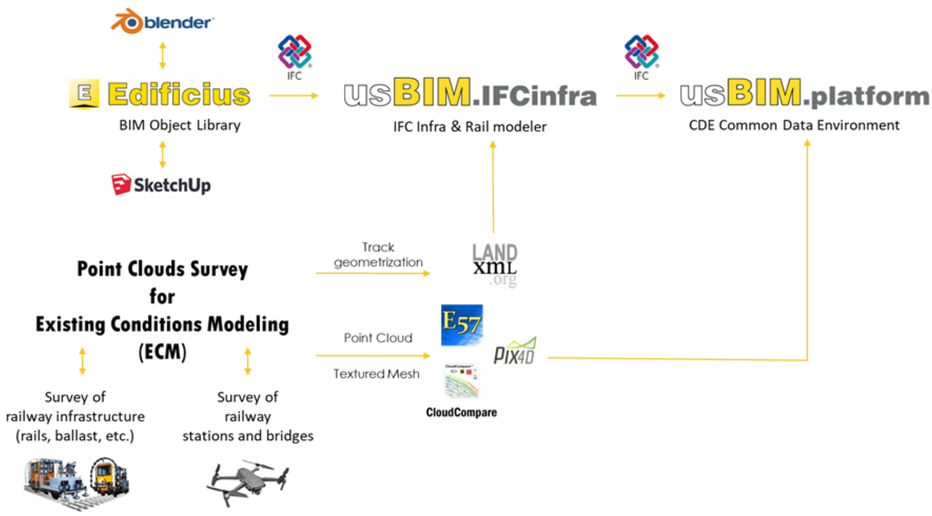


Figure 3.8 - Software ecosystem considered for the digital management of the railway infrastructure.

3.3 Results

In the context of the pilot project, the selected case study considers an existing railway line that consists of a simple track that extends around 47 km (see Figure 3.9). This line includes 12 stations, the first of which is "Cancello", and the last

“Benevento”. These two are under the management of RFI, whereas all those in between are managed by EAV.

a) b)

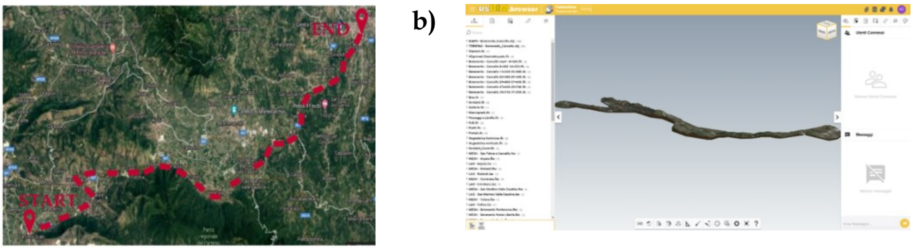
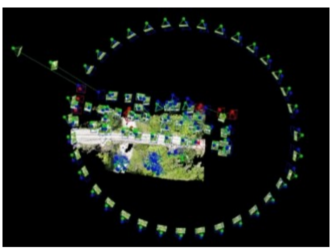


Figure 3.9 - The railway infrastructure considered for the project activities (Cancello–Benevento line): (a) geographical context; and (b) federated digital model managed in the collaborative platform.

From an infrastructural perspective, the single-track line is characterized by a standard railway gauge (1435 mm) with different kinds of sleepers (single block, bi-block) made from various materials (wood, concrete, etc.). The rails along the entire line are of the 50 UNI type. The railway superstructure consists primarily of continuously welded rails, specific ballast crushed stone, and sleepers spaced at around 60 cm apart. There are also two types of switch boxes (Westinghouse M4 and FS L88). Furthermore, along the railway line, there are around 56 level crossings (protected and unprotected by barriers) and 15 viaducts, overpasses, and steel bridges with spans greater than or equal to 3 m. There are six tunnels, of which two are shorter than 40 m, three are shorter than 500 m, and one is 816 m long. Regarding electric traction, the contact line generally consists of a fixed 120 mm^2 supporting cable and two 100 mm^2 contact wires adjusted with a specific pull, giving a total cross-section of 320 mm^2, except for certain sections in which the overall cross-section is 220 mm^2. The majority of the poles along the line are type LSF, except in certain sections where they are type M (Mannesmann). All the stations along the line are delimited from an electrical perspective by TE portals. In the case of signaling, however, the distancing of trains from one station to another still takes place via telephone block.

As part of this project, it was possible to exchange information between the various organizations and actors involved through openBIM, thus meeting requirements such as interoperability. This was also possible due to the organization of a CDE on the platform that was used (i.e. usBIM.platform), where all the information (BIM models and objects, documents, point clouds, textured meshes, and more) was loaded. Before this, to carry out the surveying activities, numerous images and pieces of information relating to the sites of interest were acquired. These activities were carried out through the use of drones for all the bridges and stations under consideration, along with a mobile mapping system, specifically a multidimensional mapping system with detection and positioning instrumentation, all installed on a single vehicle. This permitted the dynamic survey of the track infrastructure, as well as the acquisition of various kinds of information (e.g., geometry, structural conditions). This acquired information could subsequently be integrated into a single environment to support the maintenance, design, and management phases of the infrastructure.

Meanwhile, many drone flights were carried out to survey the stations and bridges in question, and analysis and processing of the acquired images were subsequently necessary. As described above, drones and state-of-the-art instruments were used, with photogrammetric techniques then used to determine the outputs (point clouds and textured meshes) relating to large areas of the survey targets. These also made it possible to return information based on a large number of points (i.e., point clouds), each of which had its data in terms of position and colour, all to the benefit of the quality and quantity of the information to be obtained. In addition, from these acquisitions, it was possible to extract information and measurements of all kinds, as well as to export subsequent data as dense point clouds, textured meshes, and more, concerning the various formats under consideration. The survey flights were planned through the use of certain kinds of software (e.g. Pix4DCaptur), taking care to cover the entire area being examined by selecting appropriate trajectories (circular, grid, etc.), as shown in Figure 3.10. Regarding the processing of the images obtained, which was performed with dedicated applications (e.g. Pix4D mapper), point clouds (.las format), and textured meshes (.fbx format) were both generated.



(a) **(b)**

Figure 3.10 - Data acquisition and processing considering the usage of drones in the case of a railway masonry bridge: (a) processing of the images acquired considering different drone flight strategies; (b) results in terms of point clouds.

Figure 3.11 and Figure 3.12 give examples of activities concerning the acquisition, elaboration, and definition of output (e.g. point clouds) from the surveys of, respectively, station buildings or railway stops, and some of the bridges, viaducts, and overpasses along the line.

(a) **(b)**

Figure 3.11 - Survey activity results in terms of point clouds (a) for a railway station and (b) for a railway stop.

(a) **(b)** **(c)**

Figure 3.12 - Survey activity results in terms of point clouds for two bridges (case (a) and (b)) and one overpass (case (c)) belonging to a railway line.

These data were used as inputs for the BIM modeling activity and were subsequently divided into two phases. In the first of these, the railway superstructure was modeled (sub-ballast, ballast, sleepers, rails, etc.), and this provided the reference for carrying out activities in the next phase. For instance, the BIM modeling for sleepers and rails was organized by considering the relative census and maintenance logics (e.g., sleeper segments and rail segments) implemented in the maintenance management systems under consideration. For the organization of the relevant BIM models, the correct positioning of the elements along the line was also taken into account using tags positioned within point clouds (e.g. different sections with different types of sleepers). The second phase, meanwhile, called for the insertion of the remaining typologies along the line.

Throughout the course of the project, various BIM object typology representations were created for the railway line under investigation and concerned with railway superstructure, electric traction, civil engineering works, and part of signalling and telecommunications. By virtue of this, it was possible to define and organize a library of BIM objects, as defined above, by framing the various characteristic elements of the railway infrastructure in question under the typologies called for by the C.I. (3D elements, groups, assemblies, etc.). An example of an object belonging to the first typological category, “BIM object with geometry”, with dedicated Property Sets, is shown in Figure 3.13. These properties are intended to transmit information and create a correspondence with maintenance management systems (for instance LINFE for EAV, or InRete2000 for RFI). In this case, a railway signal is shown. This approach has also been proposed for other typologies of the same category but belonging to other disciplines.

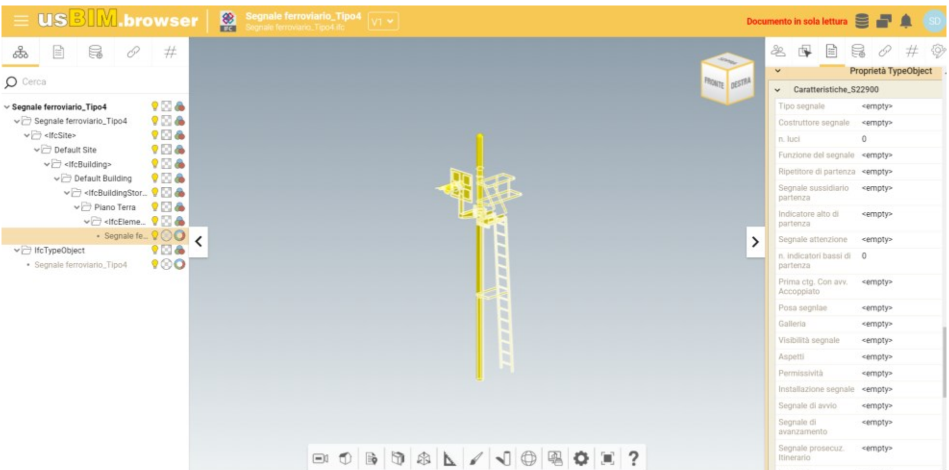
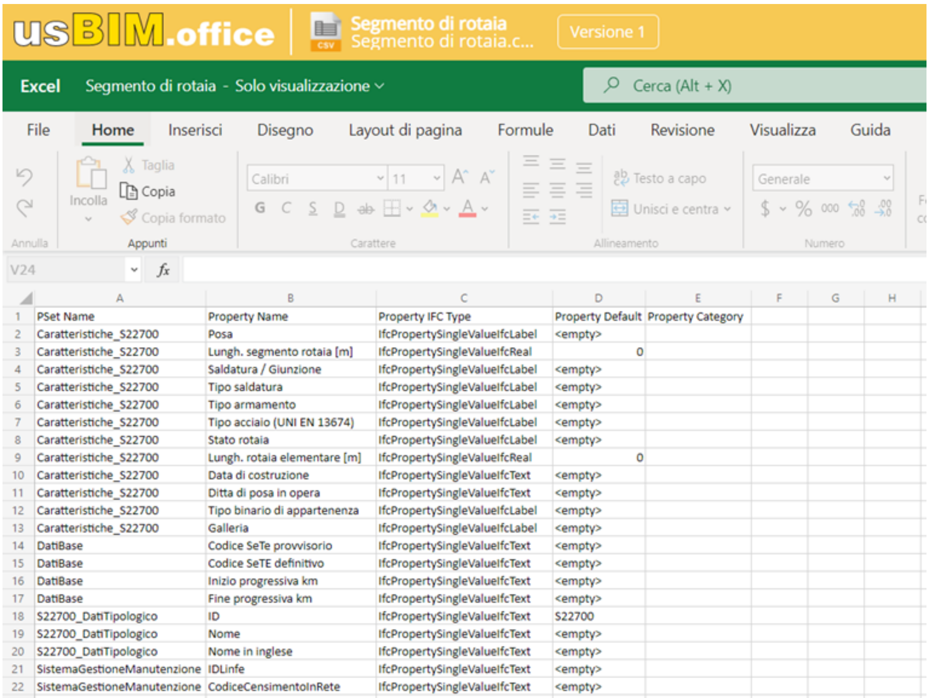


Figure 3.13 - Example of a BIM object belonging to the category “BIM object with geometry” (e.g. railway signal) and its properties.

Regarding the second category, "BIM object without geometry", since these are represented only by properties to be associated with aggregations, elements of spatial structure, zones, and systems, among other things (through IFC classes such as IfcGroup, IfcSpatialStructureElement, IfcZone, IfcSystem, etc.), a given open format (.csv format) was used for the definition and subsequent association of all the specific properties regarding the typology in question, as required by the Annexes to the C.I.. These properties were then associated with their respective entities within the BIM model of the infrastructure. Figure 3.14 shows a representative example of this category, namely, the "rail segment".



	A	B	C	D	E
1	PSet Name	Property Name	Property IFC Type	Property Default	Property Category
2	Caratteristiche_S22700	Posa	IfcPropertySingleValueIfcLabel	<empty>	
3	Caratteristiche_S22700	Lungh. segmento rotaia [m]	IfcPropertySingleValueIfcReal	0	
4	Caratteristiche_S22700	Saldatura / Giunzione	IfcPropertySingleValueIfcLabel	<empty>	
5	Caratteristiche_S22700	Tipo saldatura	IfcPropertySingleValueIfcLabel	<empty>	
6	Caratteristiche_S22700	Tipo armamento	IfcPropertySingleValueIfcLabel	<empty>	
7	Caratteristiche_S22700	Tipo acciaio (UNI EN 13674)	IfcPropertySingleValueIfcLabel	<empty>	
8	Caratteristiche_S22700	Stato rotaia	IfcPropertySingleValueIfcLabel	<empty>	
9	Caratteristiche_S22700	Lungh. rotaia elementare [m]	IfcPropertySingleValueIfcReal	0	
10	Caratteristiche_S22700	Data di costruzione	IfcPropertySingleValueIfcText	<empty>	
11	Caratteristiche_S22700	Ditta di posa in opera	IfcPropertySingleValueIfcText	<empty>	
12	Caratteristiche_S22700	Tipo binario di appartenenza	IfcPropertySingleValueIfcLabel	<empty>	
13	Caratteristiche_S22700	Galleria	IfcPropertySingleValueIfcLabel	<empty>	
14	DatiBase	Codice SeTe provvisorio	IfcPropertySingleValueIfcText	<empty>	
15	DatiBase	Codice SeTE definitivo	IfcPropertySingleValueIfcText	<empty>	
16	DatiBase	Inizio progressiva km	IfcPropertySingleValueIfcText	<empty>	
17	DatiBase	Fine progressiva km	IfcPropertySingleValueIfcText	<empty>	
18	S22700_DatiTipologico	ID	IfcPropertySingleValueIfcText	S22700	
19	S22700_DatiTipologico	Nome	IfcPropertySingleValueIfcText	<empty>	
20	S22700_DatiTipologico	Nome in inglese	IfcPropertySingleValueIfcText	<empty>	
21	SistemaGestioneManutenzione	IDLinfe	IfcPropertySingleValueIfcText	<empty>	
22	SistemaGestioneManutenzione	CodiceCensimentoInRete	IfcPropertySingleValueIfcText	<empty>	

Figure 3.14 - Example of a BIM object belonging to the category "BIM object without geometry" (e.g. rail segment).

This approach was also proposed for other typologies belonging to different disciplines (railway location, track segment, stations, section insulators, etc.). So far as the third category is concerned, namely "other BIM objects", Figure 3.15 gives an example of a railway portal and its associated properties:

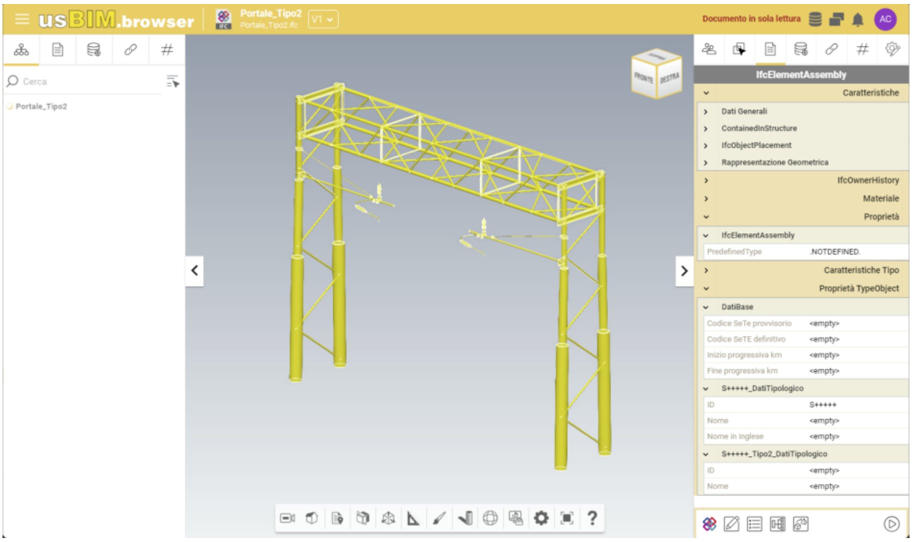
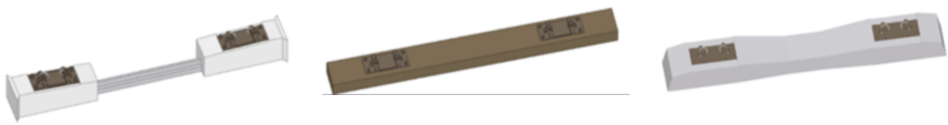


Figure 3.15 - Example of a BIM object belonging to the category "other BIM object" (e.g. railway portal) and its properties.

Finally, regarding the fourth category, "support objects", i.e. graphic objects that aid the construction of the previous categories, Figure 3.16 gives some examples (e.g., sleeper typologies).



(a) **(b)** **(c)**

Figure 3.16 - Example of a BIM object belonging to the category "support objects" (e.g. a sleeper with its types (a) bi-block (p.s.c.); (b) single-block (wood); and (c) single block (p.s.c.)).

Once the library containing the various typologies of BIM objects for the individual disciplines had been built, starting from these and the survey data, the informative models were created (around 21 IFC models). The digital model of approximately 47 km of the railway infrastructure was created using open BIM standards (principally IFC). It was possible to create a federated model through the usBIM.platform, which enabled us to combine and manage a large amount of data within the same environment (e.g., Common Data Environment), including models, point clouds, textured meshes, and documents. As mentioned above, for the development of IFC objects and models, the IFC4x2 version was considered, which made it possible, for instance, to contain alignment information within the IFC file.

Unfortunately, this information is not yet usable by users, who must extract it from the IFC file. For this reason, it was necessary to create a "fictitious" model for the alignment, to make this information available, usable, and operational to stakeholders. This solution made it possible to have 3D reference geometry (divided into various sections), to each of which specific Property Sets were associated, defining information about geometric measurements (track length, minimum height, etc.), elements themselves (curves, transitions, etc.), and all the other characteristics associated with them. Within the collaborative platform, it was also possible to update property values and documents, find any information relevant to maintenance operations, and add or federate new information (models, point clouds, etc.). This kind of approach was developed with the aim of later making this management solution integrated and interdisciplinary, through the future technology of "open CDEs", thus promoting interoperability and connection between the various systems involved (BIM-authoring, collaborative platforms, ERP systems, etc.). The project's entire process was coordinated by project managers appointed by the railway owner, who were monitored directly within the BIM environment, where the workflow functionalities were used to assign tasks and requirements to the various participants following established deadlines. For the linear positioning of the objects regarding alignment, as required by IFC standards, and now using IfcLinearPlacement, there is a need to refer and position individual objects according to the alignment with respect to a triad of axes (x, y, z) concerning the IfcLocalPlacement concept. Given this requirement, it was necessary to pass from one reference system to another, namely from the data obtained as absolute coordinates (X, Y, Z) to the information in the relevant system (s, x, y), where s indicates the longitudinal distance from the start of the alignment, and x indicates the lateral offset, and y the vertical offset of the point being considered. Figure 3.17 shows the digital solution adopted for alignment. The geometrized track was modeled as a three-dimensional BIM object with its respective associated properties (representative of certain information such as initial radius, transition type, and section length).

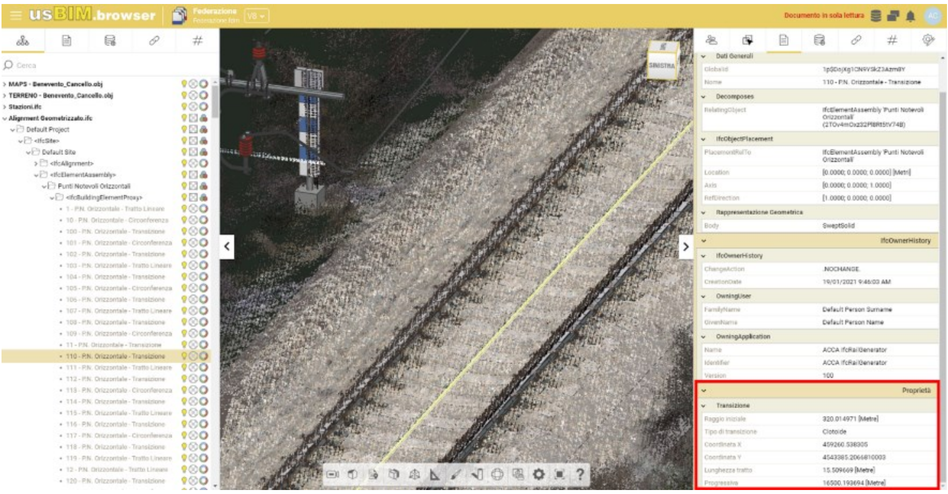


Figure 3.17 - Example of BIM model for an alignment segment with specific properties.

Regarding the construction and organization of BIM models, on the other hand, the IfcGroup class was widely used, as well as the subclasses of IfcElement (IfcZone, IfcSystem, etc.). For the structuring of the BIM models concerning the census logic, various groups of objects were organized. These groups reflect the relative organization of the assets that had been censused, and which would therefore be maintained in the management system (e.g. InRete2000 or LINFE) used by the owner or operator of the infrastructure in question. An example relating to some instantiated BIM object typologies (e.g. “rail segment”, “sleeper segment”) along with their relative properties is shown in Figure 3.18.

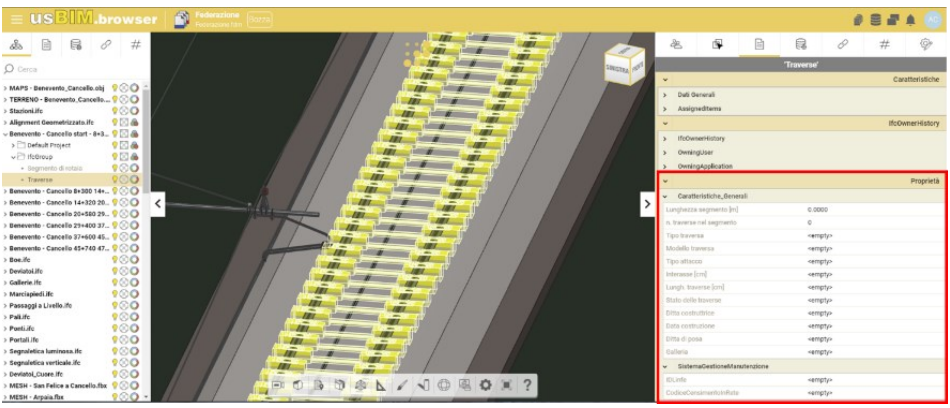


Figure 3.18 - Example of using the IfcGroup concept with specific properties.

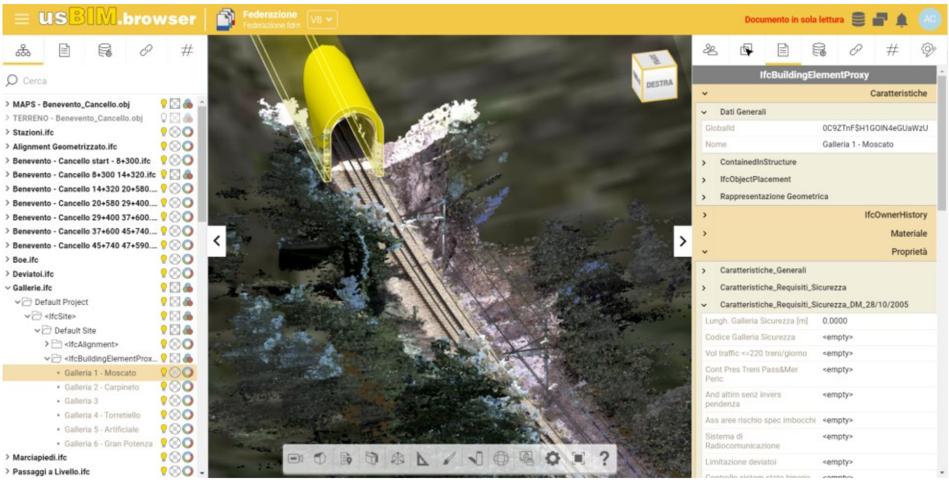


Figure 3.19 - Example of a federated view regarding a tunnel along the line (IFC models with specific PSets, point clouds, etc.).

Figure 3.19 instead gives an example of a federated view of various digitalized assets, with the tunnel, railway superstructure, electric traction, and surrounding environment represented through IFC models, point clouds, and textured meshes that are all usable within the CDE on the platform. Each type of asset present along the line is also associated with specific PSet and relative properties (e.g. regarding certain characteristics such as length, type, material, and so on).

The digitization strategy proposed for the existing assets was also applied to the bridges present along the railway line under consideration, taking into account the management scenario relative to the stakeholders involved. Indeed, regarding what was done for an existing masonry arch bridge, neither the BIM model nor any sort of digital information was available originally. The absence of design data and reference documents to support the BIM modeling and digital management phases of the work required the application of "SCAN to BIM" procedures to acquire the missing information. For the realization of the informative model, as will be described below, a series of tasks were carried out using different solutions (see *Figure* 3.20).

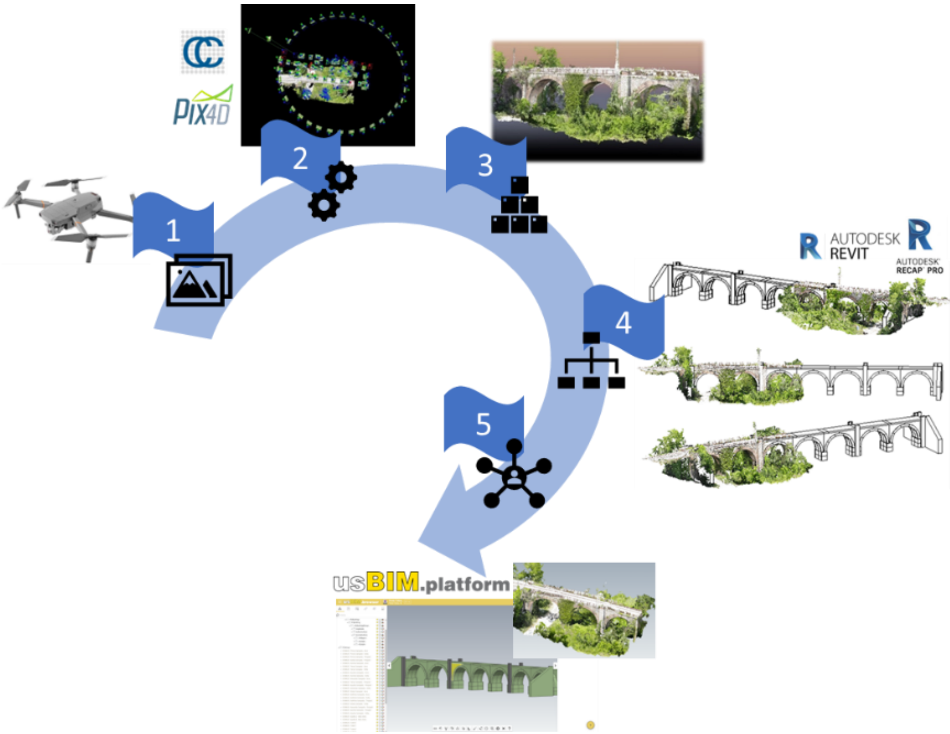


Figure 3.20 - Steps for producing information on the digitization of the masonry bridge under consideration.

The first operation carried out was the acquisition of data through the use of specific tools such as drones and tablets (point 1 in Figure 3.20). Using a drone, flight missions - subsequently transmitted to the drone itself - were planned to ensure an optimal result in terms of accuracy, consistency of the result obtained, and coverage of the entire surveyed area. Furthermore, it was ensured that the images were taken from different points of view and that some frames were sufficiently overlapped. Depending on the ground morphology and the characteristics of the targets to be surveyed, belonging to the masonry arch bridge, two types of flight were planned: one with a circular path and another with a grid path (see Figure below). Afterward, from the first processing of acquired data (point 2 in Figure 3.20), some results showed several issues (including wrong overlaps, errors, voids, and so on).

a)

b)

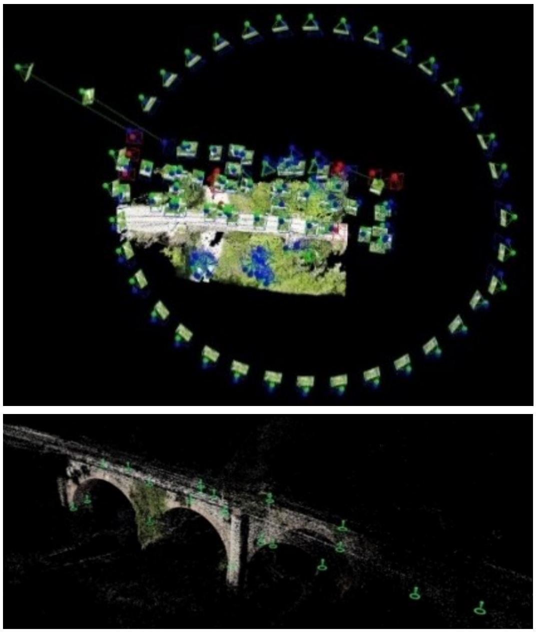


Figure 3.21 - Planning of the flight strategy of the drone (case a); and insertion of the "Tie Points" for the elaboration of the acquired information (case b).

These required the implementation of some technical specifications (e.g. Manual Tie Point) in the software used (e.g. Pix4D) and, where it was not possible to fly with the drone, the acquisition of additional images by using tablets. An instance of the results of the image processing activity (point 3 in Figure 3.20), in terms of point clouds (also obtained as textured meshes), is shown in the following figure:

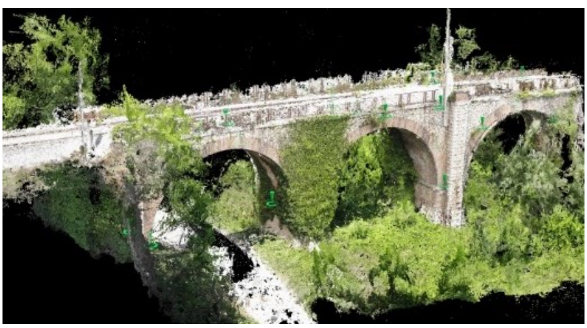


Figure 3.22 - Point cloud generation (e.g. through Manual Tie Point insertion) from image processing.

The next step, involving the import of the point cloud into the BIM modeling software (e.g. Revit), enabled the modeling and production of the informative model and related parametric BIM objects (point 4 in Figure 3.20) concerning the bridge under consideration (e.g. arch, pier, abutment, etc.). The file (e.g. in .las format) was first imported into dedicated software (e.g. RecapPRO) in order to edit some aspects of the acquired scans. The creation of BIM models was then carried out in the BIM-authoring software (e.g. Revit). The organization of the geometrical aspects took place considering the logic of decomposition of the asset according to the references considered (e.g. DOMUS and InRete2000 systems).

Figure 3.23 - BIM modeling (using Revit software) starting from the point cloud.

To achieve the pre-established project goals, the characteristics of the bridge structure were analyzed, proceeding to the organization of the BIM model following the aggregations or decompositions of the reference structural components following the context analyzed (DOMUS, InRete2000, etc.). Accordingly, it was necessary to decompose the bridge structure into its parts for an easier and more unambiguous association of the data relative to the condition of every single component of the bridge to the relative BIM model and its objects. In addition, a series of metadata were associated and referenced to BIM models, also through a collaborative environment, allowing for centralized management of information directly from the digital model (also in open format) through the digitization of records and other information deriving from the systems and contexts considered, both technological and regulatory.

By considering the point clouds, it was possible to provide a reliable representation of the bridge in the absence of other types of data. In this regard, the geometric model was made with a simplified level of detail and enriched, subsequently, by the other information (point 5 in Figure 3.20) via functionalities of the considered platform (e.g. usBIM.platform). The adoption of a specific information model (relating only to the structural part), provides an "access key" for the management of information relating to the registration of inspection results, the definition of bridge condition, and possible maintenance activities. The organization of the bridge BIM model consists of several main components, each of which was separately modeled and then assembled with all the others to obtain the overall structure. For example, Figure 3.24 below shows what was realized in the BIM authoring software being used:

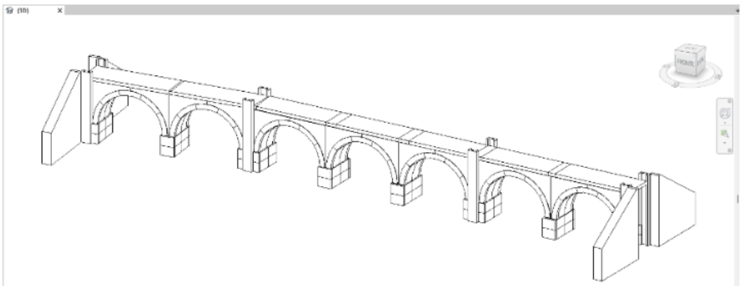


Figure 3.24 - Simplified BIM model of the bridge structure.

Depending on the structural characteristics and the material related to the superstructure, it is possible to identify the structural family to which the bridge belongs (identified by a specific alphanumeric code). Following the logic for the identification and organization of structural components with their parts, concerning the considered system (i.e. DOMUS), both the substructure and superstructure of the bridge were specified. For example, regarding the existing masonry bridge, the corresponding family is the following:

<table>
<tr><th colspan="2">Famiglia M5: Muratura – Arco in muratura con timpano chiuso</th></tr>
<tr><td rowspan="3">DESCRIZIONE:

Ponti a via superiore nei quali l'armamento ferroviario è sostenuto dall'arco in muratura. L'arcata è sostenuta dalle spalle e dalle pile. Al di sopra della volta, al fine di formare un piano percorribile, sono presenti rinfianco, cappa e riempimento contenuti lateralmente da muri longitudinali detti timpani.</td><td>COMPONENTI ORIZZONTALI:
• Arco – Scheda CO 32
• Timpano – Scheda CO 33
• Volta – Scheda CO 34</td></tr>
<tr><td>COMPONENTI PORTATI:
• Marciapiedi – Scheda CP 01
• Parapetto – Scheda CP 02
• Piazzola di rifugio – Scheda CP 03
• Soletta portata – Scheda CP 04
• Tavolato – Scheda CP 05
• Cordolo/veletta – Scheda CP 06
• Supporto strutture TE - Scheda CP 07</td></tr>
<tr><td>MECCANISMI DI COLLEGAMENTO:
• Non presenti</td></tr>
</table>

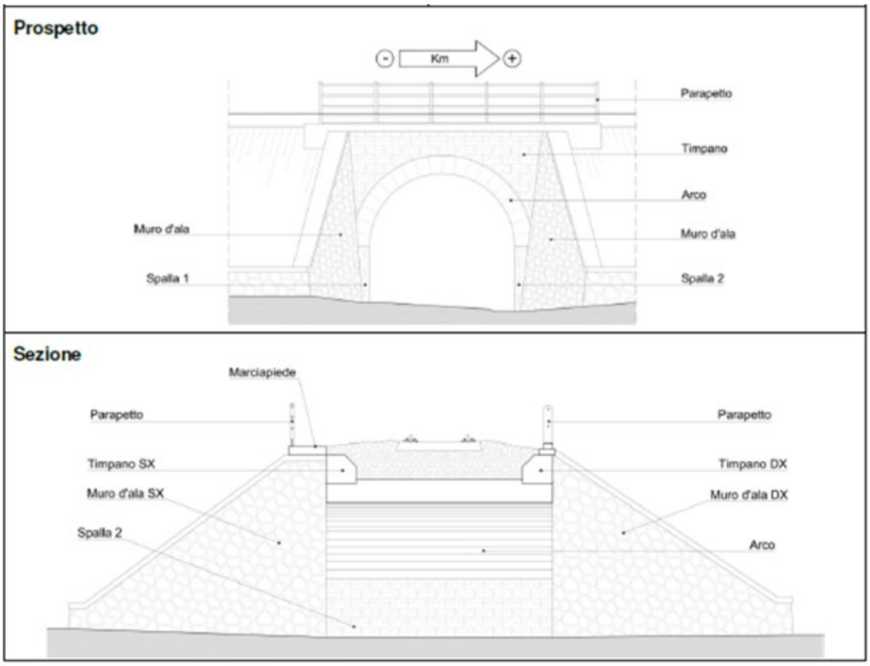
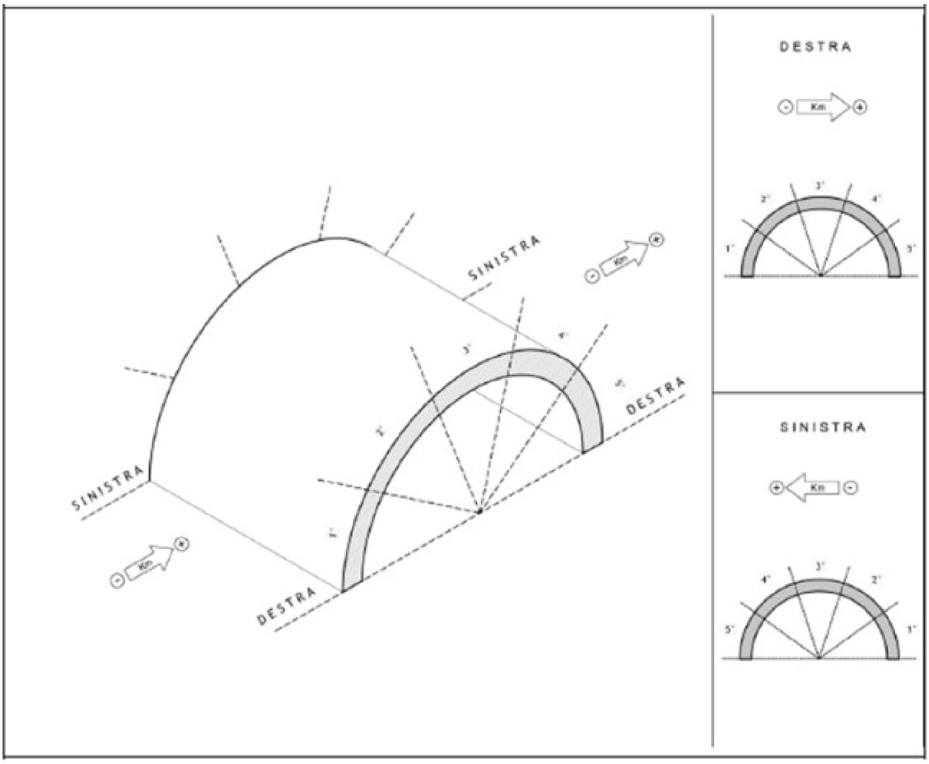


Figure 3.25 - Structural family considered for the superstructure (based on the DOMUS system).

According to what is defined by the system under consideration, the substructure may include piers and abutments, while the superstructure may belong to arches, vaults, and tympanums. In the figure below, there is a reference description (derived from the DOMUS system) for an arch with related subcomponents identified by the reference fields:



Scheda CO 32: Arco a cinque campi

DESCRIZIONE E SCOMPOSIZIONE IN CAMPI:

In DOMUS, l'arco è convenzionalmente definito come la superficie della volta visibile dal prospetto sinistro e dal prospetto destro dell'opera.
Per luci L>10 m si adotta una scomposizione longitudinale a cinque campi, individuati da piani inclinati di 36° - 72° - 108° - 144° sull'orizzontale.
Trasversalmente il componente è diviso in due parti da un piano verticale ideale parallelo alla direzione del binario tale da individuare così una parte sinistra (Sx), visibile dal prospetto sinistro, e una parte destra (**Dx**), visibile dal prospetto destro.

Figure 3.26 - Example of components and sub-components (e.g. Arch with five fields)

Regarding the structural components of the existing masonry bridge under consideration, an instance related to the overall organization can be provided in Figure 3.27:

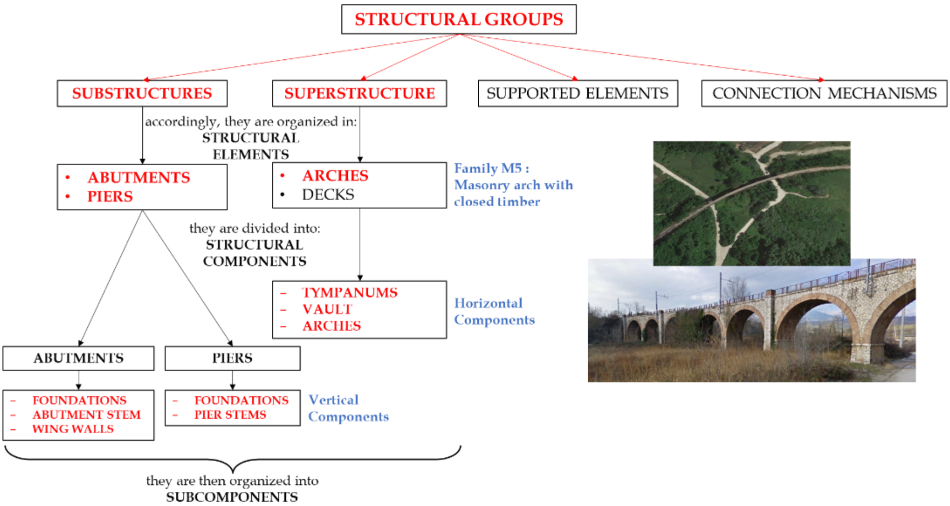


Figure 3.27 - Example of breakdown according to the logic provided by the context analyzed (i.e. DOMUS system).

To define the geometry of BIM models, data and information are organized in relation to certain reference levels identified for a bridge: (i) global structure level; (ii) aggregation level; and (iii) component level. These levels require different information from the sources considered for census and maintenance management (e.g., DOMUS, InRete2000). All structural components of the bridge were modeled, taking into account the decomposition logic for recording inspection outcomes, and associating any damage, defects or degradation found during inspection activities. This was accomplished through specific parameters (or properties) within the BIM model or digital forms linked to related BIM objects on the collaborative platform used. The property sets or digital forms will be linked to a specific component, aggregation of components or the overall structure managed on the considered CDE platform. Considering the overall structure level, the following figure shows the bridge informative model with its decomposition into fields, according to the logic provided by the context under analysis (e.g. DOMUS).

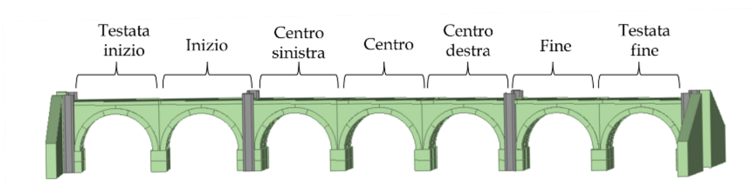


Figure 3.28- BIM model of the bridge organized according to related fields

For example, concerning structural components, five parts were modeled for arches and vaults, corresponding to the different component fields identified by inclined planes of 36° degrees each on the horizontal reference, considering the right and the left side according to the progression of the railway line (progressive kilometers), as illustrated in the following figures.

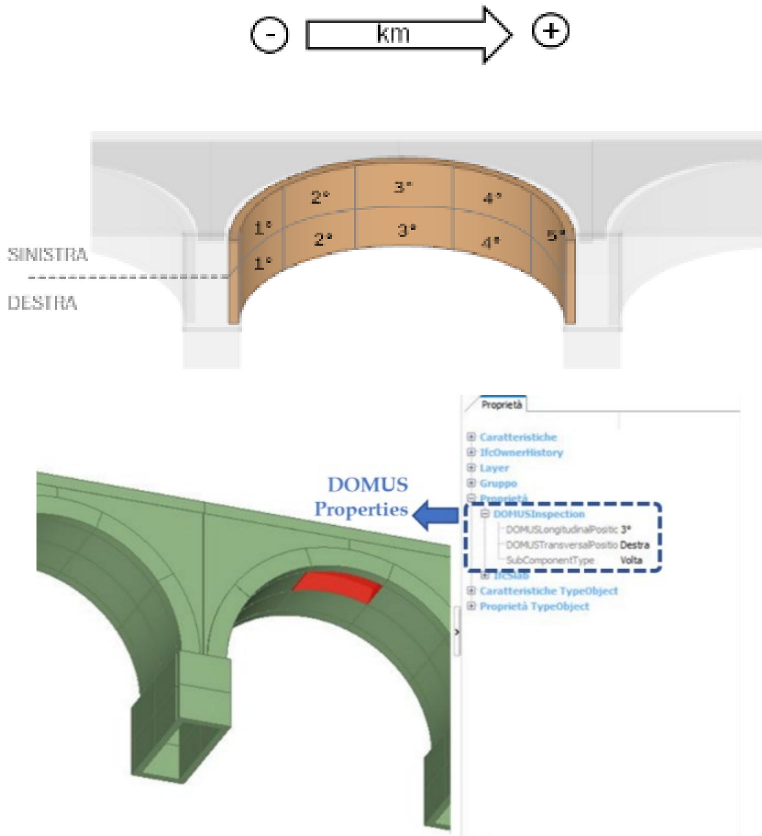


Figure 3.29 - Example of geometric organization of the BIM model (figure above) and identification of the sub-component relating to the bridge superstructure through PSets (figure below).

Within the informative model, some groups of parameters were structured to convey information related to the different levels considered, such as "DOMUS groups" and "InRete2000 groups". Through an IFC mapping phase, the digital model was exported in IFC format with a perspective of applying management based on the openBIM approach in the collaborative environment considered. Therefore, identified attribute sets correspond to the property sets associated with the relevant IFC classes (e.g. subclasses of IfcElement, IfcGroup, or IfcBuilding; in future association to the dedicated class IfcBridge is planned). The following Figure 3.30 shows an example of such implementation:

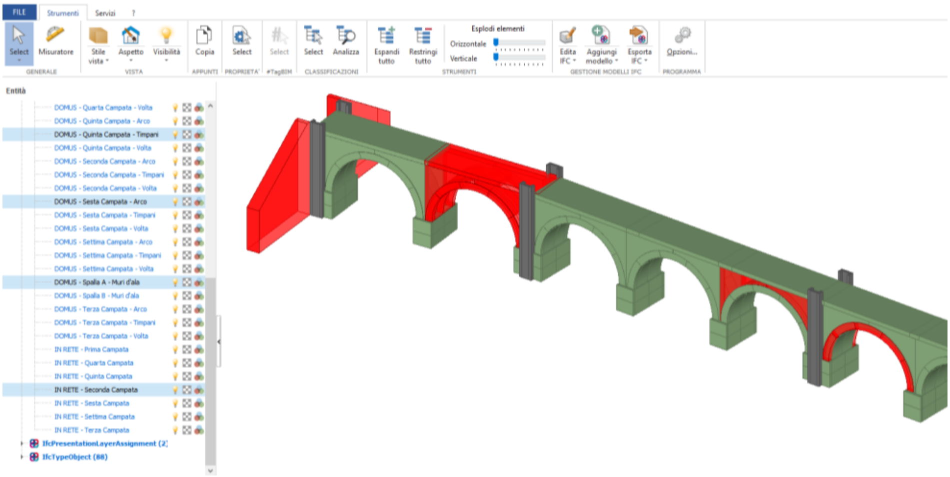


Figure 3.30 - Example of group definition and selection regarding DOMUS and InRete2000 contexts.

As mentioned above, the different reference levels (component, aggregation, structure) were associated with: (i) proposed properties, within the informative model, referred to data related to different contexts (DOMUS, InRete2000, NTC, etc.); (ii) digital forms or records, in a collaborative platform, referred to the inspections required by the DOMUS context. At the structural level, information is organized according to the requests deriving from the analyzed contexts, such as the systems being considered (DOMUS, InRete2000), and other regulatory references, for example "*Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti*"(LGP) and "Norme Tecniche per le Costruzioni" (NTC). Therefore, as regards the structure level, information can be referred to the LGP (e.g. class of attention, relative defectiveness), NTC (e.g. safety factors), DOMUS (e.g. indices regarding the bridge condition), InRete2000 (e.g. according to relative classes such as spans and so on), structural monitoring, and others besides. Other component-level information on the DOMUS context is also given in the informative model in terms of properties, describing, for example, the type of sub-component (specific field) allowing its identification, as shown in the figure below:

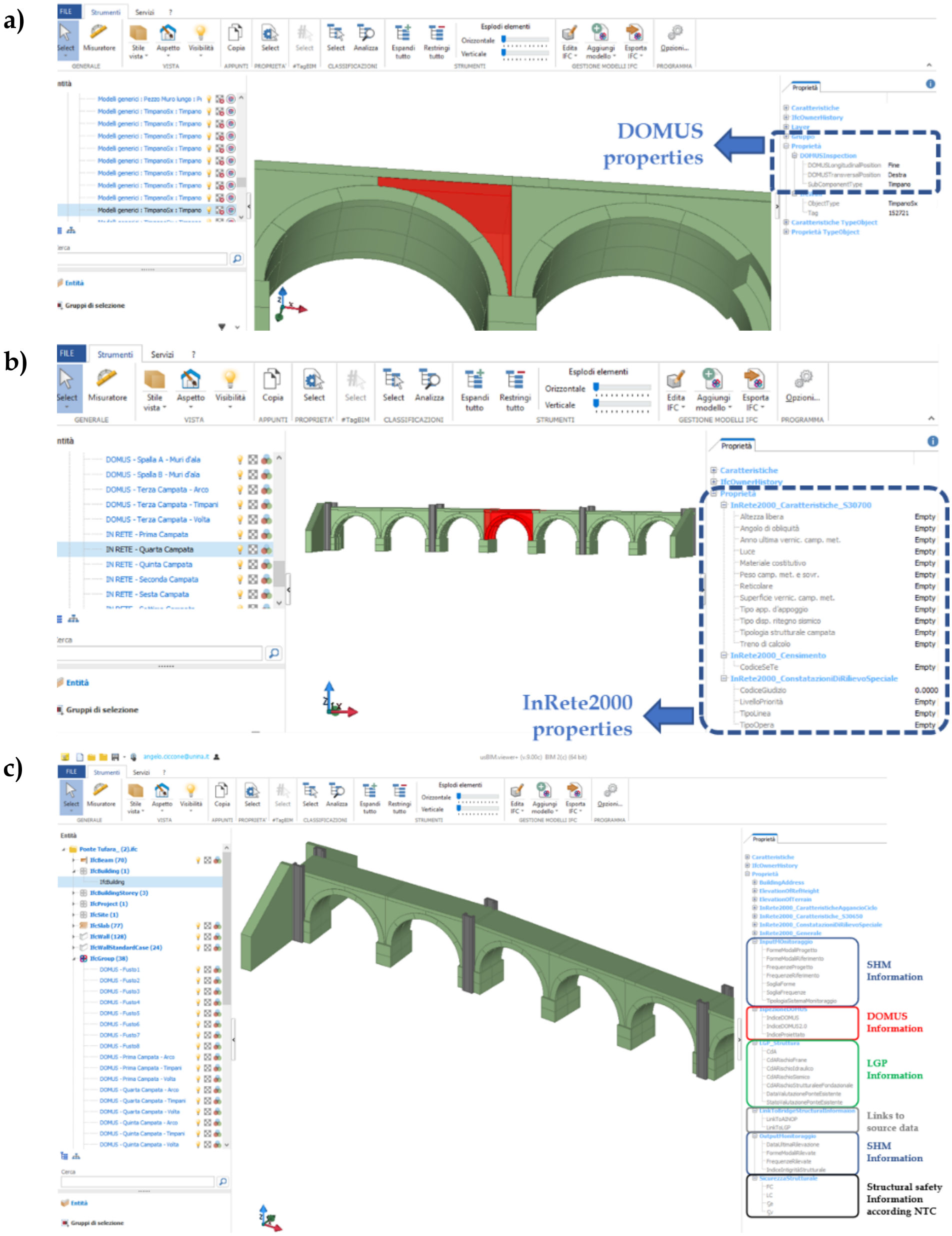


Figure 3.31 - Example of properties relating to the identification of specific components according to DOMUS context (case a); specific aggregations for InRete2000 context (case b); and other aggregations of other structural contexts (case c).

An example is also given regarding the properties required for a specific level of aggregation required by InRete2000 (e.g. considering Class S30700):

Table 3.3 - IFC properties associated with the IFC model related to class S30700 (Span) of InRete2000

PSet Name	Property Name	Property IFC Type
InRete2000_Caratteristiche_S30700	Treno di calcolo	IfcPropertySingleValue/IfcText
InRete2000_Caratteristiche_S30700	Luce	IfcPropertySingleValue/IfcText
InRete2000_Caratteristiche_S30700	Angolo di obliquità	IfcPropertySingleValue/IfcText
InRete2000_Caratteristiche_S30700	Altezza Libera	IfcPropertySingleValue/IfcText
InRete2000_Caratteristiche_S30700	Tipologia strutturale campata	IfcPropertySingleValue/IfcText
InRete2000_Caratteristiche_S30700	Materiale costitutivo	IfcPropertySingleValue/IfcText
InRete2000_Caratteristiche_S30700	Reticolare	IfcPropertySingleValue/IfcText
InRete2000_Caratteristiche_S30700	Tipo app. d'appoggio	IfcPropertySingleValue/IfcText
InRete2000_Caratteristiche_S30700	Tipo disp. ritegno sismico	IfcPropertySingleValue/IfcText
InRete2000_Caratteristiche_S30700	Peso camp. met. e sovr.	IfcPropertySingleValue/IfcText
InRete2000_Caratteristiche_S30700	Anno ultima vernic. camp. met.	IfcPropertySingleValue/IfcText
InRete2000_Caratteristiche_S30700	Superficie vernic. camp. met.	IfcPropertySingleValue/IfcText

This approach was also implemented for the other InRete2000 classes being considered (e.g. S30650, S34650), and associated with the reference IFC classes regarding structure, aggregation, or element levels. This will also make it possible, through the future development of technological connections (e.g. through the availability of APIs for the systems involved), to connect and update in a bidirectional manner the values relating to the information considered (e.g. managed as IFC properties or as digital forms on the platform).

As regards the digital forms managed in the collaborative platform, these were considered as means to digitize the inspection records, summarising a range of related information. These are linked to the global structure or the individual components, as identified previously, and refer to a series of data regarding the general characteristics of the work, location, and assessment of any defects and damage detected. Similarly to the properties included within the BIM model, forms also refer to different levels. With this goal, with regard to the DOMUS context, a series of data were summarized and some records were proposed, as shown in Figure 3.32.

a)

COMPONENT-LEVEL INSPECTION RECORD			Date : __ /__ /____ Surveyor Technician:				Province/Region: ________ Progressive km :											
n° Defect	Defect Code	Defect Type	Subcomponent Type	Componet Field of interest	Photo	Importance Factor **(B)**	Component Importance assessment **(K1)**	Intensity Assessment (K2)				Extension assessment (K3)				Degradation Evolution assessment **(K4)**	Vd,k_i	**Vd,k**
								0,5	1,0	1,5	2,0	0,5	1,0	1,5	2,0			
1								☐	☐	☐	☐	☐	☐	☐	☐			
2								☐	☐	☐	☐	☐	☐	☐	☐			
3								☐	☐	☐	☐	☐	☐	☐	☐			
4								☐	☐	☐	☐	☐	☐	☐	☐			
5								☐	☐	☐	☐	☐	☐	☐	☐			
6								☐	☐	☐	☐	☐	☐	☐	☐			
7								☐	☐	☐	☐	☐	☐	☐	☐			
8								☐	☐	☐	☐	☐	☐	☐	☐			
9								☐	☐	☐	☐	☐	☐	☐	☐			
10								☐	☐	☐	☐	☐	☐	☐	☐			
11								☐	☐	☐	☐	☐	☐	☐	☐			
12								☐	☐	☐	☐	☐	☐	☐	☐			
13								☐	☐	☐	☐	☐	☐	☐	☐			
14								☐	☐	☐	☐	☐	☐	☐	☐			
15								☐	☐	☐	☐	☐	☐	☐	☐			

b)

STRUCTURE-LEVEL RECORD	Date : __ /__ /____ Surveyor Technician: ____________ Province/Region: ________ Progressive km : ________
Reference to project data	Document code
Identification of the work	Railway Bridge km xx+yyy.yy
Se.Te. Code	Code according to census logic (e.g. for InRete2000 system)
Structural Type	Mansonry bridge
DOMUS Family	Family type according to DOMUS system (e.g. M5 - Masonry - Masonry arch with closed tympanum)
DOMUS Index	Number according to DOMUS system
DOMUS2.0 Index	Number according to DOMUS system
Projected Index	Number according to DOMUS system
Judgement Code	Number according to RFI systems (e.g. Class 0060)

Figure 3.32 - Setting up the records proposed at the structure and component level, to collect summary information on inspections and processing results from the DOMUS system.

As regards the figures above, the first record summarises a series of information relating, for instance, to the structural characteristics as well as the summary indices concerning the bridge's condition and safety (DOMUS Indices, Judgement Code, etc.); while the second summarises a series of data concerning the defects detected through inspection activities carried out following the logics relating to the system being considered (defect type, defect code, component on which the defect was found, etc.). Having considered these, along with others established by the regulatory framework (e.g. LGP), they were digitized using integrated functionalities within the collaborative platform in question. Indeed, as regards the DOMUS context, at the level of the structure, digital records such as "Structure-Level Record" were developed and referred to the structure level of the bridge, in order to record data on the last assessment of the bridge's structural conditions. As regards the LGP context, meanwhile, the forms "Scheda di censimento ponti di livello 0" (for bridge census) and "Scheda descrittiva di ispezione ponti di livello 1" (for bridge inspection) were linked as well. The following example shows the digitization of the records in digital forms realized in the collaborative environment (usBIM.platform), and linked to the bridge BIM model at the overall structure level.

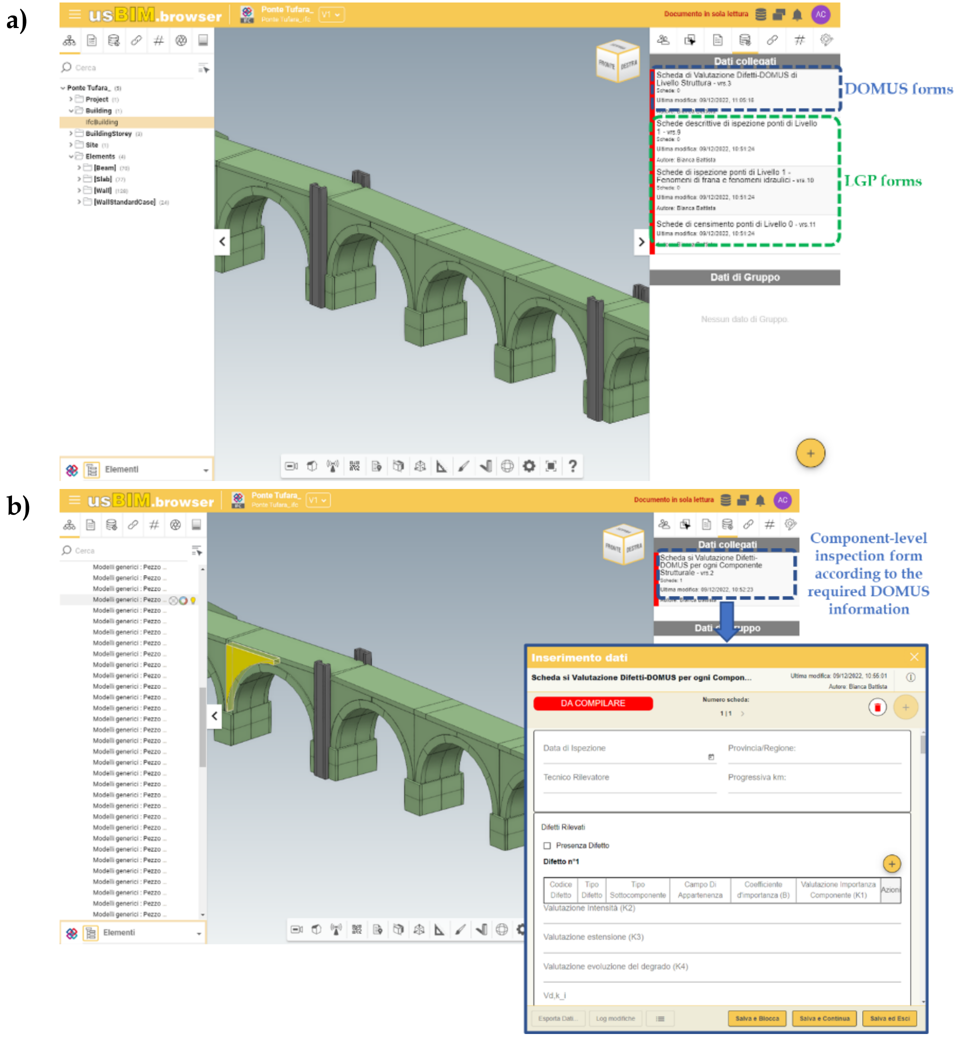


Figure 3.33 - Digitisation of the structure-level (case a) and component-level (case b) forms implemented in a collaborative platform (usBIM.platform) and associated with the IFC classes related to the bridge information model.

However, at the level of component aggregation and individual components, following the LGP context, relative forms were added to collect data related to the individual inspected elements to identify, highlight and report degradation phenomena (defect type, intensity, extension, etc.). For example, regarding the case study of the masonry arch bridge, the “Scheda di Ispezione Ponti di Livello 1 – Spalla in muratura” , ” Scheda di Ispezione Ponti di Livello 1 – Pile in muratura" and "Scheda di Ispezione Ponti di Livello 1 – Arco in muratura" were developed and linked to the identified component groups (e.g. abutments and piers). Finally, at the level of the single component, following the DOMUS system instead, a further form was developed, "Component-Level Inspection Form", concerning the data about detected defects or damage. This specific record, relating to masonry structures, could refer to all the relevant types of defects (according to RFI procedures with its Defect Catalogue) that can be detected. Then, the data obtained from inspections will be collected in these digital forms created on the platform and linked to the IFC model of the bridge. In this way, the information model will be enriched with information that can always be updated, by qualified technicians (e.g. bridge inspectors), and thus it will certainly provide a valid support tool for the strategic management and planning phases concerning the maintenance activities of the structure.

The proposal allows a simplified updating of the model by exploiting some of the functionalities of the collaboration environment (in this case usBIM.platform, the only BIM management platform certified IFC by buildingSMART International), which allows for example the updating and versioning of both of the BIM models and their related information (e.g. properties or digital forms) for individual components, aggregations or overall structures. Dynamic evolution of information, within the context of the structural management of bridges, is always tracked according to a well-determined logic. Furthermore, through the definition of specific workflows, activities are well organized, tracked, and standardized according to the procedures defined by the managing body for the inspections as well as other types of activities, through the definition of specific authorizations and possible actions. Hence, the proposed framework offers the possibility of data storing on a centralized database and managing information over time in a collaborative manner. This approach, applied to other infrastructure, will provide a means, also on a territorial scale, of prioritizing maintenance interventions by having the state-of-condition of the structures available in an up-to-date manner.

The activities regarding the survey and modeling of the current condition of railway infrastructure resulted in the management of a large amount of relevant data. This consisted of around 250 GB, including point clouds and textured meshes (for bridges and stations under investigation), IFC models (relating to the subdivision of the railway infrastructure by discipline and section (as required by the modeling plan built ad hoc for the project's aims), digitized layout elements (sleepers, rails, etc.), tunnels, bridges, railway signals and so on. Regarding the validation of the project in terms of verifying objects and BIM models, while the information was being produced (library objects and models), as stipulated in the C.I. (by following the rules and specific LOINs defined to meet the information requirements of RFI and EAV), digital workflows were produced in the collaborative environment to be used in the validation, approval, and publication of the models and documents in the collaborative platform (usBIM.platform) by the actor in charge (in this case the university, though in future this will be some generic figure charged with the role). Starting from the specifications defined in the C.I., roles and specific authorizations (read-only, execution, etc.) were defined for each actor involved in the project within the collaborative environment. In this way, it could be possible to represent the activities to be carried out regarding the various files, folders, notifications of tasks, and management of permissions associated with each of the entities involved (see Figure 3.34).

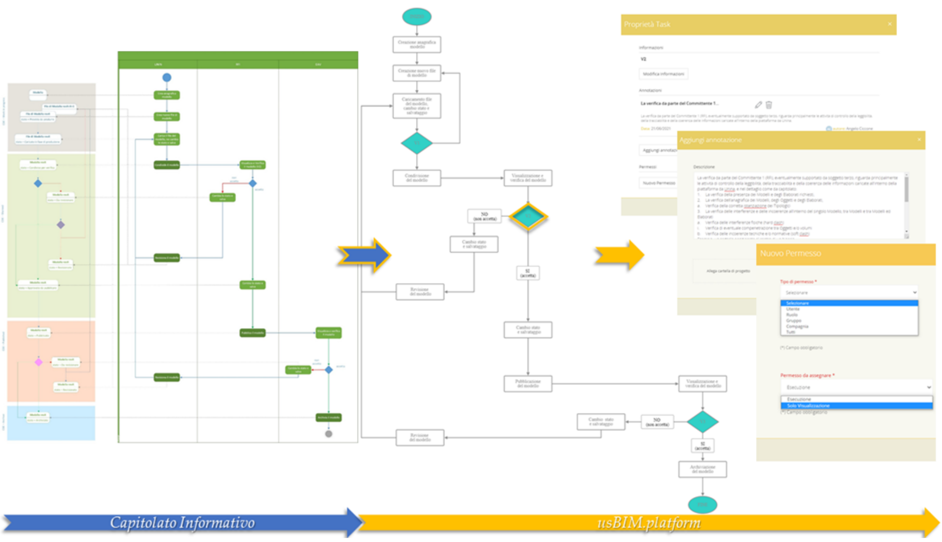


Figure 3.34 - Example of process digitization (e.g. regarding the validation process of the information content) carried out in a collaborative platform according to C.I. specifications.

Consequently, the development and digitalization of aspects of the process and its related activities resulted in the optimization of the performance of the various validation processes (previously uncoordinated and not managed on digital models), and also made the use of resources more efficient. Through these organized workflows and planned activities, stakeholders were able to keep track of the progress of the project. Figure 3.34 gives an example of the implementation, used subsequently for project activities, of a digitalized process (i.e. workflow) for the verification of models and other files, as well as their approval and publication in the CDE.

The proposed digital solution, conceived for the management of the railway infrastructure in operation, made it possible to effect quantitative and qualitative (or financial) evaluations of the railway assets, as shown in Table 3.4 and

Table 3.5.

Table 3.4 - Quantifying of railway superstructure components related to the existing line in question.

Cancello–Benevento Railway Line		Section [km]	Section [km]	Section [km]	Section [km]	Section [km]	Section [km]	Section [km]	-
Track Equipment	**Measure**	*0,510 – 8 + 300*	*8 + 300 – 14 + 320*	*14 + 320 – 20+580*	*20 + 580 – 29 + 400*	*29 + 400 – 37 + 600*	*37 + 600 – 45 + 740*	*45 + 740 – 47 + 590*	**Total**
SLEEPERS									
concrete (bi-blocks)	[-]	11819	8990	6361	13199	12363	10550	1357	64639
wood	[-]	362	0	130	277	112	236	3	1120
concrete (single-block)	[-]	776	1000	1156	1058	1089	267	329	5675
Total	[-]	12957	9990	7647	14534	13564	11053	1689	71434
concrete (bi-blocks)	[m]	7091,4	5394,0	3816,6	7919,4	7417,8	6330,0	814,2	38783,4
wood	[m]	217,2	0,0	78,0	166,2	67,2	141,6	1,8	672,0
concrete (single-block)	[m]	465,6	600,0	693,6	634,8	653,4	160,2	197,4	3405,0
Total	[m]	7774,2	5994,0	4588,2	8720,4	8138,4	6631,8	1013,4	42860,4
RAILS									
Total	[m]	15580,0	12040,0	12520,0	17640,0	16400,0	16280,0	3700,0	94160,0
BALLAST									
Total	[m]	15969,5	12341,0	12833,0	18081,0	16810,0	16687,0	3792,5	96514,0
SUBBALLAST									
Total	[m]	13320,9	10294,2	10704,6	15082,2	14022,0	13919,4	3163,5	80506,8

Table 3.5 - Type and number of objects along the considered railway line.

Cancello–Benevento Railway Line	**Measure**	**Measure**	**Measure**
BIM Objects Typologies	[-]	[m]	[m^2]
Poles	1159	-	-
Portals	26	-	-
Railway Signals	684	-	-
Railway Switches (on considered track)	18	-	-
Railway Switches (total)	32	-	-
- Switches (with lever)	17	-	-
- Switches (with switch box)	14	-	-
Tunnels	6	1939,97	-
Passenger Platforms	17	2196,39	8653,48
Level Crossings	50	319,25	-
- Protected	23	153,13	-
- NOT Protected	27	166,13	-

Based on these considerations, other considerations can be made regarding the merits of estimating the value and efficiency of a given railway asset. All this is an effective support for any interventions to be made along the line (as per the project context). Having digitized the entire line in the BIM environment, regarding the various technological systems present, it was also possible to download and subsequently make calculations regarding the quantities obtained. The digitization of this infrastructure also served as a reference for decisions relating to asset management, i.e., evaluating necessary investments, particularly regarding the takeover of management by another railway operator, namely RFI. Such investments must obviously be assessed about the adaptation of the infrastructure to standards set by the new managing group.

3.4 Discussion

The use of openBIM, for instance, as applied to the management of the railway line described in this case study, enables collaboration, communication, and the exchange of information without restricting solutions to a specific software, thus ensuring the integration of all professionals and their technical skillsets. This is made possible by the use of open formats (e.g., IFC). In this approach, IFC models act as "access keys" to information and processes related to other systems as well. It is this connection (regarding project information) between different existing ecosystems (CDE, CMMS, ERP, etc.) that gives the project added value. The project has demonstrated how the BIM modeling of existing conditions can be managed, but also how the CDE is the central point and unique source of information recording. This information is accessible to all actors at any time and place, and each of them has worked within the collaborative environment with various associated roles (visualization, editing, etc.) with the sole aim of participating in the digitalization of the existing railway line following the project's predefined objectives. The openBIM approach is thus a new opportunity for business processes to be re-evaluated and reorganized, with time-consuming activities reduced through implementation within a single environment. In this way, information is managed effectively and organically, allowing both maintenance of the centralized railway infrastructure, relative to a single federated digital model, and improved performance analysis. Through the usBIM.platform, the owner or manager of the infrastructure can manage, check, and validate (in open format) the information required for the purposes of asset management of the railway infrastructure. Over the course of the project, a series of BIM object typologies belonging to the various technical disciplines were modeled, from which it was possible to build a library of BIM objects with the level of information required for asset management. This project's activities can therefore be seen as a starting point, above all, at the company level, since the spread and evolution of BIM methodologies and associated instruments can be a reference for similar projects in the future. In the present instance, the survey and modeling of existing conditions along the railway line allowed both to obtain complete knowledge of the current technological systems and to evaluate the infrastructural gap to be closed economically and technically. The library and related geometrization of the existing layout was the necessary input for the realization of the digital model. The innovative management of concepts relating to the alignment and positioning of objects, along with other things typical of the railway infrastructure, was made possible through the use of specific software developed for the case at hand. This permitted the production of BIM objects and models under the specifications of IFC4x2, the latest version in bSI available at the time of the project. The proposed approach also required the development of dedicated software solutions (e.g., usBIM.IFCinfra) for the modeling of

information relating to the railway infrastructure in IFC4x2, supporting the development of BIM models through the management of innovative concepts (IfcAlignment, IfcLinearPlacement, etc.). The use of these open formats certainly has advantages in the management of information at the company level, since it allows define the information requirements in compliance with national (e.g., UNI1137) and supranational (e.g., ISO19650 and EN 17412) standards, to create advanced digital knowledge, as well as to enable the control and elaboration of information specifications that both the design and, above all, the future maintenance of the infrastructure will depend upon. As stated previously, the project required the definition of specific information (e.g., PSet) dedicated to asset management, which is of considerable strategic and operational interest to the organization managing the infrastructure. At the same time, further development of openBIM is undoubtedly necessary for the asset management of railway infrastructure, as far as the availability of specific standardized Property Sets is concerned, which convey information necessary for the management of relevant activities. Regarding the IFC standard, the future availability of a specification
relating to infrastructure will enable the management of various aspects that are now allowed only marginally. The integration of the contents of recent projects (IFCBridge Project, IFCRail Project, etc.) in buildingSMART will contribute to the development of a version (probably IFC4x3) that can perform various necessary operations (IFC mapping, spatial structure, etc.). The development of other standards (e.g., bsDD, IDS) and approaches (e.g., open CDE) for integration with other systems or platforms could bring significant advantages in establishing increasingly open and interoperable information management for all actors involved. The stakeholders had the opportunity to equip their company with the digital solutions that had been developed and the practices that had emerged for managing all relevant information through open formats (for the managing of models, objects, point clouds, documents, etc.) in a common digital environment (i.e., CDE), thus developing a solution for the easy management of around 47 km of an existing railway line. The research and experimentation carried out downstream of the pilot project have demonstrated considerable advantages in the optimized management of resources, materials, and company know-how, as well as coordination activities taken as a whole. As a result, the managing companies will be able to organize appropriate company

areas for the tasks of optimizing the processes related to the maintenance of the railway infrastructure and keeping all the information within the collaborative platform constantly updated, ensuring they have at their disposition data that is always current and usable, which is provided by all technicians involved in maintenance and infrastructure management. The digitalization of this in-operation infrastructure has also been of use as a reference for decision-making in asset management, i.e., in evaluating required investments.

3.5 Conclusion

This pilot project stemmed from the need for a railway owner to manage its operations and assess the condition and value of its railway infrastructure. The principal objective was to systematize information by digitalizing the infrastructure, thereby allowing assessment of any performance gaps with respect to RFI standards. The digital management strategy proposed and implemented in this case study demonstrated the effectiveness of this proposal. It had the objective of supporting the decision-making process and at the same time assisting and managing the daily activities of management, operation, and maintenance of the railway's assets. OpenBIM demonstrated that it supports the exchange of information between all actors involved in the process, and showed the ability to support the digitalization and management of the railway infrastructure for the purposes of managing the lifecycle of assets by supporting information connections with other systems (e.g., inRETE2000 and LINFE). At the same time, there remains a need for a specific IFC dedicated to infrastructure that can integrate the domain of railway infrastructure from both a geometric and semantic perspective. This digital solution also made it possible to form quantitative and qualitative estimates of the value of the infrastructural assets present along the railway. These considerations can determine assessments of the assets' efficiency and support the decision-making process in any interventions to be carried out along the line (as per the project's objectives). The results obtained from this pilot project have certainly offered important insights regarding the development of the IFC standard in the field of asset management, and, by improving the efficiency of railway infrastructure safety maintenance, concerning the possible definition of new practices for the corporate management of processes. This research project has shown that such solutions can be integrated and implemented to make the operation and safety of an existing railway infrastructure more efficient. The managing company will be able to use the results of the pilot project, as obtained through the implementation of the proposed methodology in the Benevento–Cancello case study, to manage the entire railway infrastructure for which it has responsibility. Given the considerable efforts made towards the implementation of this project, and its innovative nature concerning the application of openBIM, the research team was nominated at the 2021 buildingSMART Awards and was one of three finalists in the "Asset Management using openBIM" category. The results obtained by the project with respect to project goals (e.g., infrastructure compliance with RFI standards and management and maintenance of the railway infrastructural asset) were very encouraging, and both companies, EAV and RFI, have learned fundamental lessons, in particular, regarding possible future scenarios involving the use of digital systems and new technologies (based principally on openBIM), which can certainly optimize the management processes of railway infrastructure.

Chapter 4

4. Defining digital strategies in a BIM environment to manage existing R.C. bridges in the context of Italian regulation.

4.1 Introduction

Bridges and viaducts, which are used by both rail and road networks, consist of elements that are complex in terms of construction, design, and execution and which are expensive in terms of the resources used in their management, control, and maintenance.

As is well known, bridges and viaducts are highly exposed to processes of structural deterioration induced by various climatic conditions, aging, and by the weight of traffic loads. Consequently, there is an ever-increasing need to improve bridge management [6]. In the event of earthquakes or other natural events, the exposure and vulnerability of a built asset (e.g., existing bridges) must be taken into account. A thorough assessment of whatever deterioration or defects can be made and a subsequent diagnosis and maintenance strategy can be adopted to guarantee the safety, durability, and functionality of the bridge [180]. In Italy, transport networks are characterized by a large number of crossing constructions (e.g., bridges), due to the morphological configuration of the country as well as the presence of waterway networks. This heritage is highly heterogeneous in terms of origin, typology, and characteristics. As time goes by, multiple factors linked to the continuous development and evolution of transport networks make it necessary to evaluate the safety of infrastructural assets (principally bridges) in an updated and organized regulatory framework. Considering a lifecycle-oriented approach, for the management and maintenance of bridge safety, the use of new approaches, solutions, and digital tools is necessary [6,16,19,21,22,180–183]. Among the most applicable digital technologies is building information modeling (BIM). Early concepts related to BIM date back to the 1970s [21], but nowadays, it can be considered as an operational technology for use in the construction sector, aimed at creating, storing, and managing information relating to an asset (e.g., building or infrastructure) during the construction's entire lifecycle. To date, the application of BIM methodologies has mostly involved the context of new projects. However, it can be applied to each phase of the asset life cycle including the management phases [3,5,73,184,185]. Additionally, in the case of bridges, BIM applications in the management and maintenance phases come relatively late. Given that digitization of existing infrastructure has recently been started, it is reasonable to expect that in the immediate future, infrastructural heritage will be available in the form of three-dimensional, parametric, and informative models. Hence, supporting these new methodologies, there has been a growing demand in this area. To accomplish this, various tools and technologies (visual programming, IoT, machine learning, and more) can be used. With this aim, it has been developed an all-encompassing digital solution, considering different BIM technologies available today, for supporting parametric 3D modeling activities in addition to the processing, integration, and management of information, in the context of the Italian regulation, regarding existing reinforced concrete bridges.

4.1.1 Regulatory context for the management of bridges

Bridge management can be understood as the optimal planning of inspection and maintenance activities, to preserve the value of infrastructure, thus optimizing costs throughout a given installation's lifecycle while ensuring the safety of users and sufficient quality of service. In the United States, the regulation regarding bridge management has involved institutions and organizations such as the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO). After other relevant events, bridge management systems (BMS) are adopted, and additional regulations, manuals, and guidelines, regarding the assessment and verification of existing bridges, are issued. In the field of the verification of existing structures, in the case of the United Kingdom, other documents were issued. In Europe, the Council of the European Union included the transport sector in its list of critical infrastructure a few decades ago

(*Directive of the Council of the European Union 2008/114 EC,* 2008). In Italy, the regulatory framework is fragmented into various ministerial circulars, specific guidelines, provincial regulations, and stipulations of the various groups operating in the transport sector. With the current NTC2018 and the related Circular of 2019, sensitivity about the structural safety management and maintenance of existing structures has certainly increased. Following the catastrophic events (e.g., which occurred on the Polcevera viaduct), the regulatory framework was updated (e.g., Decree No. 109 of 2018, Law No. 130 of 2018, and Ministerial Decree No. 430 of 2019). Mostly, in the context of infrastructure management, regulatory provisions have concerned the institution of the AINOP (*Archivio Informatico Nazionale delle Opere Pubbliche*) and the definition of the LGP approach (Figure 4.2). Indeed, the AINOP was set up for the census of public civil works on managing bodies and authorities. It was established to record all the information required for public infrastructural assets (road and railway bridges, tunnels, etc.), present on the national territory, and is managed through a digital platform (see Figure 4.1 and Figure 4.2) where information must be organized in sections (according to the type of infrastructure, including road bridges), subsections, and other specific input areas where census data, technical data, administrative and economic–financial data, structural monitoring data, maintenance data, safety data, works, and others have to be recorded.

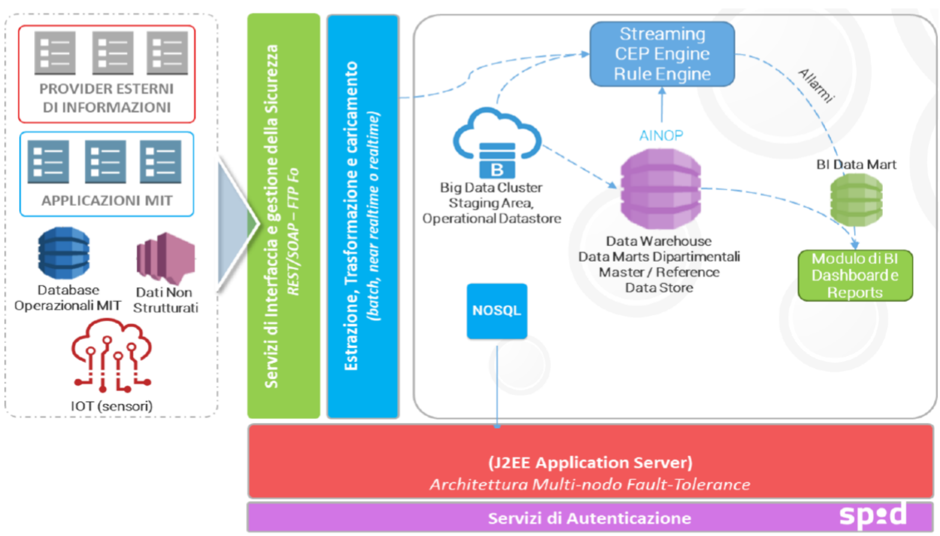


Figure 4.1 - AINOP web-service architecture.

These sections are managed through a web platform, where through specific roles, it is possible to :

- "identify a civil work and its location in the geographical context;
- view data, information, and documents of the work structured in a sort of virtual dossier;
- receive information that will allow the technical monitoring of the work, with a view of preventing criticalities, also through intelligent warning systems regarding the state of the infrastructure;
- identify possible workflows to efficiently implement, maintain, manage and decommission the work".

As mentioned above, the platform will be accessible to participating actors according to several expected roles. Some of them include:

- a "supervising party" (Article 13, comma 6, Law No. 130/2018), monitors the implementation status of the interventions identified through the CUP (Single Project Code) pertaining to the public works identified with the IOP (Public Works Identifier issued by AINOP) code and the related economic-financial resources allocated using the information in the BDAP (Public Administrations Data Bank).
- a "conferring party" (Article 13, comma 4, Law No. 130/2018), namely the public organizations that are responsible for providing data to AINOP. For example, it may be represented by the managing body or owner of the civil infrastructure.

However, considering AINOP's current setting, there are other types of identified parties, relating to other types of activities, such as "Public", "Inspection Parties", "AINOP parties", and "System Administrators" currently not covered by the work under consideration but also involving with the same proposed approach.

The Italian guidelines entitled "*Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti*" (LGP) were published by the Superior Council of Public Works (C.S. LL. PP.) and then adopted at a ministerial level (Ministry of Infrastructure and Transport) [186]. As shown in Figure 4.2 b, the LGP multilevel approach is based on the definition of a CdA (Classe di Attenzione) parameter that influences bridge management activities (such as interventions, structural monitoring, preliminary or in-depth assessments of structural safety, etc.) [187]. By considering the bridge data collected employing the LGP Annexes, it is possible to record and process them to obtain information on risk, intervention priority, in-depth structural safety assessments, and condition status.

(a) **(b)**

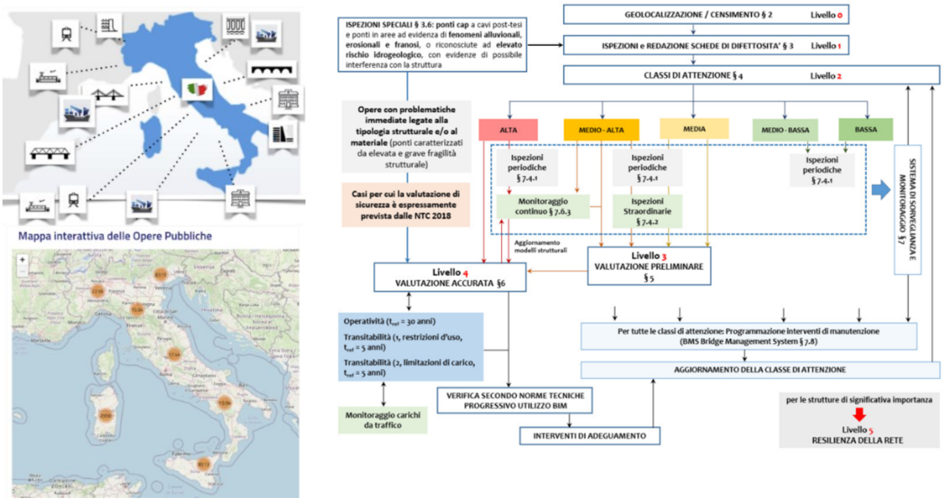


Figure 4.2 - The AINOP platform and relative interactive map of public works (a); multilevel approach and related analysis levels according to the LGP (b).

Taking a new perspective on the management of civil works in BIM, in Europe, directive 2014/24/EU suggests introducing BIM methodologies in the field of public procurement. Italy has implemented this directive (considering Legislative Decree No. 50 of 2016), allowing the authorities to request the use of such methods and digital tools. Subsequently, in 2017, Ministerial Decree No. 560 of 2017 was issued. This introduced the procedures and times for the gradual introduction of BIM methodologies for the modeling and management of information, regarding buildings and infrastructural assets in public works, in addition to the concept of interoperability as performed through non-proprietary open formats and platforms. In August 2021, Ministerial Decree No. 312 was issued to implement a series of new measures for the use of BIM, introduce further changes to the previous decree, and identify the reward criteria for the use of BIM. Additionally, the LGP addresses the integration of existing systems in service so far (e.g., BMS, ERP) with BIM methodologies. All this should be included in an overall framework of information management, which aims to ensure the appropriate safety level of the national infrastructure assets, based on the progressive adoption of information with related objects, common data environments, and interoperable platforms of data.

4.1.2 Problem statement and goals

As also emerges from the analysis of the regulatory context, there is a need to digitalize the management of existing bridges, with the aim of not only creating BIM information models but also of enabling new ways to process and manage information relating to the definition of structural safety, risk, and priority intervention. Currently, such information is not yet managed through a BIM-based approach. Additionally, the existing systems used today by managing bodies or authorities are still not ready and organized to fully meet the new requirements. Indeed, there is a lack of any all-encompassing BIM-based solution to manage the required information under recent Italian regulations. To achieve that, a new digital organization of context-related information — a recent approach introduced by the ISO 19650 series and the UNI EN 17412-1 through the definition of the Level of Information Need (LoIN) — was put forward. Starting from the definition of the specific LoINs, it has been proposed a digital framework (i.e., RCBFramework) enabled by dedicated scripts and algorithms, developed in a programming application, and subsequently integrated into the BIM environment. This framework has been developed for a specific type of road bridge (namely, reinforced concrete girder bridges), but given its approach, particularly from an IT perspective, it could in the future be extended to apply to other types of bridges or viaducts. Moreover, the proposed solution is enabled by the development of a specific input environment in which all necessary information is provided. By processing the inputted data via custom-designed scripts and algorithms implemented in visual programming (VP) and authoring environments, BIM models with synthesized information regarding risk, intervention priorities, and structural safety were created and then managed in a collaborative environment. The use of a specific collaboration environment allows the organization of a collaborative-type work involving various technicians and supports the information management organized according to the adopted LoIN approach. Considering therefore specific requirements, it was also proposed the development of a methodological proposal for information management with reference to activities required by the AINOP context.

In conclusion, the proposed digital strategy was subsequently applied to some case studies to test the capabilities and effectiveness of the proposed approach in the analyzed regulatory context.

4.2 Overview of the application of BIM methodologies in the management of existing bridges

4.2.1 Analysis of the BIM scenario

Building information modeling has been defined by the National BIM Standard as "a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward". The information that is generated and exchanged adopting proprietary formats guides the user toward specific solutions. Meanwhile, in openBIM, digital solutions developed with several open standards in mind—such as Industry Foundation Classes (IFC), Model View Definition (MVD), Information Delivery Manual (IDM), and so on—can enable and support the open exchange of information among all the professionals involved on a project [3,13,18,24,75,89,96,120,188–192]. However, the definition of BIM models should be carried out according to the widespread 'use case' concept, which establishes a common language for BIM applications throughout all lifecycle phases. In the case of the scenario under investigation, some use cases, such as record modeling (RM), asset management (AM), and maintenance and repair information (MRI), may be considered. On the other hand, as regards the details of the BIM model itself, reference can be made to specific "Model Uses" [14]. This help identifies the kind of information that is required, delivered, or integrated into the BIM models.

In the context under analysis, it can refer to model uses such as "Algorithmic Modeling", above all regarding geometry generation, as well as "Building Inspection" and "Asset Maintenance", for a more thorough assessment of information and documentary aspects in the management context of a civil asset. To define what information is needed for BIM modeling and information management activities, alphanumeric and documental information relating to O&M activities predominates over geometric information, and these are fundamental to ensure the control of the condition status and bridge performance over time [5,19,21,89,193]. Regarding the management of civil infrastructure, specifically in the case of bridges, several studies [5,167,183,194] consider the level of development (LOD) approach for their developments and proposals. The widespread application of such an approach has led to the development of some differences between LOD standards in different countries [15]. In addition to this existing LOD concept, a new approach has been proposed by the ISO 19650 series, i.e., level of information need (LoIN). The new framework is different from LOD; indeed, with this new approach, it is possible to: (i) improve the information quality; (ii) reduce the risk of errors about the interpretation of requirements and control of compliance with contractual requests; and (iii) improve the process effectiveness, producing only the most necessary information, thereby avoiding waste, surplus, or a lack of information. This concept, accordingly, was subsequently defined in a recent standard, UNI EN 17412-1, which has also been adopted in Italy, introducing the relevant aspects (at the geometric, informative, and documentary level) for the creation of the information needed to define a digital model. Given that this approach was recently issued, there is still a lack of specification and related applications to real scenarios, including the case of bridge management. For this reason, it has been proposed a LoIN setting for bridge management in the cases under investigation.

4.2.2 BIM methodologies integrated with other technologies

In the AECO sector, for the creation of a civil infrastructure model, there are many software vendors and their software solutions. This software can be used for creating CIM models or performing simulations and analyses in different domains (transportation, structures, water, energy, etc.). In addition, some vendors also provide APIs (application program interface) and SDKs (software development toolkits) for customizing their tools.

In the field of civil infrastructure, some applications (BIM-authoring or other software) can be used for different uses [5,53,177,188,194–196]. Usually, these are referred to some vendors such as Autodesk (e.g., Revit, AutoCAD, Civil 3D, InfraWorks, Structural Bridge Design, Navisworks, etc.), Bentley (e.g., MicroStation, ProjectWise, RM Bridge, Power Rail Track, Power InRoads, etc.), CSI (e.g., SAP200, CSiBridge), Tekla (e.g., Tekla Structures, Tekla Bimsight), Graphisoft (e.g., ArchiCAD), and so on, in addition to visual programming tools (e.g., Dynamo or Grasshopper) that can support activities related to the BIM-authoring applications. Therefore, the possibility of using VP tools (e.g., Dynamo, Grasshopper, etc.) permits automated or semi-automated operations for the development of solutions for model building and information management [54,188,197–199]. In the design phase of a bridge, these tools can be efficiently used for the development of different scripts for the generation of Bridge Information Models (BrIMs), demonstrating a consistent reduction in modeling times [195]. In the specific context of bridge management, some information (e.g., relating to inspections) can be managed by developing structured workflows and scripts created in VP environments, starting from input data in an organized and structured way [5]. In the infrastructure field, BIM can be successfully applied to the design phases of infrastructure such as railways [195,198–201]. As also for buildings, in the context of bridges, these methodologies can be applied to the management of risk-related information [64,82,88,101,113,192]. BIM can also be used for the digitalization of existing bridges in addition to supporting the registration and maintenance of relevant information, both historical and current through the use of databases connected to the digital model [5,75,89,92,113,185,193,195]. BIM methodologies can be assisted and integrated with other technologies as well. For instance, Internet of Things (IoT) technology could be considered to support smart structural evaluations and develop "intelligent" management of a bridge's lifecycle [100,102,113] also combined with other means such as IFC [100,113,116,122,202]. Furthermore, specific tools, namely bridge management systems (BMS), can also provide decision support for the entire lifecycle of a bridge. In this direction, several studies [96,180,182,183,192,203,204] consider a possible integration between BMS, BIM methodologies, and other technologies as well, such as advanced computing and imaging techniques, to improve reliability and efficiency in bridge management [90,92,180,205]. As far as existing bridges are concerned, complete digitalization is necessary with the goal of supporting the management and maintenance of specific characteristics over time. This digital reconstruction can be put into action with automatic or semi-automatic methodologies that use survey data (e.g., point clouds) to generate models, for example, in IFC format, or for the automatic detection of the bridge elements and related damage information [85,89–91,94,107]. In addition, between BIM and FEM, the adoption of an adequate parametric strategy allows one to manage highly complex projects and facilitates collaborations between different disciplines or technicians [93,206,207]. BIM models, built following specific O&M requirements, can enable the extraction and exchange of data directly with existing asset management systems [4]. Digital management can also be supported by other solutions, such as collaborative platforms. These enable a common data environment (CDE) to be structured and organized according to national (i.e., the UNI 11337 series, in Italy) or international (e.g., the ISO 19650 series) standards. Several studies [3,8,9,16,202,208,209] prove the effectiveness of using CDE platforms, digital tools, or other systems to support activities related to infrastructure including bridges. Moreover, an important aspect in the construction sector is interoperability, understood as the ability of two or more systems, networks, or applications to exchange information between themselves [11,181,202,210,211]. When BIM applications have to be defined, interoperability issues and application compatibility logic in addition to their update times should be taken into account [22,181]. This can be performed through non-proprietary open formats such as IFC (ISO 16739-1), promoted by buildingSMART International (bSI). As has been demonstrated by various practical sources (e.g., Bridge Information Modeling Standardization by FHWA and the National BIM Guide for Owners by NIBS), some open standards, such as IFC and LandXML, can describe many aspects of a bridge throughout its lifecycle [93,96,167,191]. The latest bSI projects (IfcBridge, IfcRail, and so on) enable increasingly well-performing versions of the IFC standard capable of representing these assets both geometrically and semantically. In particular, the IfcBridge project [191], concerning IFC extension for bridges, has enabled the issue of a related version of the IFC schema (IFC4.2). Applications of visual programming could be considered to build and export bridge information models according to the IFC4.2 release [191]. Although it is currently withdrawn, this has been considered in versions that are currently in development by bSI (e.g., IFC 4.3 or the latest IFC 4.4.0 version) for the infrastructural field. Indeed, in the O&M scenario for road infrastructure, IFC applications remain limited due to a lack of specific semantics [167]. At the same time, the open BIM approach can be considered for the management of all in-operation assets (including bridges) belonging to an existing road or railway infrastructure [3,167].

Thus, according to the state of the art and what was stated previously, there is a need to define an all-encompassing BIM-based approach for the management of existing bridges and to underline the lack of a specific BIM solution for the generation, processing, and management of information related to a specific regulatory context. To date, information is still managed almost entirely at the level of asset management platforms, without full integration with collaborative BIM platforms and interoperable data models for an effective exchange of information and bridge management. The digital solution proposed processes and manages all the required information employing specific workflows based on a developed framework, and through the use of some environments and technologies (programming environment, BIM-authoring software, Visual Programming solution, and a BIM collaborative platform).

4.3 A BIM-based solution for managing existing R.C. bridges in the context under investigation

4.3.1 Organization and objectives of the proposal

Thus it has been defined as an operational framework with which one can digitally manage a significant proportion of the bridges and viaducts that are part of the Italian infrastructural heritage, namely R.C. girder bridges. This proposal demonstrates, via case studies selected because of their different characteristics, the capabilities of the proposed digital framework for generating diverse bridge configurations, and managing and processing information related to the context under analysis. In this scenario, the solution was able to quickly generate BIM models starting from input data, such as plano-altimetric alignments and structural characteristics (number of piers, beams, etc.), through information entered in a custom-made input (developed in Excel). Specifically, the proposal considers girder bridges made of reinforced concrete (whether cast in situ or prefabricated), with bridge decks consisting of a grillage of beams (longitudinal and transversal beams), with any kind of longitudinal or transversal positioning, piers with single columns or multi-columns, and any kind of relative positioning between the piers or abutments and decks. The solution was developed with the aim of not only representing these bridges geometrically but also enabling the management of information processed through scripts and algorithms, integrated into the visual programming environment, beginning with input data and relating to the condition and structural safety of the bridge under consideration. The use of a collaborative environment (i.e., usBIM.platform) was necessary to support the proposal based on the LoIN setting, where the bridge information model was considered as the center of digital workflows which involved various technical figures (e.g., structural engineers). These can take place in the common data environment built under the specific regulatory context (e.g. UNI 11337, ISO 19650).

In conclusion, the following objectives were considered: (i) development of a data input environment in addition to the organization of specific BIM objects following a LoIN setting; (ii) definition of an IT solution to be implemented in a BIM environment; (iii) development of specific procedures for the generation of BIM models, for the processing and updating of the information over time-related to the required activities (census, survey, inspection, risk assessment, structural safety assessment, etc.); (iv) development of a methodological proposal for information management under the AINOP context; (v) testing and implementation of the proposal on selected bridge cases.

4.3.2 Identification of necessary data and definition of information strategy

A part of the proposed development consists of the generation of BIM models, in accordance with specific information requirements based on geometrical, information, and documentation settings. The required information was selected following the regulatory references under consideration (i.e., NTC, AINOP, and LGP). Analyzing different sources, different levels of information have been identified: (i) a global level, which refers to information referring to the global bridge structure; and (ii) an element level, which refers to information relating to any structural bridge component (e.g., beams, columns). Accordingly, this information was organized into five layers depending on the regulatory source, as shown in Table 4.1.

Table 4.1 - Definition of layers related to bridge information in the considered context.

Layers	LGP	AINOP	NTC
L0	✓	✓	
L1	✓		
L2	✓		
L3	✓		✓
L4	✓		✓

As far as the LGP is concerned, on the other hand, these are organized in a multilevel approach (see Figure 4.2). Regarding the proposed mode of organization (Table 4.1), Layer 0 is characterized by information referring to both the AINOP and LGP. As regards the AINOP, this refers to the information requested and present in some forms (e.g., Technical Annex A of the LGP). Meanwhile, the LGP, for survey information, refers to the relevant form (e.g., Annex A of the LGP —Level 0 bridge survey forms). The information identified at this level aims to have no duplicates. Layer 1, on the other hand, refers only to the LGP and provides information about the inspections that are carried out using visual surveys and collected through relevant forms (Annexes B, C, and D of the LGP). For instance, Type B Annexes require information distinguishing between the type of material (steel, prestressed or cast in situ concrete, masonry, etc.) and the element or part of the structure (pier, deck, etc.). Furthermore, there is a catalog of defects (Annex C of the LGP), which, for each element or part under consideration (beam, arch, etc.), reports a series of characteristic parameters for each defect (e.g., the severity of defect "G", the extent of defect "k1", the intensity of defect "k2") with relevant descriptions and an associated range of numerical values that can be assumed. Finally, in the case of particularly vulnerable elements, such as the reinforced concrete beams with post-tensioned cables, "special" inspections are required, and the resulting information can be collected in a relevant form (Annex D of the LGP). Layer 2 deals with the classification of assets via the definition of the Class of Attention (CdA), both in relation to an overall value and according to individual risk (structural and foundational, seismic, landslide, hydraulic), to establish a priority for the in-depth analyses, structural checks as well as for the planning of necessary maintenance. Five attention classes are defined (high, medium-high, medium, medium-low, and low). This parameter is defined by gathering data collected in previous levels. Layer 3, in the context of the LGP, involves a preliminary assessment of structural safety starting from some preliminary CdA definition for the bridge in question (e.g., medium-high, medium). Layer 4, finally, refers to the in-depth structural safety assessment. In the context of the LGP, a thorough assessment of safety must be performed in some cases such as where the CdA is high or where specific instructions have been given derived from the previous level (Level 3). This layer consists of information relating to both the NTC and the related circular as well. With regard to the LGP, these establish the different levels of analysis for the bridge under consideration (complete adequacy, operability, transitability NTC 2018—type 1 and transitability CdS—type 2). Each state refers to precise requirements relating to the coefficients, for materials and actions, to be considered for the verification.

Given this information, the strategy took into account the final export of the bridge model in IFC format as well. Considering this standard, semantic extension strategies can refer to two types of approaches: static (class definitions or related attributes) and dynamic (use of PSet/Properties or the proxy class concept) [88,201]. For this proposal, so far as alphanumeric information is concerned, reference was made to the second approach (development of PSets and related properties). Each identified layer is characterized by different sets of information organized in the BIM-authoring environment through the creation of parameters and associated, depending on the case, with either a structure or element level (see Table 4.2, Table 4.3, and Table 4.4). The subsequent IFC mapping procedure takes place using scripts, subsequently integrated into VP environments (e.g., Dynamo), which allow one to define the related configuration file automatically.

Table 4.2 - Layer-related information (i.e. PSets) for the BIM modeling and management activities in the Italian regulatory context.

Layer	IFC Class	PSet	Description
0	IfcBuilding	SBM_L0_BridgeStatus	*General information about the bridge's in-service status*
		SBM_L0_Classification	*Information regarding transport networks or waterways*
		SBM_L0_ConsequenceClasses	*Information about consequence classes*
		SBM_L0_DesignDocuments	*Project information (at different design levels) and maintenance documents*
		SBM_L0_DL22012004	*Information about DL n. 42 on 22 January 2004*
		SBM_L0_GeneralInformation	*Information about the bridge (e.g., IOP Code, name, owner, etc.)*
		SBM_L0_GeometricalData	*Geometrical data and characteristics (e.g., spans, lengths, etc.)*
		SBM_L0_HydrogeologicalRiskDocuments	*Documents about hydrogeological risk*
		SBM_L0_InspectionsMonitoringHystory	*Information about the previous inspections and monitoring activities*
		SBM_L0_Localization	*Information about localization and seismic hazard*
		SBM_L0_MaintenanceHystory	*Information about previous maintenance plan and related operations*
		SBM_L0_ProjectData	*Information about the project (e.g., designers, approvals, codes)*
		SBM_L0_RoadNetwork	*Information about road networks and daily traffic levels*
		SBM_L0_StructuralInformation	*Information about structural characteristics (regarding elements, materials, etc.)*
	IfcSite	SBM_L0_GeomorphologicalData	*Information about the site morphology*
1	IfcBuilding	SBM_L1_LastBridgeInspection	*Information about the last inspections through numerical values (e.g., DR)*
		SBM_L1_StructuralSketchforLastInspection	*Information about the last inspections through a link to*

			drawings, photos, and other
	IfcSite	SBM_L1_LastGeotechnicalInspection	*Information about the last geotechnical inspection*
		SBM_L1_LandslideRisk	*Information about the landslide risk (state of activity, type, etc.)*
		SBM_L1_HydraulicRiskGeneralInformation	*General Information about hydraulic risk*
		SBM_L1_HydraulicOverflowRisk	*Specific information about hydraulic overflow risk*
		SBM_L1_HydraulicErosionRisk	*Specific information about hydraulic erosion risk*
2	IfcBuilding	SBM_L2_CdABridgeInformation	*Information about the CdA values as a result of the implemented approach*
	IfcElement	SBM_L2_ElementInformation	*Information about condition status related to each structural element*
3	IfcBuilding	SBM_L3_BridgePreliminaryCheck	*Bridge structure information regarding a "preliminary" structural verification*
	IfcElement	SBM_L3_ElementPreliminaryCheck	*Structural element information regarding a "preliminary" structural verification*
4	IfcBuilding	SBM_L4_BridgeStructuralVerification	*Bridge structure information about an "accurate" structural verification*
	IfcElement	SBM_L4_RCBeamStructuralVerification SBM_L4_RCColumnStructuralVerification SBM_L4_RCWallStructuralVerification SBM_L4_RCFoundationStructuralVerification SBM_L4_RCSlabStructuralVerification	Structural element information regarding an "accurate" structural verification

Table 4.3 - Example of information regarding a particular 2nd Layer PropertySet (i.e. SBM_L2_CdABridgeInformation).

Property Set	Property Name	Meaning
SBM_L2_CdABridge Information	CdA	*CdA overall value for the considered bridge*
	CdAStructuralAndFoundationalRisk	*CdA value regarding the considered risk (Structural and Foundational Risk)*
	CdASeismicRisk	*CdA value regarding the considered risk (Seismic Risk)*
	CdALandslidesRisk	*CdA value regarding considered risk (Landslide Risk)*
	CdAHydraulicRisk	*CdA value regarding considered risk (Hydraulic Risk)*
	RelativeDefectiveness	*Information about the condition of the bridge and its structural elements*
	CdAReport	*Information about the CdA report*
	LastOrdinaryInspectionDate	*Date of the last ordinary inspection*
	OrdinaryInspectionsFrequency	*Frequency regarding ordinary inspections activities*
	LastExtraordinaryInspectionDate	*Date of the last extraordinary inspection*
	ExtraordinaryInspectionsFrequency	*Frequency regarding extraordinary inspections activities*
	LastSpecialInspectionDate	*Date of the last special inspections*

In addition, some information was conveyed through parameters that express summary information. For instance, concerning structural safety, the Safety Factor parameter (considered as the ratio between capacity and demand) was used. Considering the property set SBM_L4_RCBeamStructuralVerification, shown in Table 4.4, the property BendingSF,min expresses the minimum coefficient for bending safety among all the sections considered for a structural element (beams, columns, and so on). This approach is also considered for the other types of verification, and in general has been applied both at global (e.g., P-Δ, structure regularities, etc.) and elemental (e.g., shear, torsion, etc.) levels.

Table 4.4 - Example of information regarding a specific Property Set (i.e. SBM_L4_RCBeamStructuralVerification) related to the 4th Layer for a generic R.C. beam.

Property Set	Property Name	Meaning
SBM_L4_RCBeam StructuralVerification	BendingSF,min	*Minimum Safety Factor (Bending Moment) among all sections of the considered element.*
	ShearSF,min	*Minimum Safety Factor (Shear) among all sections of the considered element.*
	TorsionSF,min	*Minimum Safety Factor (Torsion) among all sections of the considered element.*
	Zita,e,min	*The ratio between the maximum value due to seismic load, carried by the considered structural element, and the related value considered in the design of new construction.*
	Zita,v,min	*The ratio between the maximum value due to variable vertical load, carried by the considered structural element, and the related value used in the design of new construction.*

4.3.2.1 Definition of the proper LoIN in the context being analyzed

Taking into account what has been stated previously, there is a need to specify information requirements for the creation and management of BIM models per the scenario under investigation. The new approach related to the UNI EN 17412-1 standard provides a precise method for the definition of the level of information need by identifying: purpose (why), milestones (when), actors involved (who), and objects of exchange (what). In this respect, information should be organized according to geometric, alphanumeric, and documental aspects. The adoption of this new approach is justified by the fact that it is needed to manage all the information that is strictly necessary for specific use and related purposes. In this regard, Table 4.5 clarifies and summarizes, in detail, the LoIN considered regarding geometric, informational, and documental information consistent with the purpose and phases that were identified. The first thing to be analyzed was the purpose. Record information, managing risk, and checking and monitoring structural safety were considered. Another aspect consisted of the identification of the lifecycle phase. Information models may refer to the management phases including any structural sub-phases (e.g., structural safety assessment, retrofit interventions, etc.). Actors, instead, refer to the specific structural activity being considered in the scenario under investigation (e.g., bridge structural engineer, bridge inspector, and so on). Following this new approach, several LoINs for the single component, global structure, and other aspects (such as site, project, etc.) have been proposed. According to the UNI EN 17412 Annex (e.g., type B), a suggested form was considered to specify and list the necessary information requirements. Below, an instance of a LoIN for a bridge element is shown.

Table 4.5 - Example of proposed LoIN for the bridge component (e.g. R.C. beam).

Information Delivery Milestone			**Maintenance Phase**
Purpose			**Record information, manage risk, check and monitor structural safety**
Actor			**Structural Engineer**
Object			"Beam"
	Geometrical Information		Requested
		Detail	*Simplified representation*
		Dimensionality	*3D*
		Location	*Absolute*
		Appearance	*Digital*
		Parametric behavior	*Not Requested*
	Alphanumerical information		Requested
		Identification	*IdentificationCodes*
		Information content	*SBM_L2_ElementInformation* *SBM_L3_ElementPreliminaryCheck* *SBM_L4_RCBeamStructuralVerification* *PSet_Condition* *LocalizzazioneDifetti*
	Documentation		Requested
		Set of documents	*Technical documents and drawings, inspection reports and other information (photos, videos, etc.), monitoring reports and other information (raw data, graphs, etc.), design documents, etc.*

In the case of the bridges considered in this proposal (i.e., reinforced concrete bridges), the 'simplified representation' of the bridge elements (beam, column, etc.) was chosen. This considers the modeling of the reinforced concrete part only, without the reinforcement. As regards alphanumeric information, this refers to the proposed parameters and related PSets (e.g. considering what has been proposed in section 4.3.2), which manage information derived from the census, inspection, structural assessment, and so on. In some cases (e.g., CdA), alphanumeric information is also obtained by processing other data (via scripts or algorithms belonging to the proposed RCBFramework) inserted in the input environments developed for the specific application. As regards documentation, this refers to information (e.g., images or sketches, photos, technical drawings, forms, schedules, structural reports, etc.) related to the activities of the structural bridge management.

4.3.3 Defining a digital approach for the structural management of bridges in a BIM environment

Since there is a clear need for automatic support for the creation and management of digital models and related information, it has been developed a BIM-based solution (the RCBFramework) and a digital strategy, as described in Figure 4.3, which supports the following activities: (i) data entry (based on specific BIM objects and the data input environment); (ii) 3D model generation; (iii) model information management; and (iv) asset information management. In some cases, the IT frameworks were built through the collection of classes, which provided the implementation lines for the application being developed [212]. The structure of the proposed framework was supported by scripts and algorithms written in the CPython and IronPython programming languages, frequently used and integrated into visual programming environments. The architecture of the proposed RCBFramework follows the well-known MVC pattern. This pattern, used in programming, organizes code into blocks (i.e., Model, View, and Controller) to keep them distinct and ensure the code's maintainability. The adoption of an advanced IT approach makes it possible to generalize the solution developed, in terms of the IT model, both for the generation of the BIM object and the information management, so that it is implementable in other kinds of BIM authoring environments.

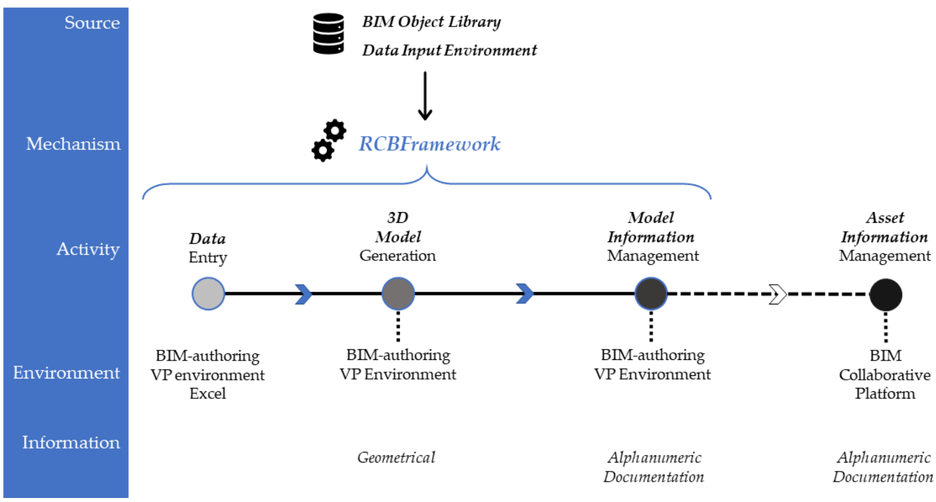


Figure 4.3 - Proposed strategy to manage structural bridge information in the context under analysis.

The following framework was structured according to classes and modules with different levels of abstraction or specialization. Therefore, following an object-oriented programming (OOP) approach, the code is organized into IT classes, which define a means to represent categories of objects (beam, column, etc.), with several attributes, which define the characteristics of the category of objects being represented (identification, dimensions, etc.). IT classes are supported by the inheritance mechanism, which can be significant when code reuse strategies are applied. In addition, several methods are set to support CRUD ("Create", "Read or Retrieve", "Update", and "Delete") operations related to specific data concerning the various components of a bridge. For example, the "retrieve" methods permit rapid editing operations of the geometry and information associated with some BIM objects. This framework organization was developed to be extendable to other types of bridges as well. Indeed, to achieve such an extension, it will be necessary simply to develop new packages, modules, classes, and methods related to other kinds of bridges and their associated functionalities.

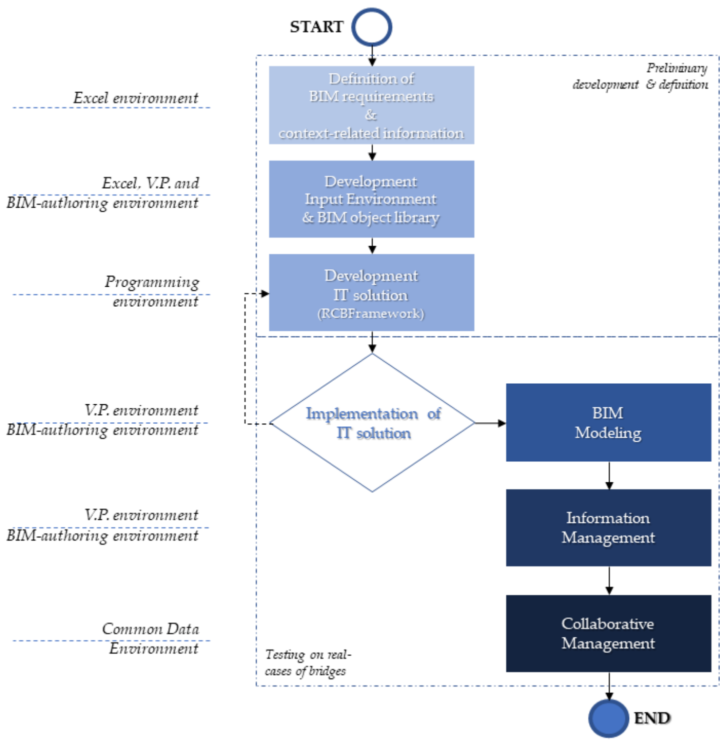


Figure 4.4 - Activities and workflow related to the development of the proposed solution.

Figure 4.4 describes the activities considered for the development of the proposed digital solution. These were considered with the aim to test the proposed solution on the selected real cases of R.C. bridges. Therefore, Figure 4.3 and Figure 4.4 present a series of environments and applications. BIM-authoring software of Autodesk, i.e., Revit, mainly using Dynamo as an integrated VP environment has been considered. In addition, the Excel application has been chosen for organizing data flows with the Dynamo environment. These data will be necessary for creating and updating BIM model information. This environment gives the possibility of implementing developed scripts and communicating with Revit through its API solutions. The proposed solution largely involves the definition of custom nodes that integrate scripts developed in the IronPython language. Finally, the implementation of the IT framework (i.e., RCBFramework)—in the BIM environment—required some time for building a tailormade solution (through methods and their scripts) that considers the peculiarities and characteristics of the bridges under analysis. However, this approach could be improved and extended in the future (e.g., through the development of other scripts and procedures) to consider other types of work.

4.3.3.1 Data Entry Input and BIM Object Library Setting

As a starting point, a specific BIM object library and a data entry environment have been developed, which supported the model generation and information management activities in the analyzed context. In this environment, data were inputted, arranged in specific tables, and then collected in organized lists to be retrieved later and used by the proposed framework implemented in Dynamo (e.g., DAO modules). Information, for instance, derived from surveys or inspection activities, was entered through an input interface, sometimes also using macros developed ad hoc. These data were successively retrieved by scripts, implemented in the VP environment, and recorded in the specific parameters set in the BIM-authoring environment. Following the information requirements defined previously, a BIM object library was developed. This was carried out considering the use of BIM-authoring software (i.e., Revit). Thus, a library of BIM objects (i.e., Revit families) was set, each related to typological elements pertaining to the bridges under analysis, specifically developing further families that can represent the specific features of the structural components belonging to the bridges in question. This approach enables the reuse of such components for the digitalization of other bridges with similar characteristics (e.g., bridges belonging to the same transport network) or extension in the future, with the addition of other Revit families, to other bridge typologies that are not considered in this proposal. For the generation of the geometry, information acquired by the surveys, existing drawings, and original documents were taken into account. These objects were considered as a starting point to be called up by the proposed framework, in addition to alignment information, for the definition of the bridge information model. Therefore, to move towards the automation of modeling procedures, the generation of BIM objects was carried out through the proposed "RCBframework", implemented in the integrated VP environment, and the APIs made available by the authoring environment.

4.3.3.2 3D Model Generation

As far as construction is concerned, a bridge is always built from the bottom up, i.e., proceeding from the foundations to the deck, and then on to the construction of the road or railway. In BIM modeling of a bridge, however, beginning with the infrastructure alignment, the construction of the model proceeds from top to bottom. The proposed framework, for the generation of the geometric part of BIM models, considers the concept of alignment (e.g., 3D polyline) as one of the input data sources to organize, arrange and create the structure of the bridge and its components, each of which is relatively positioned (in terms of angles, distances, etc.). The generation of the bridge, by considering the alignment data and other information (number of spans, number of piers, etc.) inserted through a specific input environment (e.g., Excel forms), allows for automating the generation of the model and some of the information associated with it. This saves time compared to standard manual modeling procedures in BIM-authoring environments. However, the approach defined by the framework needs to be contextualized in the authoring environment that is used, and with respect to the availability of related APIs. For this reason, classes and methods allow for implementation via dedicated developments in each environment under consideration (e.g., Dynamo, Grasshopper, etc.). In this proposal, implementation of the RCBFramewok was realized in the Dynamo environment. This required the development of classes and methods, starting from the RCBFramework (e.g., in terms of classes and methods), with the subsequent definition of the related IT objects. The implementation of these procedures allows the production of BIM models, in the BIM-authoring environment, after being exported in IFC format through the implementation of other specific procedures. These, along with the selected information, were subsequently managed in the BIM collaborative platform.

4.3.3.3 Model Information Management

The information management implied by this framework which is consistent with the relevant regulatory framework has the objective of developing a data model aimed at integrating the BIM models that originate from the generation solution described above. This data model was also built taking into consideration the structure of the IFC open format and what was reported in Table 4.2, Table 4.3, and Table 4.4. Accordingly, it was divided into five layers, each of which contains a reference to the IFC class and associated property groups. Regarding the previously described IT approach, in the case of information management, some attributes (e.g., ordinaryForms, specialForms, PsetForms, etc.) for specific classes (e.g., LongBeam class) were provided to associate, for instance, the information that derives from the inspection forms (e.g., ordinary, special, etc.) to the parameters and properties that were processed. According to the organization proposed previously, it is possible to write, record, and extract data relating to the various inspections that take place over time. Therefore, the proposed framework contains the fundamental logic for the development of any changes regarding information management, for instance via proposed CRUD operations (e.g., in specific modules) for the expected information related to the elements that make up the bridge. Indeed, for each layer, the relative module was defined (e.g., base_im_L0_control.py for layer 0). Layers following layer 1 (e.g., from layer 2 to layer 4) were characterized by additional instructions for processing synthetic information regarding, for instance, the condition of a structural element (e.g., relative defects) or related to structural safety (e.g., structural verifications). Additionally, through the development of different methods, some reports are automatically developed (in .txt format) and referenced to the BIM objects of interest through specific parameters (e.g., considering URL data type). The purpose of a report is to make available bridge data, in a more useful and synthetic manner, via specific parameters (e.g., percentage variation over time of the relative defect parameters, such as k1, k2, and I, according to the LGP setting). Therefore, once the BIM model was developed, from both a geometric and informational point of view, a method related to the IFC export settings of the BIM model was created as well. This enables the correct writing of the configuration file (given the specific BIM-authoring software, e.g., Revit) for IFC mapping operations concerning the structure of the IFC standard in question. Thus, the procedures defined in the solution following the RCBFramework implement the logic for updating BIM models of bridges from an information point of view, where model information can be updated (via CRUD operations) following the latest inspections that have been carried out. This proposal allows the digital model to be updated following inspections and the automatic tracking of the evolution regarding the conditions of the bridge and its structural elements, as well as the management of information related to the assessment of structural safety via synthetic parameters (e.g., safety factors).

4.3.3.4 Asset Information Management

Having introduced the part of the digital strategy adopted for the creation and management of BIM models at both geometric and information levels, it is also necessary to manage the documental level belonging to the LoIN settings identified previously. Indeed, LGP suggests the adoption of collaboration platforms and data-sharing environments for the effective and transparent management of a given asset. Following international (e.g., the ISO19650 series) or national (the UNI11337 series, Ministerial Decrees, and further updates) regulation context in force concerning BIM, it is possible to use “interoperable platforms by means of non-proprietary open formats” with data “that can be requested at any stage and by any actor”, with information flows (relating to contracting authorities and related procedures) to be carried out “within a data sharing environment, where the digital management of information processes takes place” in addition to a series of requirements such as accessibility of roles-based figures, traceability of operations, support of various types of formats, and so on. Following this suggested direction, a specific BIM management platform has to be considered. This platform should also support digital workflows, involving various professional figures in a single collaborative environment. Thus, this kind of digital management allows the model to be interpreted as an “access key” reference, where information is always available and accessible to the professionals involved (structural engineers, maintenance technicians, bridge inspectors, etc.), which can manage and update the information about the bridge according to various structural contexts (census, surveys, inspections, structural safety assessment, maintenance activities, etc.). Within the framework of specific scenarios (e.g. AINOP), further developments have also been proposed, concerning new model-based information management (based on specific information requirements) and digital collaborative processes (based on openBIM) that involve interested parties.

4.4 Results

The results obtained after the implementation of the proposal are described in the following, providing a digital strategy suitable for application in the Italian regulatory context. The results have been achieved regarding real cases of reinforced concrete girder bridges. The expected results, in this case for R.C. girder bridges, include (i) the generation of BrIMs according to proposed LoINs; (ii) implementation of the proposed solution for processing and managing relevant information in the context under investigation; and (iii) organization and management of structural information and related collaborative workflows. The first two results were achieved utilizing the specifically developed framework (RCBFramework), in addition to the availability of specific BIM objects and a data input environment. The third result is accomplished through the use of a collaborative environment and its related features.

4.4.1 Description of the selected case studies

The applicability of the proposal is tested on judiciously chosen real-life cases with different characteristics. Specifically, girder bridges were managed with the considered approach. The first two consist of a road viaduct and a highway bridge, both made of reinforced concrete (see Figure 4.5).

The road viaduct (see Figure 4.5a) was built in the second half of the 1980s. It consists of a total of 34 m spans, giving a total length of about 1200 m. The spans are characterized by a transversal section with a total width of 11.30 m. The decks are made of four prefabricated post-tensioned R.C. beams, arranged with an interaxis distance of around 2.8 m, connected on-site with five transverse beams and a slab of cast-in-situ reinforced concrete. The piers are made of a single circular column of reinforced concrete and, on top, a beam with a support system consisting of several R.C. blocks. The second case study (see Figure 4.5b) involves a highway bridge, built in the early 1960s and made of three simply supported bridge spans. The decks are 24 m wide and made with a grillage of transverse and longitudinal beams. Each span is characterized by 10 longitudinal beams of R.C. cast in situ with an interaxis distance of around 2.4 m. The two side bridge spans are 8.84 m long and include three transversal beams, while the central span is 18.62 m long and includes four transversal beams. The decks, piers, and abutments are all made of reinforced concrete cast in situ. The three spans also have non-rectangular decks with a deviation angle of around 44 degrees. Support devices consisting of lead plates of various sizes are placed on top of piers and abutments. The piers consist of rectangular section columns in the central part and polygonal section columns in the end parts of each bridge pier. These cases were also selected to test the capabilities of the proposed framework in generating BrIMs for different configurations of the bridge structure, regarding the different geometries of the constituent elements and the arrangement of the structural elements along the bridge's alignment.

(**a**) (**b**)

Figure 4.5 - (a) Real case of road viaduct; (b) real case of a highway bridge.

Considering further developments carried out for supporting the information management required by the AINOP context, a third case study was considered. It consists of a highway viaduct, also made of reinforced concrete (see Figure 4.6). It was built starting in 1969 and has 25 simply supported decks with a span of 45.00 m. The deck is characterized by an overall width of approximately 19.10 m and contains traffic lanes of approximately 3.75 m, while the slab is made of prefabricated slabs and contains both roadways separated by a central new jersey-type barrier. The width of each roadway, with independent flows, is approximately 8.7 m. The deck also consists of six prestressed concrete beams arranged approximately 3.40 m apart and joined by the upper slab and four prestressed concrete transverse beams. The prestress reinforcement of the beam is realized through pre-stressed strands and a post-tensioned cable placed in a conduit. For the traditional reinforcement, the use of ribbed bars was envisaged. The piers consist of two stems made of box-type elements and connected at the top by a reinforced concrete beam on which the beams are supported. The two columns of each pile are founded on a single plinth which is supported by piles. Over the years, the bridge was affected by several rehabilitation works that mainly involved the strengthening of the bearing supports, the maintenance of the support devices, and the cortical renovation of the prestressed concrete beams.

Figure 4.6 – Another case study related to an existing highway bridge.

4.4.2 *Implementation of the proposal*

What was proposed, successively, was implemented by defining workflows that involved Excel, IronPython, Dynamo, and Revit along with the use of the collaborative platform. Excel software was used as an environment for the management of input data through the development of ad hoc input interfaces, both for BrIM generation and information management. Dynamo, meanwhile, was used as an environment for the implementation of the scripts and algorithms that were developed in the programming environment (as shown in Figure 4.7 below). Dynamo and Python interacted via the "Python Script" node, where the code can be written using the Python language. This allowed implementation, via scripts and algorithms in the Dynamo environment, of the proposed IT structure that constitutes RCBFramework. In the Dynamo environment, starting from the provided classes by the framework, the necessary implementations for the case studies were developed within several "Python script" nodes (e.g., "ge_im_model.py", which includes more than 2000 lines of code referring both to the generation of models and the information management activities), as highlighted in the blue boxes of Figure 4.7. Retrieving data from inputs built in Excel, the solution implemented in Dynamo allowed us to instantiate the IT objects and generate associated BIM objects with related information. Specifically, in the "Model Generation" box (in orange, see Figure 4.7), the use of the "Family Types" node was planned as an input to the method for the creation of a relative element (e.g., longitudinal structural beams). For each component of the bridge (beam, column, wall, etc.), a specific Revit family was developed (e.g., LongitudinalBeam.rfa) in accordance with the reference IT class for the bridge component in question (e.g., "LongBeam" class). This logic was applied to all the structural components of the bridge. These implementations use the available APIs, from both Dynamo and Revit, for supporting the generation of the bridge information model and the information management activities in the regulatory structural context under analysis. This logic was applied to all the structural components of the bridge.

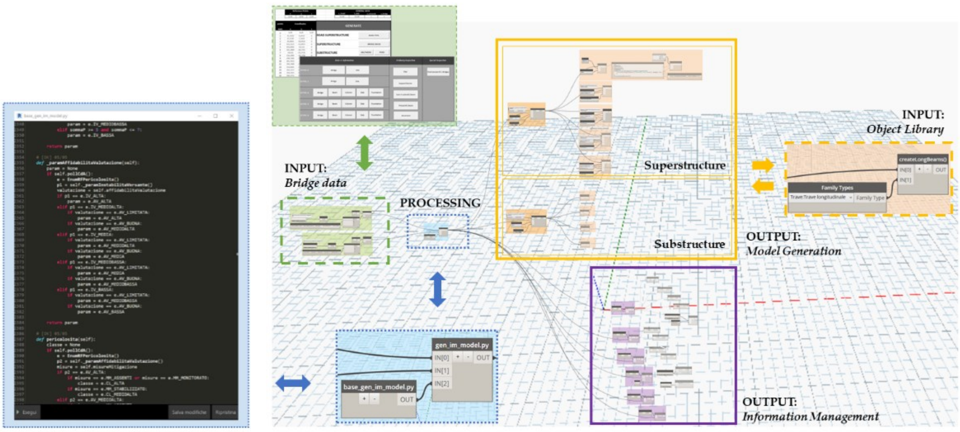


Figure 4.7 - Dynamo architecture for supporting the proposed solution concerning model generation and information management activities.

The modular organization of the proposed framework, in the Dynamo environment, considered a set of initial input data, organized in tabs or macros built in Excel, for the definition of the informative model (e.g., coordinates of characteristic points, slopes, distances of structural elements, etc.) and information management activities (e.g., data derived from inspections, data for scripts defined for the processing of the CdA, etc.). Afterward, these data, which are functional for the definition of the different instances of the IT classes provided for the framework, were collected in appropriate tables built to feed the procedures implemented in Dynamo. IT model contains generalizations of the bridge elements (beams, columns, foundation, etc.) and, therefore, the IT classes and their relationships. The input data will then be imported from some scripts implemented in Dynamo (e.g. via "Data.ImportExcel" node), and then retrieved from the IT model prepared for the generation of the BIM model and information management activities. For example, as in the case of the bridge alignment definition, specific classes and methods were defined to generate the alignment for the arrangement of the bridge elements. Several scripts (as shown in Figure 4.7) were implemented in Dynamo to enable the definition of the bridge alignment (e.g., method "polygonal_bridge()"), from which to then also obtain references for the generation of the bridge substructures. This method required a set of initial information such as a starting point, section lengths, section slopes, initial bridge height, final bridge height, and others. All this led to the output alignments for the definition of the BIM models of the bridges under consideration, as shown in Figure 4.8.

4.4.2.1 Definition of context-related BIM models

Starting from bridge alignment, along with specific settings for local reference systems and relative distances or slopes, the positioning of the bridge's structural elements was carried out both in the case of the alignments of the linear elements (e.g., beams) and the contours of bidimensional elements (e.g. slabs). Subsequently, this information was necessary to obtain the BIM objects. A similar reasoning was used for the piers, and related reference systems were also set for them. Furthermore, by processing the relationships and spacing between the various components of the considered bridge, the script allowed obtaining the correct positioning of the BIM objects, avoiding relative interpenetration. In the case of the piers, the positioning and generation of related BIM objects are linked to the deck information. The definition of BIM objects was carried out according to specific requirements (i.e. LOINs). Hence, the generation of the BIM model began with the generation of the structural bridge decks and their components, before moving on to the development of the piers and abutments—in other words, following a top-down system of modeling. Considering the modeling phase, in the case of both bridge superstructure and substructure, specific data (slopes, distances, etc.), provided during the input phase (e.g. through Excel forms), were considered by the developed framework. Starting from Dynamo instructions (see Figure 4.7), the generation of the BIM model, both for the road viaduct and highway bridge, as shown, respectively, in Figure

4.8 has been carried out. As may be noted in the following figure, a complete BIM model was produced, consistent with the information provided in the input phase (alignment, bridge or element characteristics, and so on). In addition, to manage the complexity of non-rectangular decks, the attribute "beta" was added to the class related to the bridge pier, representing the angle formed between the axis of the pier itself and the longitudinal axis of the bridge deck being considered. This was then related to the alignment and relative position of the bridge's structural elements. Once the BIM models of the bridges were built, they were ready for the next phase of information management.

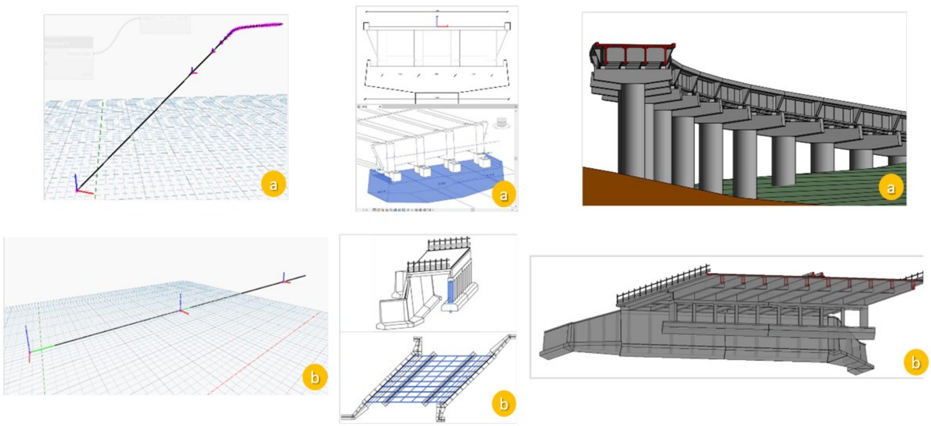


Figure 4.8 - Generation of a BIM model by means of the proposed solution (Revit and Dynamo), for the road viaduct (a); and the highway bridge (b). Modeling phases consist of bridge alignment definition (1); BIM objects creation and relative position.

4.4.2.2 *Information management within the context under investigation*

Following the generation of the BIM models, the information that has to be managed regarding the bridge and its components refers to what was defined previously. As explained here, the data model was organized according to the proposed information layers (see Table 4.1).

As shown in Figure 4.9, necessary data derived from original documents, surveys, inspection activities (regarding the annexes considered by the regulations), and so on were entered through input interfaces (e.g. Excel macros), which saved the information in tables that were later retrieved by scripts.

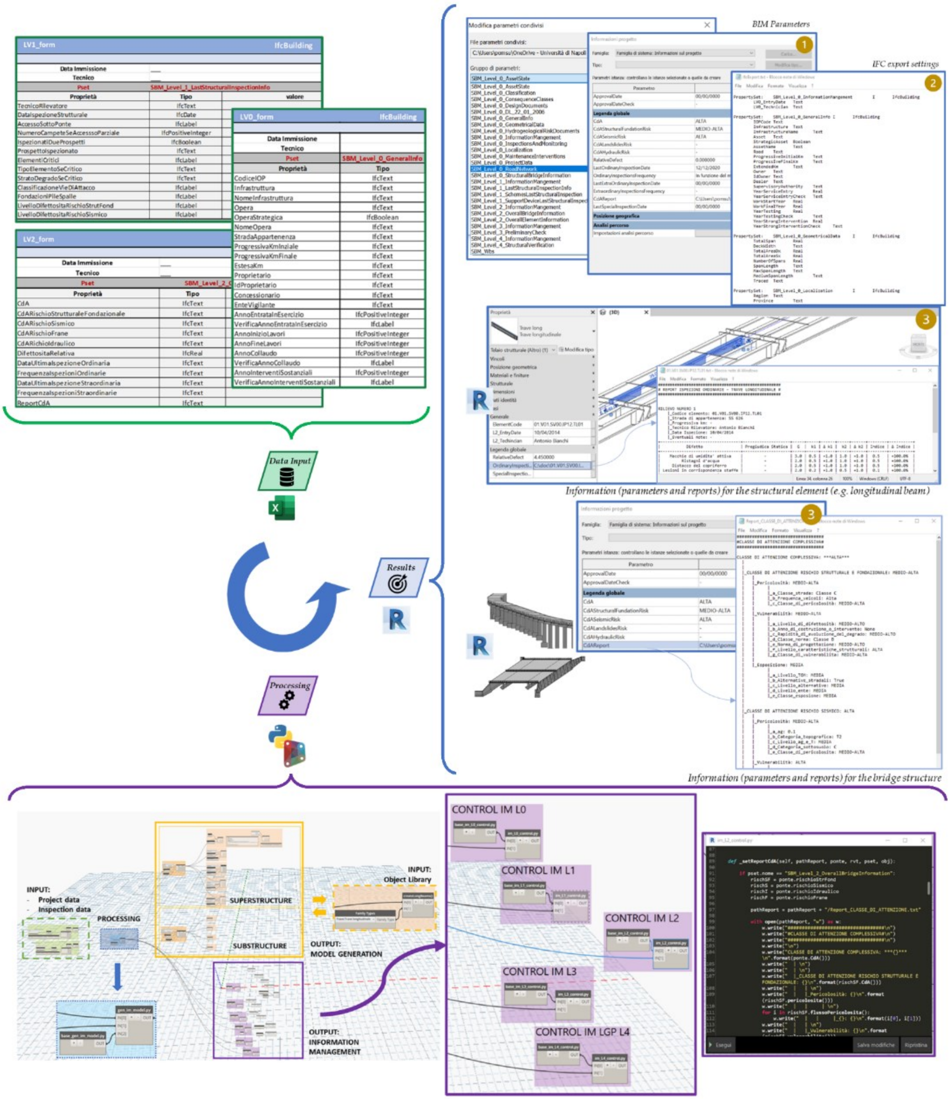


Figure 4.9 - Organization of information layers in the BIM environment (Revit and Dynamo) for the definition of a specific workflow for saving, processing, and recording information, starting from acquired data. (1) Definition of BIM parameters and relative association to element categories; (2) definition of an automatic procedure for the exporting of IFC models; (3) association and updating of BIM parameters and summary report both for structural component and bridge structure.

Subsequently, in the Revit environment, using certain instructions implemented in Dynamo, the creation of the parameters and their association with the reference Revit categories (e.g. Project Information, Structural Framing, etc.) were carried out. Considering what has been shown in Figure 4.9, some inputted data can be used not only for the enhancement of associated parameters but also for the processing of the summary information for the other information layers (e.g. the CdA parameter) following the logic derived from the context under investigation (e.g. LGP). As previously described, the employed methodological approach defines IT classes and related methods. For instance, in the case of the digitalization of CdA information, individual risks (structural and foundational risk, seismic risk, landslide risk, and hydraulic risk), with related primary and secondary parameters, have been encoded. Accordingly, the CdA algorithm, after having processed and gained the related values, associated them to bridge structure as BIM parameters. To achieve this, the processing of the "Relative Defectiveness" value (DR) is necessary for the definition of the CdA values. As suggested by the LGP, DR is a numerical indicator of the condition status. This can be specified about a single element, homogeneous groups of elements, or the whole bridge structure. Based on the defects that are encountered, which are described by filling in the relevant forms, through calculation of characteristic parameters (G, k1, k2, etc.), it is also possible to define the DR value obtained as Σi (Gi × k1,i × k2,i). Gi, k1,i and k2,i represent, respectively, the importance, intensity and magnitude of each defect detected during an inspection. These are defined on the basis of a specific catalog of defects provided by LGP (as a specific Annex C of the LGP). Accordingly, related scripts and algorithms were developed, and successively implemented in Dynamo, to make these operations available, with related output information, in a BIM environment, as shown in the following figure. As shown in Figure 4.9, some reports were generated (in .txt format) through other scripts that were implemented. For the single structural component of the bridge, this report was proposed for summarizing, for each inspection, data used in determining the DR value, to have access to the relative defect history.

As regards the bridge structure, another .txt file summarizes, for each inspection, data and values that were used in determining the CdA, for the overall value, and single risk values. Both in the case of a single element or the bridge structure, this is automatically linked and recorded in the corresponding parameter (regarding a URL-type value). All this was carried out to keep BIM models constantly updated with the latest information, ensuring greater readability of the information obtained during processing. Additionally, this proposal allows the determination of the resulting information related to risk definition and structural safety for the bridge under consideration. As regards information layers L3 and L4, synthetic parameters (e.g. Safety Factor, as also proposed in Table 4.3) relating to bridge or element condition, obtained after structural assessments, were taken into account. This information was later integrated into the informative model of the bridge as well. For all this target information (e.g. CdA, SFs, etc.), the implemented scripts in the Dynamo nodes, using data provided in the input phase, process it to obtain the specific information of interest (e.g. Table 4.3 and Table 4.4) and then update the BIM model, associating the values thus obtained within the proposed parameters (e.g. through the "updateLayer" method). Accordingly, once data are available referring to the results of structural assessments (considering vertical loads, seismic actions, etc.), e.g., for a generic structural component, such as a longitudinal beam, obtained data can be referred to shear, bending moment, torsion, and other possible effects. This information refers to a certain level of analysis or verification (e.g. considering the LGP setting for a bridge status: Adequate, Operational, etc.), later specified in some parameters in the BIM environment (e.g. "StatusOfStructuralVerification", "SBM_L4_BridgeStructuralVerification"). However, as a result of subsequent inspections or necessary monitoring activities, it is also possible to update these managed values over time. CRUD operations were prepared and implemented via the procedures integrated into the various Dynamo nodes. In addition, to manage the evolution of condition status related to the bridges being considered, some parameters, such as "relativeDefectivenessVariation", were defined as well. This is related to the relative defectiveness variation in question (for element, aggregation, or anything else in consideration) following consecutive inspections. It can be used to provide graphic views or to analyze related data to understand the evolution of the bridge condition status. Following the evolution of a bridge's condition status, since the proposed approach can also track updates following inspection activities and structural assessments, in this context, the use of a collaborative platform (i.e., usBIM.platform) was also considered for the management of required information (according to the proposed LoINs), as shown in Figure 4.10.

1)

2)

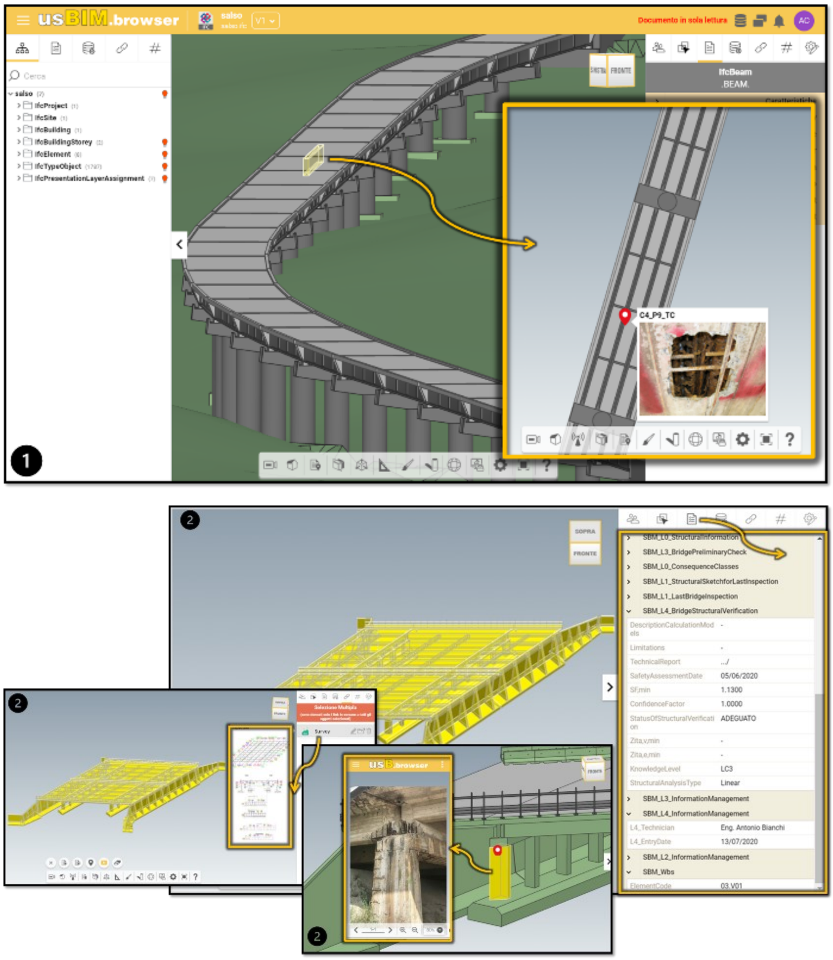


Figure 4.10 - The management of information by using the collaborative platform (usBIM.platform) according to the proposed LoIN setting, both at the global and local level, in the case of (1) the road viaduct and (2) the highway bridge.

This environment consists of an IFC-certified platform (https://technical.buildingsmart.org/services/certification/ifc-certification-participants) and is characterized by several functionalities that can support bridge management activities. Therefore, BrIMs were loaded into this platform and conceived as the front end for reading and managing the information related to it. First of all, a Common Data Environment was organized in accordance with the relevant standards (UNI 11337, ISO 19650). Platform features allow us, for example, to define workflows for process control with advanced task management functions, procedures for reviewing or validating the associated information (e.g. gate function), and the integration of significant data through advanced functions for BIM data management. Another "link" function enabled the integrated management of the bridge data, allowing the association and storage of some of the documentary information collected during the various sub-processes that constitute the management phase (inspection, interventions, etc.). By considering these features, it was possible to record and associate documentation, specifically reports (relating to inspections, structural or geotechnical assessments, etc.), photos (relating to the overall condition of the structure or its component), manuals, documents, and other items regarding both bridge components and the total structure. The tools of the collaborative platform allowed the exploitation of the information through the model using graphic filters, links, and images associated with BIM objects, thus facilitating their accessibility. This environment also made it possible to update the values of the defined properties (e.g. Table 4.2, Table 4.3, and Table 4.4) and enabled the management of the versioning of the models derived from the structural context in question.

Under the AINOP scenario, further developments focused on the definition of a proposal for new information management in the BIM environment, based on IFC models (developed according to specific information requirements) and digital collaborative processes involving the parties concerned. As a result of this proposal and what was previously defined, the information required by the context was recorded and referenced with respect to a 3D and parametric model, including collaborative processes that made it possible, for example, to organise and standardise the procedures for feeding or updating information and reporting any issues. AINOP structure was therefore organized within the considered platform, according to both its sections and subsections. By integrating and linking the required information, better control and centralization of information about public works (including bridges and viaducts) was facilitated by referencing what was required within the BIM model. Information was then extracted and synthesized, integrating some of it within the BIM models and their objects. Hence, information retrieval is facilitated by realizing intelligent links with the BIM model and its components. This new management, regarding the monitoring of the condition status along with the structural safety of the civil work (in this case a bridge), will favor the development of a more realistic plan of action concerning intervention priorities and prompt maintenance activities, now benefiting from all-encompassing management of information based on informative models. The use of a collaborative environment, which would allow all BIM models (in IFC format) to be visualized and managed, and allow the user to organize and use information (including BIM models, documents, etc.), also made it possible to support the proposal based on the new LoIN framework for the management of geometrical, alphanumeric and documental information.

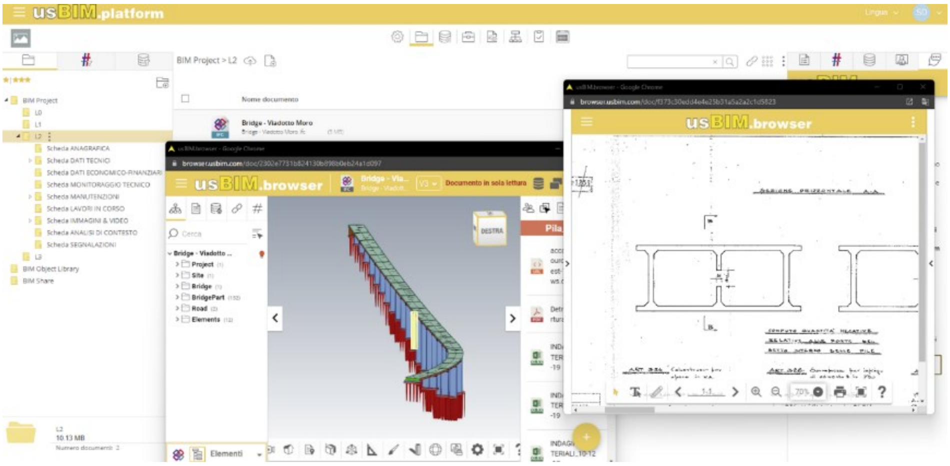


Figure 4.11 - Use of the BIM collaborative environment (i.e. usBIM.platform) for the applications developed.

Currently, such information is not yet managed through BIM-based approaches, and in addition, existing systems used today by authorities or managing bodies are not yet ready to fully meet the new requirements arising from the new regulatory environment (including AINOP provisions).
Following this proposal, both from a geometric and semantic point of view, it was necessary to specify information requirements for the creation and management of bridge BIM models. Considering what has been established in section 4.3.2.1, there is a need to consider an appropriate LoIN - with its geometric, alphanumeric, and documentary information – and be consistent with the scenario analyzed (e.g. AINOP) and the latest regulation framework (e.g. UNI EN 17412-1). An example of LoIN pertaining to element-level information is given in Table 4.5. After having chosen a simplified geometric

representation of the bridge elements following the purposes considered, alphanumeric information is considered along with data regarding the identification of the bridge and its constitutive components also in accordance with the logic of the Asset Management system being considered (i.e. Argo system). Accordingly, the Property Sets (both standard and user-defined), defined both at the element, aggregation, and structure level associated with the reference IFC classes, were defined to convey information regarding the census, inspection, maintenance, and other contexts considered by the requests of the AINOP subsections. As for the documental level, the information being considered relates to plans, photos, technical drawings, reports, and diagrams (on the subject of intervention scheduling, structural inspections, maintenance plans, etc.). The bridge and its components, developed from a geometric point of view, were then semantically enriched with data and information through standard procedures and with the support of advanced mechanisms or services (e.g. through functionalities of the considered platform such as usBIM.editor, usBIM.bsDD, and usBIM.bsDDeditor). However, this proposed workflow for bridges could be applied to other types of infrastructure (such as roads, railways, tunnels, etc.). The information management, carried out with the use of a collaborative environment (e.g. usBIM.platform), has pursued several purposes: (i) to fulfill the LoIN required by the considered proposal; (ii) to enrich the BIM model from informative and documental points of view, linking it to information concerning the bridge's condition (e.g. regarding present defects); (iii) to develop a proposal to virtualize the AINOP platform on the BIM collaborative environment that was considered, for connecting and facilitating information exchanges between supervising and conferring parties, and standardizing information flows based on informative models. To date, the AINOP platform still requires information to be delivered through reports and other documents (e.g. using .pdf, .doc, .png formats) uploaded in specific boxes of relative subsections.

The purpose of this application is to promote the census, recording, and management of the infrastructural works pertaining to Italian heritage, providing a proposal for new digital management based on informative models managed in a BIM collaborative environment. The advantages of using BIM, especially in the case of bridges and viaducts, lie in the efficient organization and management of information resources, centralized on a three-dimensional reference (information models), as a means to overcome criticalities due to the fragmentary nature or delocalization of information in 2D documents or drawings alone. Therefore, the application under consideration aims to facilitate the various parties involved in the organization of all required information and developing digital workflows, with specific roles and activities, based on digital and interoperable models of the infrastructure. The platform used (i.e. usBIM.platform) made it possible to manage and link any type of file and information to the IFC model, by using its specific functionalities. For the proposed information management, a specific AcDat was organized following the UNI 11337 series, providing different working areas according to the processing states of the information content. Under the working area assigned to the publication of the contents (i.e. L2 status) with the client (e.g. which could be carried out by the relative ministerial authority), the BIM model in IFC format was uploaded. This represented an access key and a means of linking to all the information that is required by the AINOP web platform. Subsequently, the structure of AINOP was replicated and organized into several folders representing the subsections of which AINOP is composed. Indeed, as required by Ministerial Decree 439/2019, information is referred, for example, in a census record folder, a technical data folder, an economic-financial data folder, a technical monitoring folder, a maintenance folder, a work-in-progress folder, a context analysis folder, and so on. Indeed, the information contained within these folders was then linked to the BIM model and its components relating to the viaduct under investigation. This will facilitate faster validation of the information provided, which is now organized and coordinated with respect to a three-dimensional informative model. Future validation activities could also take into account counter-checking procedures that may be made available and performed within the collaborative environment being used (such as the one used, i.e. usBIM.platform). Furthermore to document-type information, specific data were also provided using properties and attributes of IFC classes within the BIM model itself. On the other hand, regarding the activities related to the different roles covered, for example, the conferring party will have to check - before publishing what is required in the specific working area - the adequacy and correctness of the information to be provided. Moreover, in the case of any possible issues, it will have to make the necessary revisions and re-upload the exact information to be submitted again to the supervising party. Afterward, the latter will check the compliance, completeness, or lack of information in relation to the different folders. Therefore, regarding the activities that are foreseen in charge of the conferring and supervising parties, digital workflows have been proposed (implemented in the AcDat set on the collaborative platform being used, i.e. usBIM.platfom). These allow us to cover and regulate activities concerning, respectively, information sharing required for the civil work (by the conferring party) and the control/validation of what has been published by the conferring party (by the supervising party). All this was proposed considering the "working levels" (L) and "verification levels" (LV) according to the UNI 11337 standard. In particular, BIM workflows were provided, as shown for example in the following figures:

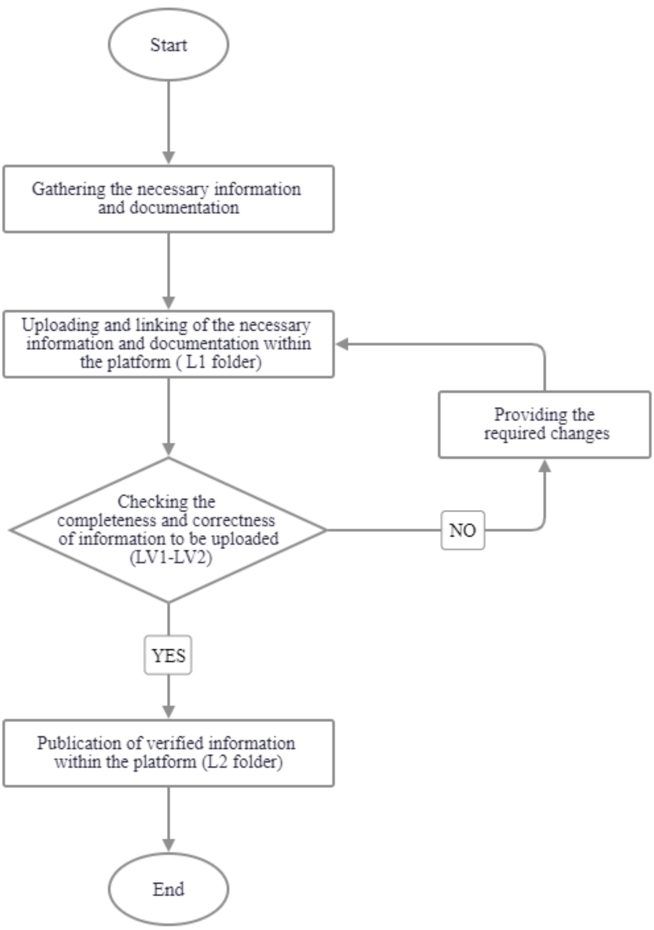


Figure 4.12 - Example of BIM Workflow for the Conferring Party (in usBIM.platform).

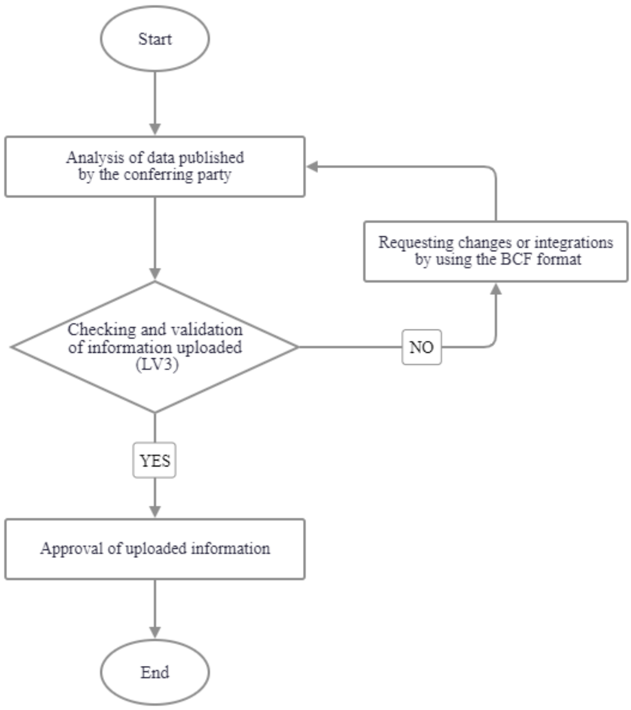


Figure 4.13 - Example of BIM Workflow for the Supervising Party (in usBIM.platform).

As regards information management activities, for a correct exchange of information that enables bilateral dialogue between the supervising and the conferring parties, it is necessary to unambiguously clarify, for the involved parties, the meaning associated with exchanged information (e.g. identification of the bridge or its parts). This should be done following what is required by the AINOP (IOP code, etc.) and what is defined within the asset management system, in the charge of the conferring party (e.g. a managing body or authority) and with which it manages infrastructure (Bridge Management Systems or Asset Management systems more generally for any infrastructure).

Considering the case study of a highway bridge (managed by the company "Autostrade per l'Italia"), logic proper to its asset management system, i.e. the ARGO system, was also considered. In this regard, the "Bridge Parts" of the IFC model reflect the parts of the bridge structure considered by ARGO. This correspondence can also be realized for the bridge structure and every single structural component. Clearly, these correspondences consider different IFC entities, whose instances related to the informative model were labeled according to the logic considered. This is done by assigning a specific name and description to the identified class (e.g for subclasses of IfcElement or other classes used to describe the bridge components). An example related to the characterization of bridge parts (in the box on the left) and a bridge component (in the box on the right) is shown in the figure below.

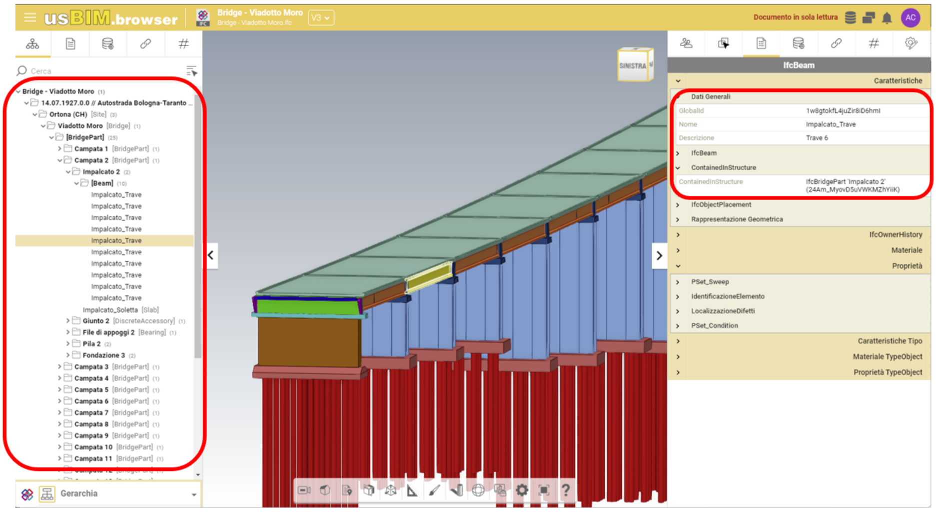


Figure 4.14 - An example of naming for a bridge component (e.g. Beam).

Another aspect to be considered is related to the recording of the information on the condition status of the bridge itself. In order to manage this type of information in regard to the case study, documents, technical reports, multimedia material (photos, videos, etc.), and other elements were carefully analyzed in relation to a specific inspection (carried out in 2019) to identify defects and damage in the structural elements (as shown in the Figure 4.15) and then to be able to digitize this information for AINOP purposes.

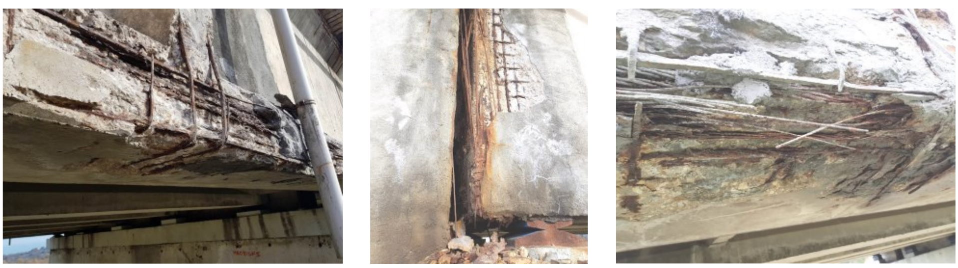


Figure 4.15 – Example of condition status detected during bridge inspections (e.g. for structural beams and support devices).

Figure 4.16 - Overview and mapping of deck structures status with indication and details related to the constitutive elements.

The following proposal has methodological relevance, as it is applicable to any possible update of inspections over time. In relation to this condition status, an assessment of structural safety was also considered, following the requirements of the technical regulations in force, and the design of the retrofitting of the viaduct under consideration. Hence, for the purposes of information modeling, an integration of a heterogeneous data set was envisaged for recording the latest location and entity of the detected defects on the structural elements. All this was done to provide synthetic information within the information model placed as the basis for the information management required by the AINOP. To do this, two new sets of attributes were considered, subsequently mapped as Property Sets regarding the IFC model, which can be associated with all the components of the structure parts that make up the bridge. In detail, a standard Property Set called "Pset_Condition" and a user-defined Property Set called "Localisation_Defects" were considered. This latter is considered for the defect identification of parts of structural components (according to the logic of the management systems being considered, in this case, ARGO). Both PSets, therefore, will be associated with the subclasses of IfcElement and other classes representing the other structural components. An example is given in the table below with the corresponding values.

Table 4.6 - Example of a property set (e.g. PSet_Condition) related to a structural element (e.g. beam).

PSet_Condition			
Name	***Property Type***	***Data Type***	***Value***
AssessmentDate	IfcPropertySingleValue	IfcDate	26/02/2019
AssessmentCondition	IfcPropertySingleValue	IfcLabel	5,15
AssessmentDescription	IfcPropertySingleValue	IfcText	Corrosion of reinforcement bars and concrete cover cracking.
AssessmentType	IfcPropertySingleValue	IfcLabel	Ispezioni
AssessmentMethod	IfcPropertyReferenceValue	IfcDocumentReference	repository links
LastAssessmentReport	IfcPropertySingleValue	IfcLabel	Medium CDA
LastAssessmentDate	IfcPropertySingleValue	IfcDate	28/08/2019
AssessmentFrequency	IfcPropertySingleValue	IfcTimeMeasure	6 months

The possible values are consistent with the meaning associated with the individual properties as defined by the buildingSMART site. For example, in detail, the possible values of the properties "AssessmentCondition" and "LastAssessmentReport" were made in compliance with the LGP, considering the relative defect value DR and CDA respectively.

As the other PSets, e.g. concerning the localization of defects, an example of the related properties with their values is proposed:

Table 4.7 - Example of PSet (e.g. LocalizzazioneDifetti) in the case of a structural element (e.g. beam).

LocalizzazioneDifetti			
Name	***Property Type***	***Data type***	***Value***
TipoDifetto	IfcPropertySingleValue	IfcText	Concrete degradation
InquadramentoCampoDirezioneTrasversale	IfcPropertySingleValue	IfcLabel	1
InquadramentoCampoDirezioneLongitudinale	IfcPropertySingleValue	IfcLabel	1
InquadramentoCampoDirezioneVerticale	IfcPropertySingleValue	IfcLabel	1
InquadramentoFacciaDirezioneTrasversale	IfcPropertySingleValue	IfcLabel	Destra
InquadramentoFacciaDirezioneLongitudinale	IfcPropertySingleValue	IfcLabel	Avanti
InquadramentoFaccia	IfcPropertySingleValue	IfcLabel	Avanti

Clearly, in this case, the specific properties of the previous table are a function of the Asset Management system being considered. However, this approach also allows for the definition of other properties or other associated values to be considered when considering the logic of any Asset Management system. In the case under consideration, the defect identification takes place according to the logic of the asset management system considered, i.e. ARGO system. Once the type of defect in the element has been identified, its precise location is carried out according to certain logical steps. Below is an example in the case of structural elements relating to a grillage deck:

– Partitioning of the element into different parts (if provided), according to its geometry, can be organized into parts in the longitudinal direction (n) and the transversal direction (m).

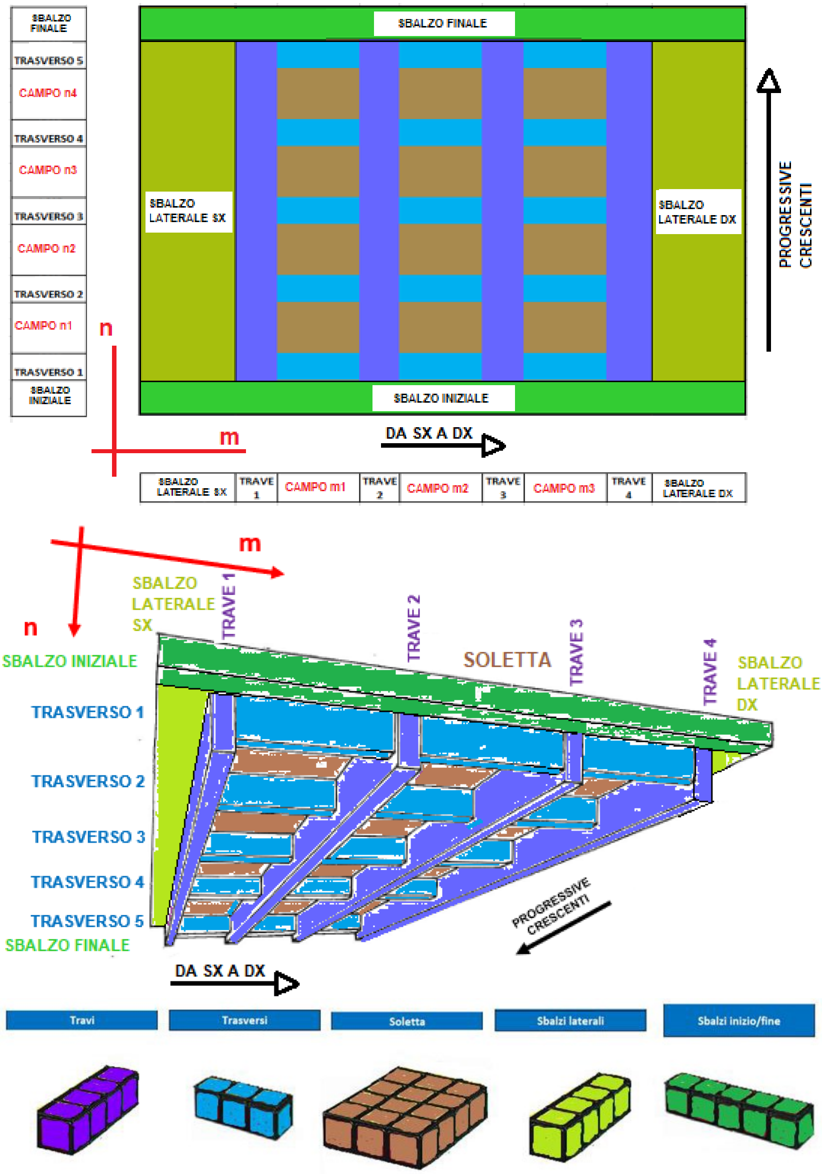


Figure 4.17 - Example of the organization in fields of the elements belonging to the bridge deck structure related to the case under consideration.

– Subsequently, the association of the defect with the possible subparts, into which it is possible to organize the individual elements, is carried out (see figures above and below):

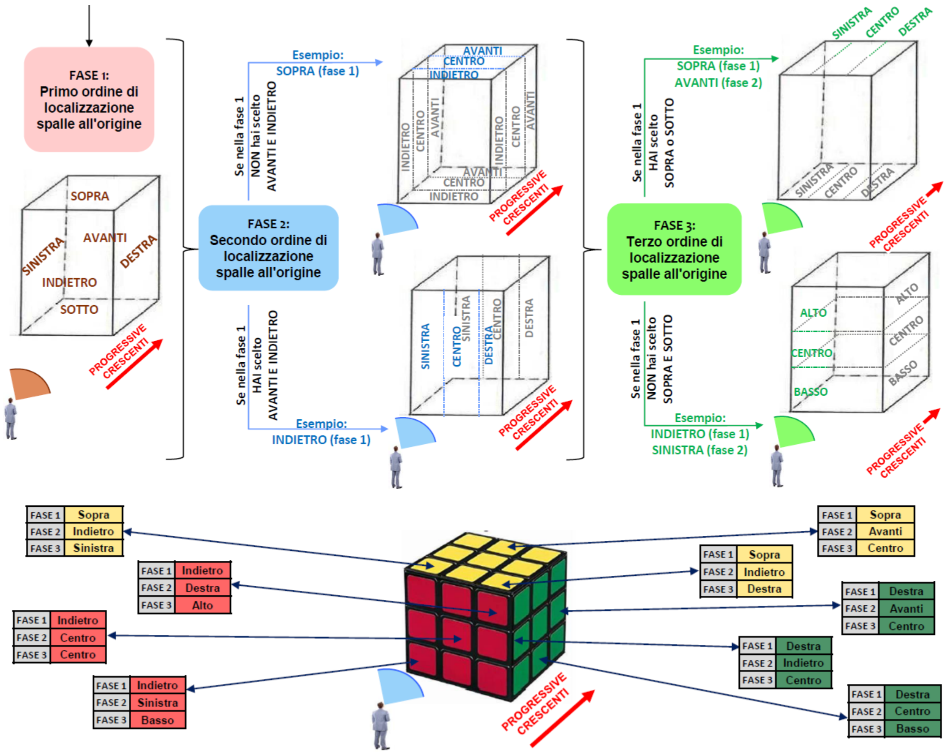


Figure 4.18 - Organisation of the structural element into subfields with which it is possible to associate the defect or damage detected.

To virtualize and digitalize defect recognition, according to the logic described above, a series of properties were proposed with the aim of identifying the part of the element involved and of associating the type of defect to this part. Accordingly, appropriate value lists were defined for each of the proposed properties. The possible defects, on the other hand, refer to the forms in Appendix C of the LGP. The logic of organising the structural components of the bridge (e.g. decomposition into sub-parts) takes into account the reference system within the Asset Management system under consideration. However, this digitization strategy could be generalized to integrate any method for identifying and localizing defects or damage on structural elements based on this kind of logic. In this regard, the following figures show some examples concerning the PSets developed (e.g. Pset_Condition, LocalizzazioneDifetti) within the informative model managed in the digital platform considered:

a)

b)

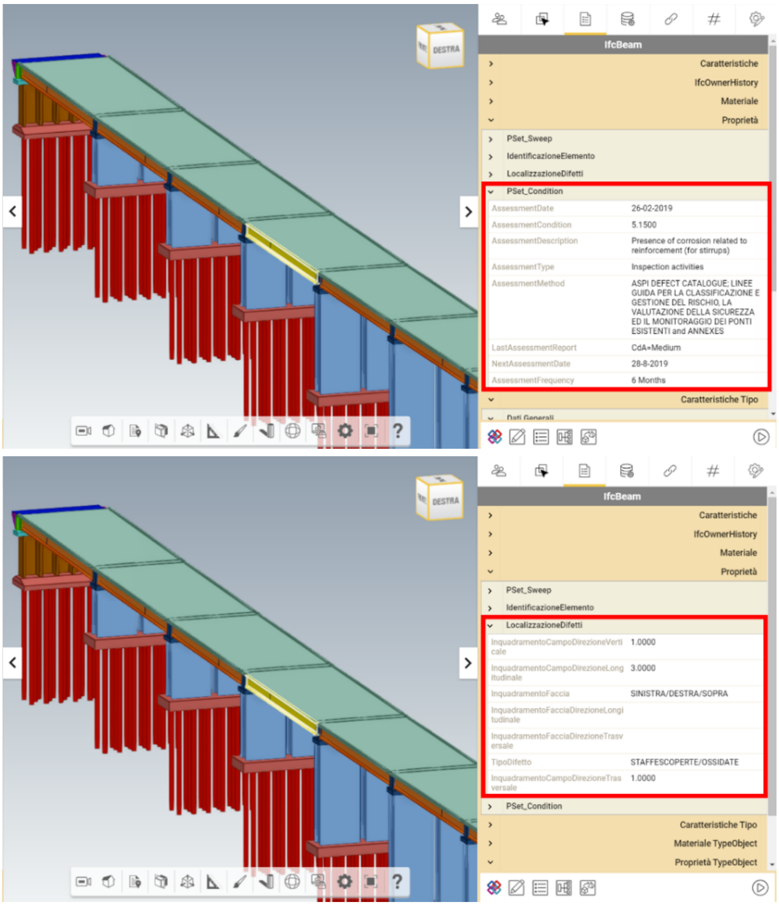


Figure 4.19 - Example of property values on the existing condition (e.g. longitudinal beam) managed in the digital environment (usBIM.platform).

Therefore, semantic enrichment, related to the definition of the proposed IFC properties, was conducted in accordance with the allowed values provided by the proposal. To accomplish the informative modeling consistent with the established LoINs, other required information was fully digitized by using functionalities of the considered environment. For example, records provided in Ministerial Decree No. 430/2019 (e.g. "Anagrafica Base" and "Anagrafica di opera" for road bridges and viaducts) were digitized and linked to the informative model, for collecting general and specific data related to the bridge under consideration (by using usBIM.data functionality). This allows BIM data management activities and the creation of customized forms for entering and storing significant and referenced data on the BIM model. The following figures show instances of records that were digitized and associated with the bridge structure:

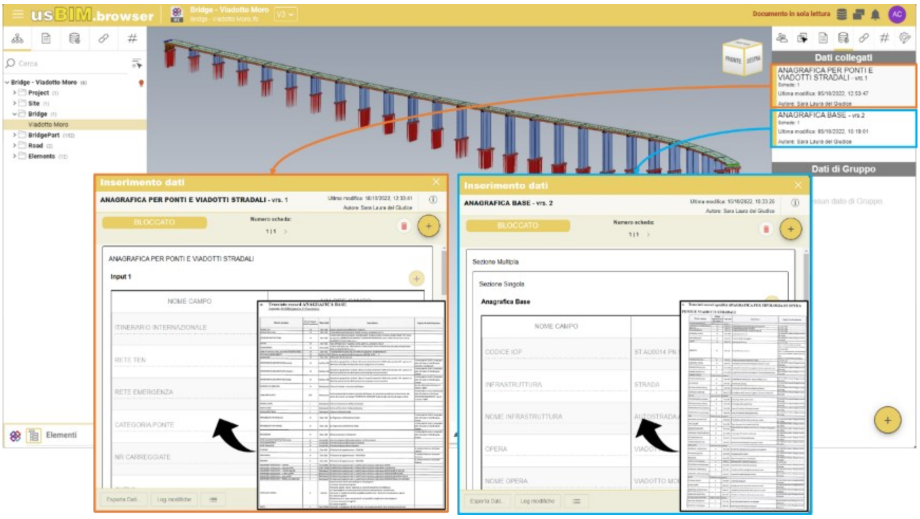


Figure 4.20 - Digitisation and association of required records to the bridge structure.

Furthermore, to the IfcElement subclasses, along with other classes relating to the bridge components, it was possible to link (via the "link" function available on the usBIM.platform) corresponding documentation, data, and information required by the several subsections of the AINOP. This was done in order to have a complete technical and informative overview of the individual structural component and the overall structure of the bridge, based on a BIM model.

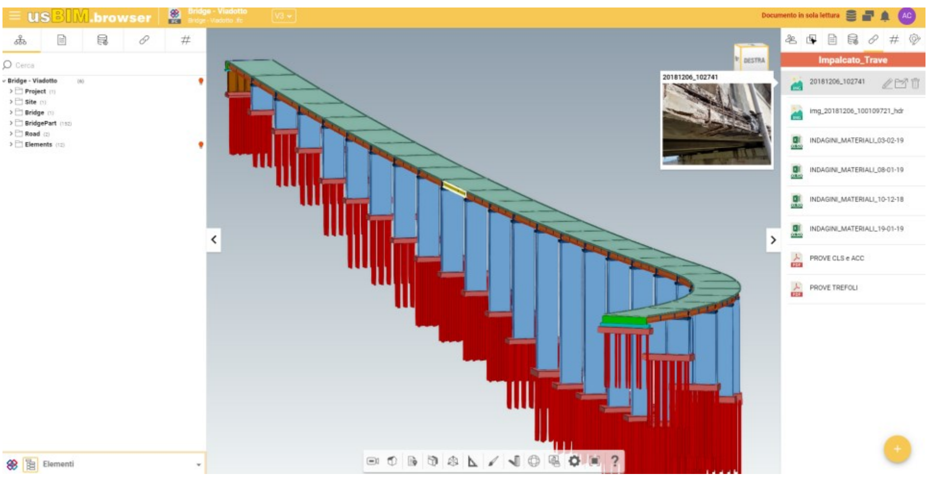


Figure 4.21 - Example of digital links regarding information required by the AINOP (e.g. concerning the condition status of a longitudinal beam).

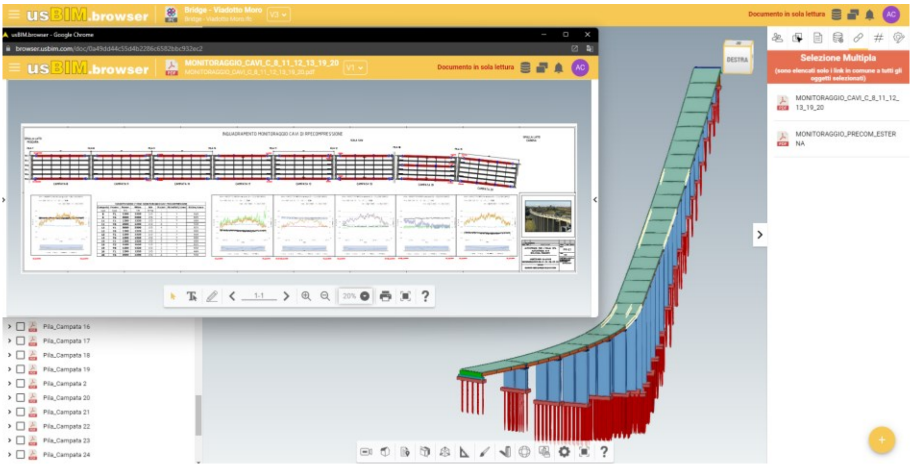


Figure 4.22 - Example of digital links regarding information required by the AINOP (e.g. concerning the bridge monitoring data).

With the aim of adopting a fully open BIM approach, also BIM Collaboration Format was considered. This aimed at facilitating open communication and improving processes based on IFC models, simplifying collaboration among the several parties involved (e.g. conferring and supervising parties), and quickly identifying and exchanging recommendations, insights, and feedback on problems or critical issues identified. In particular, it enables the exchange of notes, images, and other reports during the management of activities managed in a shared common environment such as a CDE.

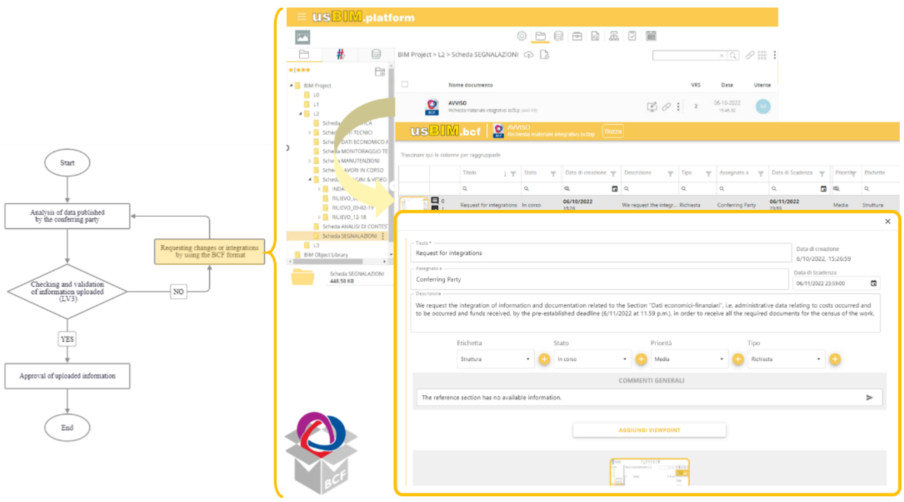


Figure 4.23 - Communication and interaction based on BCF applications for documentation to be provided.

As shown in Figure 4.23, adopting BCF-based workflow, a possible notification was simulated, by the supervising party, for a request of integrative information that was missing or insufficient, after being requested to the conferring party, within a given deadline. An issue concerning the "Economic-Financial data" folder was simulated, where a BCF file was generated and then placed in the "Notifications data" folder in AcDat. In support of this notification, information was provided in terms of status, priority, type, images, and other related details. This means allowing issues to be communicated quickly, and also referring them to the informative model of the bridge. The following figure shows the example in question. After defining within the collaborative BIM platform (usBIM.platform) different roles (e.g., Supervising and Conferring Parties), through the submission of a BCF file, the supervising party can report, to the conferring party, the request for missing data and documentation. For instance, Figure 4.23 refers to information pertaining to the "Economic and Financial Data" Tab, considered for the census of the work under the AINOP scenario. Through the use of a specific functionality (usBIM.bcf), integrated within this collaborative platform, it was possible to generate a BCF file, which was subsequently inserted into the "Reporting Tab" of the defined AcDat. As shown in the figure considered, this alert, created by the Supervising Party and defined through the BCF file, was specified by defining some characteristics (through images and descriptions) aimed at defining some aspects of the alert including the type, priority, status, deadline and others in order to locate and resolve the emerging issue. All this is envisaged by specific processes digitalized in the BIM platform by defining specific workflows, as highlighted in Figure 4.23. Hence, this approach was considered with the aim of overcoming approaches based on traditional communications (e.g. via email), allowing for easier communication, location and resolution of issues identified and referred to an information model (in IFC format) of the work. As a result, using BCF file format, it was possible to enable processes and provide a new tool for resolving issues related to information exchange via a new and digital collaboration based on the openBIM.

4.5 Discussion

As analyzed previously, there is an evident need to develop a new all-compassing approach based on BIM technologies for the management of bridges according to new requirements in the Italian regulatory context. Several studies [5,84,96,102,120,180,213] derived from the literature show examples of effective solutions to manage existing bridges; however, if related to different contexts, they are not suitable to meet the regulatory information requirements that arose from the analysis of the regulatory context in force in Italy today. With this in mind, it was necessary to develop an ad hoc solution to achieve the proposal goals. This solution, defined at the beginning both from an information (e.g., LoINs definition) and procedural (e.g., the definition of an IT framework for the generation of BIM models and the information management activities) point of view, provides a feasible solution for managing one of the most widespread bridge typologies in Italy, i.e., existing R.C. girder bridges, meeting the requirements arising from the regulatory context under investigation. The contribution and scope of this proposal have been to provide a BIM solution with which one can manage structural information (regarding the census, inspection, risk definition, and structural safety activities) for bridges. Given the need for management based on a BIM framework, derived also from the regulatory context (e.g., LGP) in a clear manner, the developed solution aims to define tailor-made BrIMs (following the proposed LoINs) along with their information management in the analyzed context. These models represent an "access key" and a means for managing synthetic information sometimes processed in other systems (BMS, FEM, etc.). This proposal supports the definition of recurring workflows, regarding the data requests, to update external databases or digital platforms for the management of infrastructures (e.g., AINOP). Given its methodological approach, this solution can also be applied to other regulation settings, after having specified the required information and related logical flows to define them.

Following the proposal goals, as stated before, a series of outcomes were achieved. Previously, customized LoINs were set, providing an organized reference for modeling and information management activities due to a lack of LoIN specifications in the context under investigation. Indeed, in the case of bridges, unlike the existing LOD approach [5,89,102,167,194], the LoIN approach establishes and optimizes the strictly necessary information, favoring saving resources. Accordingly, a BIM object library was developed related to the typological bridge elements considered, allowing the future reuse of such components for the digitization of other bridges with similar characteristics, or the extension, in the future, towards other bridge typologies not considered by this proposal. To support the model generation and information management activities, a data entry environment was necessary to collect and organize, in specific tables, the data (e.g., derived from censuses, surveys, or inspection activities) to be subsequently retrieved by the proposed framework implemented in Dynamo. For this purpose, data were entered via ad hoc interfaces (e.g., macros in Excel). Information management activities are therefore not limited to associating parameters with the BrIM model, but a sort of application that filters, processes, and synthesizes the required data to support the planned decision-making processes. In addition, the BIM model is constantly updated in terms of structural risk and safety information by means of proposed and customized solutions to the needs (e.g., CdA determination) dictated by

the regulatory setting. Indeed, the development and implementation of CRUD operations within the proposed digital solution allow the construction, modification, and updating of the information regarding BrIMs. Through the methods and procedures developed, the automatic processing of some information (e.g., reports linked to BIM models) was also conceived, concerning both the overall structure of the bridge and its components in addition to the retrieval at any moment of various scenarios that have occurred over time (e.g., data related specific inspections). These allow possible comparisons aimed at more thorough appraisals of a bridge's condition and, therefore, suggestions for more appropriate and timely interventions. All this, therefore, has been possible using the solution proposed, based on the module structure and IT pattern in question (i.e., MVC), which provides an organization that is simpler and easier to use, maintain, and improve in the future. Considering this proposed framework, the evolution of the condition status and the management of a bridge's structural safety were also supported by the use of a collaborative platform that was essential to manage and support the required LoIN setting. The validity of the proposal has been compared to what was previously only possible manually. For instance, through the regulatory procedures implemented via the developed scripts and algorithms, the same numerical results, related to what was previously obtained by the manual development of such procedures, were achieved. Applied to the real case studies, this proved a rapid development of modeling activities regarding the BrIMs related to various configurations (e.g., single or multicolumn piers, rectangular or non-rectangular decks, etc.), in addition to processing and managing the information required by the context under investigation. This organizing structure also allows to automate, starting from a built input environment (e.g., through macros in Excel), the generation of a BrIM, and the information exchange supported by open formats such as IFC. The related procedures are carried out in an automated manner by scripts and algorithms, which allows for reducing times and errors when compared to the equivalent manual practices.

As regards the actual limitations of this work, these consist of the following: (i) the approach defined by the considered framework should be contextualized concerning the specific BIM-authoring tool, VP environment, APIs, and programming integrations under consideration;

(ii) the developed solution is capable of generating, processing, and managing information related to reinforced concrete girder bridges. Therefore, when developing BIM solutions, interoperability issues, and application compatibility logic, in addition to application update times, should be taken into account [11,181,211]. In the development of this work, it was considered the adoption of open formats (e.g., IFC) and APIs in addition to the use of a BIM collaborative platform, ensured the compatibility of the developed solution among the several environments considered. In this way, data accessibility has been made independent of the specific solutions and times for all actors involved (bridge engineer, project manager, etc.). However, all these issues can be overcome and improved by other studies or developments that will also allow considering this solution for other types of bridges (composite bridges, steel bridges, etc.). This will enable, by means of the development of additional methods and procedures, starting from the framework setting that has been arranged, such as future integrations. The further application of other open standards (e.g., bSDD, IDS, etc.) along with the openCDE APIs, will enable the guarantee of better interoperability within the whole AECO software ecosystem for the infrastructure management such as existing bridges. Moving from the needs arisen before, it can easily be understood how this proposal, supported by a specific IT framework along with information and data managed centered on BrIMs together managed in a unique collaborative environment, will favor expeditious evaluations (on risk, structural safety, condition status, etc.) of bridges, facilitating relative decision-making and management processes.

The development of a methodological proposal, also taking into account the openBIM approach, was aimed at the gathering and management of information, for the needs of AINOP, on existing bridges and viaducts. This was based on the availability of a digital model in IFC format, in addition to the use of other open standards and services (including bsDD and BCF) through certain functionalities offered by the collaborative platform used. This IFC model-based proposal allows the information exchange between the Supervising and Conferring parties digitally, considering the openBIM approach. This was aimed toward the rapid enrichment and referencing of the required data on the bridge BIM model. This proposal was also prepared to address recursive procedures for updating data concerning for example the condition of the structure (e.g., due to inspections), by adopting technological solutions based on open APIs that will enable inter-platform communication between digital environments. The use of the suggested methodology leads to a significant time reduction regarding the access and use of information managed by IFC models conceived as "access keys" to the relevant data, allowing the supervising party to check and validate all the information required by the AINOP context. This is made possible by the organisation of a specific CDE to enable digital communication on a collaborative platform, by reporting integrations or revisions on missing materials or other issues on it. The definition of a tailor-made IFC model and related semantic enrichment (e.g., the definition of Property Set) enabled the information management according to what is required by regulatory (NTC, AINOP, LGP) and asset management contexts. Due to the preliminary definition of the LoIN, the information covered by the proposal developed is strictly necessary for the management of existing bridges, which are very widespread in Italy due to the morphology of the country.

4.6 Conclusion

When managing large-scale infrastructure and related assets (e.g., bridges and viaducts), current regulations require innovative approaches that are drawn from different skills, and not only those related to structural engineering (e.g., computer science, electronics, etc.). The innovation of this proposal consists of the development and implementation of a digital solution for the storage, processing, and management of information based on tailor-made information models developed according to the appropriate information requirements arising from the context under investigation. As also shown previously, there are no all-encompassing solutions for information management in the context analyzed (e.g. LGP, NTC, and AINOP). Accordingly, the management of bridges, from census to the management of structural safety, has been included in an overall framework of information management that aims to ensure the appropriate safety level. This solution meets the regulatory requirements in terms of the progressive adoption of information models of the infrastructure, which allow the effective and transparent management of the asset through the use of common data environments and interoperable platforms of data, construction objects, and information models. This methodological proposal, based on the adoption of the openBIM approach, was also aimed at the management of the information required by the AINOP context, for existing bridges and viaducts, enabling and regulating information exchanges between the supervising and the conferring parties. The objective was to quickly enrich and reference the required information on the bridge BIM model. This proposal leads to a significant reduction in the time for accessing and using the information managed via IFC models, managed within a CDE, conceived as "access keys" to the relevant data, enabling easier and digital checking and validation of the information content to be provided. This proposal, as conceived, could also lend itself to future integrations with other systems (e.g. ERP platform, Asset Management systems) for closer integration with managing authorities' systems, enabling a higher-performing solution for bridge management activities. From census activities to the management of structural safety, it provided an effective solution for the management of bridges, ensuring an appropriate and reliable source of reference for acquiring information regarding the structure itself, as well as for tracing the evolution of risk and intervention priorities over time.

Chapter 5

5. Conclusions

What has been proposed in this thesis mainly aims to prove the effectiveness of the application of BIM and in particular openBIM solutions in structural engineering, with special regard to infrastructure and civil works. BIM methodologies offer an opportunity to improve, re-engineer and modernize the existing processes and practices that characterize some of the phases of an asset life cycle (building or infrastructure). As is well known, BIM has been widely applied in the design phases [5,73,155,161,171]. From a strategic perspective, the management of information relating to the entire lifecycle of an asset (e.g. a building, bridge, etc.) can be particularly significant, e.g. for managing bodies or authorities. At the same time, the evolution of the regulatory framework, regarding both the design and management phases of civil works worldwide, also increasingly requires the adoption of more open and transparent approaches and technologies, such as openBIM. Digital platforms alone (e.g. via websites) are no longer sufficient to support collaborative and interdisciplinary work based on real "digital twins" [17,19,21,214]. This requires the adoption of BIM methodologies, particularly of the open BIM, to enable information exchanges and processes based on open standards for data modeling (e.g. through IFC) and process definition (e.g. through IDM, MVD, IDS, etc.). In this way, significant benefits are achieved in terms of overcoming technological barriers in the use of data among the actors involved, the evolution of professional skills, and the optimization of time and cost resources.

As described in **Chapter 2**, there are still practices and processes, such as those related to applying for structural authorizations and permits to building authorities, which need to be fully digitized, for instance by means of open BIM solutions [1]. So far, the assessment of the structural safety of buildings or other types of civil work (e.g. bridges), with related outcomes and other structural information, is typically reported in unstructured sets of documents (tables, drawings, reports, etc.). This happens even if BIM workflows, platforms, and standards are adopted. Generally, the BIM database provides input data for the structural design, but most of the data produced by structural designers, according to the structural codes, do not fully integrate into the BIM database along with other context-related information. These data are not easily recorded, especially in openBIM standard file formats such as IFC. Therefore, in the context of digital procedures for permit applications in the field of seismic structural engineering, this thesis has proposed an open BIM approach for the integration of structural information to support the activities of building authority bodies [1]. To this end, an openBIM solution (i.e. through the development of a related IDM and MVD, considering the IFC schema) has been proposed for integration and information exchange within a BIM-based environment. This has enabled the production of context-related IFC models (a part of the delivered ICDD solution considered for these applications) which have then allowed us to transfer and validate design solutions more easily (e.g. through possible checks carried out within the e-permit platform by BAB technicians), in addition leading to a reduction of the deliverables required for seismic-authorisation applications. The implementation of the proposed solution in a case study proved the effectiveness of the solution aimed at the innovative delivery of necessary information to building authorities to obtain seismic authorization permits. In this regard, the implementations within a business structural software, which integrates into a BIM environment, make it possible to save time in the implementation of a completely new mechanism. In order to support digitization also with regard to seismic permitting processes in structural engineering, the adoption of openBIM led to a series of benefits, including: (i) a reduction of costs related to the management of software licenses; (ii) the creation of a database related to digitized projects that may also be used for other structural uses (e.g. prioritization of activities, vulnerability studies at territorial scale, etc.); (iii) unrestricted access to information through information exchange based on standardized file formats (e.g. IFC) and solutions (e.g. ICDD); and (iv) the consequent avoidance of workflow fragmentation, thus improving collaboration among all actors involved in the process. To underline the significance of this proposal, this work stemmed from the "Str.E.Pe." research project (conducted by the Department of Structures for Engineering and Architecture of the University of Naples Federico II in collaboration with ACCA Software, Campania region, BAB of Avellino, and the

Municipality of Montemarano), which was awarded as the winner of the "Professional Research" category at the buildingSMART Awards in 2019.
With regard to **Chapter 3**, its contents focus on the topic of existing infrastructure management. The last few years have been characterized by the application of BIM methodology, sometimes entailing the adoption of openBIM, certainly with successful applications in design phases worldwide [160,161,195,203,215–217]. However, there are also applications related to O&M phases and the broader context of Asset Management [3,4,21,23,113,202]. As the research also showed, BIM and openBIM applications have been carried out regarding bridges [2,50,218,219], tunnels [7,163,194], railways [3,159,176] roads [23,167], and so on. Therefore, this chapter deals with work carried out in the context of a pilot project in which the author participated. Regarding this context, to manage maintenance operations as well as assess the condition and value of its railway infrastructure, the client (in this instance EAV) required the systematic organization of information by digitizing the existing infrastructure, enabling an assessment of possible performance gaps for the standards of the national railway network manager (in this instance RFI). The proposed digital management strategy, implemented on a real case of an existing railway line with associated civil works (bridges, buildings, tunnels, etc.), has proven its ability to digitally support and manage the day-to-day management related to the assets along the line. In addition, the decision-making process concerning the investments to be made along the line, to meet the required infrastructural standards, was also supported by quantitative and qualitative estimates of the value of all infrastructure assets. The proposed solution, based completely on the openBIM approach, supported the open exchange of information among all actors involved, allowing the digitization of the infrastructure for the purposes of asset lifecycle management in accordance with the existing systems in use today (e.g. inRETE2000 and LINFE). At the same time, there remains a need for a specific infrastructure-dedicated IFC that can integrate the railway infrastructure domain, both geometrically and semantically. Indeed, a key aspect for the full implementation of openBIM solutions will be determined by the availability of the latest developments and upgrading related to the IFC standard (towards an IFC 4.3 or IFC 5 version that will arrive in 2023) in the field of infrastructure. Because of this new IFC's capacity to cover, both semantically and geometrically, the complete digitalization of infrastructure, it will enable a

broader dissemination of openBIM solutions. The results obtained from this pilot project have certainly offered important insights for the development of the IFC standard in the field of asset management, by improving the efficiency of safety maintenance of railway infrastructures for a possible definition of new practices for company process management. Given the size of the project to be digitized (about 50 km of the railway line), and its goals in terms of the innovative application of openBIM (e.g. the use of the IFC 4x2 version, the most recent at the time of the project in the bSI context), the author and the research team were nominated at the BuildingSMART Awards 2021 among the three finalists in the category "Asset Management using openBIM". The results of the project have shown that the use of digital systems and new technologies can be a solution for optimising the processes involved in the operation and management of existing infrastructure, and for making their activities more efficient and safe.
As regards **Chapter 4**, following the requirements of the Italian regulatory setting, the topic of the structural management of existing bridges is addressed. In Italy, regulatory activity concerning the management of existing bridges has recently been affected by updates that require the adoption of innovative approaches. These call for a speedy and pragmatic deployment of certain methodologies, such as BIM, when dealing with topics regarding census, survey and risk classification, as well as the evaluation and monitoring of structural safety. As highlighted above, there are no dedicated solutions for information management in the analyzed context (LGP, NTC, and AINOP), from census to structural safety management. The proposal aimed to ensure the preservation of adequate structural safety levels through the digital management of data and information in a BIM environment. It is based on a developed framework that supports BIM modeling and information management activities. Following appropriate information requirements, it enabled the storage, processing, and management of information based on custom-built informative models. In the structural setting under consideration, several technologies and tools, namely BIM-authoring, a CDE platform, and visual programming, in addition to programming in Python, were considered. In addition, the proposal included the definition of a specific BIM object library (following the new Level of Information Need setting) and a custom-made input environment. Regulatory requirements were met, in terms of effective and transparent management of the asset through the use of common data environments and interoperable

platforms of data, and information models with their parametric objects. Accordingly, this proposal and its implementation were tested on a series of selected bridge cases, having different characteristics. Supported by the IT framework that had been developed and data handled within the BrIMs that had been produced, and successively managed in a collaborative environment, the proposal allowed for rapid assessments in terms of risk, structural safety, the status of the condition, and other aspects. Further developments were also aimed at the gathering and management of information required by AINOP. As regards the openBIM approach, the proposal was also based on the availability of a digital model (in IFC format) as well as the use of other open standards and services (including bsDD, and BCF). Through the rapid populating and referencing of the required data on the bridge BIM model, information exchanges among the parties involved (conferring and supervising parties) were addressed to support the recursive procedures of updating data on the structure's condition (e.g. following inspections). In the future, these may be automated by applying technological solutions based on open APIs that will enable communication among digital platforms and integration with management authority systems, allowing a more performant solution for bridge management activities and for feeding into databases such as AINOP. These applications, realized within the context of a research project (coordinated by the RELUIS consortium), favoring a better organization of the information required, led to a reduction in the time needed to access information by using IFC models as “access keys” to AINOP-relevant information (e.g. through the organization of a specific CDE and the use of BIM platform functionalities for supporting data enrichment, communication and collaboration based on open BIM strategies). In conclusion, a series of benefits emerge from the adoption of this proposal for bridge management, including expediting traditional procedures for BIM modeling, improving accessibility or traceability of information that is constantly updated for monitoring structural safety over time, and supporting decision-making processes related to the structural management of these bridges.

Appendix A

Example of information regarding the "building" level:

IfcClass	PSet	Properties		
-	*Name*	*Type*	*Name*	*Description*
IfcBuilding	OverallStructuralRC BuildingInformation	IfcLabel	AnalysisMethod	*Analysis Method (linear, non-linear, static, dynamic, etc.)*
		IfcLabel	StructuralType	*Type of structure (frame, wall, mixed equivalent, etc.)*
		IfcReal	DesignWorkingLifeCategory	*Design life of the building*
		IfcLabel	BuildingCategory	*Usage class*
		IfcBoolean	RegularityInPlan	*Compliance with the conditions regarding regularity in plan, for a building, required by the Standard.*
		IfcBoolean	RegularityInElevation	*Compliance with the conditions regarding regularity in elevation, for a building, required by the Standard.*
		IfcBoolean	TorsionalDeformability	*Verification on torsional deformability*
		IfcReal	P-DeltaDirX	*Effects of geometric non-linearities due to earthquake in the X-direction*
		IfcReal	P-DeltaDirY	*Effects of geometric non-linearities due to earthquake in the Y-direction*
		IfcReal	BehaviourFactor	*Behaviour factor*
		IfcLabel	DuctilityClass	*Ductility Class*
		IfcReal	DesignTechnical Standard	*Technical Design Standard*

Example of information regarding the "site" level:

IfcClass	PSet	Properties		
-	-	*Type*	*Name*	*Description*
IfcSite	GroundAnd Environmental Conditions	IfcLabel	GroundType	*Soil category*
		IfcLabel	TopographicCategory	*Topographical category*
		IfcLabel	SeismicZone	*Seismic zone*
		IfcReal	UlsPga	*PGA value considering the Ultimate Limit State*
		IfcReal	DlsPga	*PGA value considering the Damage Limit State*
		IfcLabel	WindZone	*Wind zone*
		IfcLabel	SnowZone	*Snow zone*

Example of information regarding the "building storey" level:

IfcClass	PSet	Properties		
-	-	*Type*	*Name*	*Description*
IfcBuilding Storey	OverallStorey Information	IfcBoolean	RigidDiaphragm	*Compliance with the conditions specified in the standard for the rigid floor deck*
		IfcReal	StoreyCheckBendingSF	*Minimum SF value related to the bending moment effects, with reference to the verification section of the deck*
		IfcReal	StoreyCheckShearSF	*Minimum SF value related to the shear effects, with reference to the verification section of the deck*

Example of information regarding the "element" level (e.g. beam):

IfcClass	PSet	Properties		
-	-	*Type*	*Name*	*Description*
IfcBeam	ULSStructural Verification RCBeam	IfcLabel	TypeOfBeam	*Type of beam (e.g. frame beam, floor-slab beam, stair beam, coupling beam, etc.)*
		IfcReal	BendingSFStartSectionUpperBound	*Minimum SF value related to the bending moment effects related to the upperbound of the element start section*
		IfcReal	BendingSFStartSectionLowerBound	*Minimum SF value related to the bending moment effects related to the lower bound of the element start section*
		IfcReal	BendingSFMidSectionUpperBound	*Minimum SF value related to the bending moment effects related to the upper bound of the element mid section*
		IfcReal	BendingSFMidSectionLowerBound	*Minimum SF value related to the bending moment effects related to the lower bound of the element mid section*
		IfcReal	BendingSFEndSectionUpperBound	*Minimum SF value related to the bending moment effects related to the upper bound of the element end section*
		IfcReal	BendingSFEndSectionLowerBound	*Minimum SF value related to the bending moment effects related to the lower bound of the element end section*
		IfcReal	ShearSFStartSectionCriticalZone	*Minimum SF value for shear effects related to the critical zone of the element start section*
		IfcReal	ShearSFSectionNotCriticalZone	*Minimum SF value for shear effects related to the not critical zone*
		IfcReal	ShearSFEndSectionCriticalZone	*Minimum SF value for shear effects related to the critical zone of the element end section*
		IfcBoolean	CapacityDesignM2S3	*Shear demand obtained from structural code requirements*
		IfcReal	DuctilitySFStartSectionUpperBound	*Minimun SF value related to the ductility considering the upper bound of the element start section*
		IfcReal	DuctilitySFStartSectionLowerBound	*Minimun SF value related to the ductility considering the lower bound of the element start section*
		IfcReal	DuctilitySFEndSectionUpperBound	*Minimun SF value related to the ductility considering the upper bound of the element end section*
		IfcReal	DuctilitySFEndSectionLowerBound	*Minimun SF value related to the ductility considering the lower bound of the element end section*
		IfcReal	TorsionSFStartSection	*Minimum SF value for torsion effects related to the element start section*
		IfcReal	TorsionSFMidSection	*Minimum SF value for torsion effects related to the element mid section*
		IfcReal	TorsionSFEndSection	*Minimum SF value for torsion effects related to the element end section*

IfcClass	PSet	Properties		
-	-	*Type*	*Name*	*Description*
IfcBeam	SLSStructural Verification RCBeam	IfcReal	DeformabilitySF	*Minimum SF value related to the maximum displacement of the element*
		IfcReal	SteelStressLimitationSFStartSection	*Verification of service related to the start section of the steel element*
		IfcReal	SteelStressLimitationSFMidSection	*Verification of working stresses in the mid section of the steel element*
		IfcReal	SteelStressLimitationSFEndSection	*Verification of working stresses in the end section of the steel element*
		IfcReal	ConcreteStressLimitationSFStartSection	*Verification of working stresses in the start section of the reinforced concrete element*
		IfcReal	ConcreteStressLimitationSFMidSection	*Verification of working stresses in the mid section of the reinforced concrete element*
		IfcReal	ConcreteStressLimitationSFEndSection	*Verification of working stresses in the end section of the RC element*
		IfcReal	CrackControlSFStartSection	*Minimum SF value related to the start section of the element.*
		IfcReal	CrackControlSFMidSection	*Minimum SF value related to the middle section of the element.*
		IfcReal	CrackControlSFEndSection	*Minimum SF value related to the end section of the element.*
		IfcBoolean	Vibration	*Verification related to the vibration limit state*

Author’s bibliography

“***Structural e-permits: an openBIM, model-based procedure for permit applications pertaining to structural engineering***”.
Authors: V. Ciotta, A. Ciccone, D. Asprone, G. Manfredi, E. Cosenza. Published in the “Journal of Civil Engineering and Management”. https://doi.org/10.3846/jcem.2021.15784.

“***Integration of structural information within a BIM-based environment for seismic structural e-permits***”.
Authors: A. Ciccone, V. Ciotta, D. Asprone. Published in the “Journal of Civil Engineering and Management” https://doi.org/10.3846/jcem.2023.18460.

“***Application of openBIM for the Management of Existing Railway Infrastructure: Case Study of the Cancello–Benevento Railway Line***”.
Authors: A. Ciccone, S. Di Stasio, D. Asprone, A. Salzano, M. Nicolella. Published in the Special Issue “Buildings and Infrastructures Management: Models Strategies and Evaluation Tools” of the “Sustainability” Journal. https://doi.org/10.3390/su14042283.

“***Defining a Digital Strategy in a BIM Environment to Manage Existing Reinforced Concrete Bridges in the Context of Italian Regulation***”.
Authors: A. Ciccone, P. Suglia, D. Asprone, A. Salzano, M. Nicolella. Published in the Special Issue "Future Prospects in Sustainable Engineering Development for Transport Infrastructures and Systems" of the “Sustainability” Journal. https://doi.org/10.3390/su141811767.

“A review on the Implementation of the BIM Methodology in the Operation Maintenance and Transport Infrastructure”.
Authors: J. Jerez Cepa, R. M. Pavón, M. G. Alberti, A. Ciccone, D. Asprone. Published in the special issue “Building Information Modeling (BIM): Current Status, Application and Trends” of the “Applied Science” Journal. https://doi.org/10.3390/app13053176 .

References

1. Ciotta, V.; Ciccone, A.; Asprone, D.; Manfredi, G.; Cosenza, E. Structural E-permits: An openbim, model-based procedure for permit applications pertaining to structural engineering. *J. Civ. Eng. Manag.* **2021**, *27*, 651–670, doi:10.3846/jcem.2021.15784.
2. Ciccone, A.; Suglia, P.; Asprone, D.; Salzano, A.; Nicolella, M. Defining a Digital Strategy in a BIM Environment to Manage Existing Reinforced Concrete Bridges in the Context of Italian Regulation. *Sustain.* **2022**, *14*, 1–27, doi:10.3390/su141811767.
3. Ciccone, A.; Stasio, S. Di; Asprone, D.; Salzano, A.; Nicolella, M. Application of openBIM for the Management of Existing Railway Infrastructure: Case Study of the Cancello–Benevento Railway Line. *Sustainability* **2022**, *14*, 2283, doi:10.3390/su14042283.
4. Heaton, J.; Parlikad, A.K.; Schooling, J. Design and development of BIM models to support operations and maintenance. *Comput. Ind.* **2019**, *111*, 172–186, doi:10.1016/j.compind.2019.08.001.
5. Bazán, Á.M.; Alberti, M.G.; Álvarez, A.A.; Trigueros, J.A. New perspectives for bim usage in transportation infrastructure projects. *Appl. Sci.* **2020**, *10*, 1–22, doi:10.3390/app10207072.
6. Kaewunruen, S.; Sresakoolchai, J.; Zhou, Z. Sustainability-based lifecycle management for bridge infrastructure using 6D BIM. *Sustain.* **2020**, *12*, doi:10.3390/su12062436.
7. Yin, X.; Liu, H.; Chen, Y.; Wang, Y.; Al-Hussein, M. A BIM-based framework for operation and maintenance of utility tunnels. *Tunn. Undergr. Sp. Technol.* **2020**, *97*, 103252, doi:10.1016/j.tust.2019.103252.
8. Poinet, P.; Stefanescu, D.; Papadonikolaki, E. Collaborative Workflows and Version Control Through Open-Source and Distributed Common Data Environment. *Lect. Notes Civ. Eng.* **2021**, *98*, 228–247, doi:10.1007/978-3-030-51295-8_18.
9. Bucher, D.F.; Hall, D.M. Common data environment within the AEC ecosystem: Moving collaborative platforms beyond the open versus closed dichotomy. *EG-ICE 2020 Work. Intell. Comput. Eng. Proc.* **2020**, 491–500.
10. Rivera, F.M.; Vielma, J.C.; Herrera, R.F.; Carvallo, J. Methodology for Building Information Modeling (BIM) Implementation in Structural Engineering Companies (SECs). **2019**, *2019*.
11. Grilo, A.; Jardim-Goncalves, R. Value proposition on interoperability of BIM and collaborative working environments. *Autom. Constr.* **2010**, *19*, 522–530, doi:10.1016/j.autcon.2009.11.003.
12. Azhar, S. Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadersh. Manag. Eng.* **2011**, *11*, 241–252, doi:10.1061/(ASCE)LM.1943-5630.0000127.

13. Musella, C.; Serra, M.; Salzano, A.; Menna, C.; Asprone, D. Open BIM Standards: A Review of the Processes for Managing Existing Structures in the Pre- and Post-Earthquake Phases. *CivilEng* **2020**, *1*, 291–309, doi:10.3390/civileng1030019.
14. Succar, B.; Saleeb, N.; Sher, W. Model Uses: Foundations for a Modular Requirements Clarification Language. **2016**.
15. Abualdenien, J.; Borrmann, A. Levels of detail, development, definition, and information need: a critical literature review. *J. Inf. Technol. Constr.* **2022**, *27*, 363–392, doi:10.36680/j.itcon.2022.018.
16. Dang, N.S.; Kang, H.; Lon, S.; Shim, C.S. 3D digital twin models for bridge maintenance. *Proc. 10th Int. Conf. Short Mediu. Span Bridg.* **2018**, 1–9.
17. Sacks, R.; Brilakis, I.; Pikas, E.; Xie, H.S.; Girolami, M. Construction with digital twin information systems. *Data-Centric Eng.* **2020**, *1*, doi:10.1017/dce.2020.16.
18. Moretti, N.; Xie, X.; Merino, J.; Brazauskas, J.; Parlikad, A.K. An openbim approach to iot integration with incomplete as-built data. *Appl. Sci.* **2020**, *10*, 1–17, doi:10.3390/app10228287.
19. Errandonea, I.; Beltrán, S.; Arrizabalaga, S. Digital Twin for maintenance: A literature review. *Comput. Ind.* **2020**, *123*, doi:10.1016/j.compind.2020.103316.
20. Tagliabue, L.C.; Cecconi, F.R.; Maltese, S.; Rinaldi, S.; Ciribini, A.L.C.; Flammini, A. Leveraging digital twin for sustainability assessment of an educational building. *Sustain.* **2021**, *13*, 1–16, doi:10.3390/su13020480.
21. Lu, Q.; Xie, X.; Heaton, J.; Parlikad, A.K.; Schooling, J. From BIM towards digital twin: Strategy and future development for smart asset management. *Stud. Comput. Intell.* 2020, *853*, 392–404.
22. Cavka, H.B.; Staub-French, S.; Poirier, E.A. Developing owner information requirements for BIM-enabled project delivery and asset management. *Autom. Constr.* **2017**, *83*, 169–183, doi:10.1016/j.autcon.2017.08.006.
23. Shah, R.; McMann, O.; Borthwick, F. Challenges and prospects of applying asset management principles to highway maintenance: A case study of the UK. *Transp. Res. Part A Policy Pract.* **2017**, *97*, 231–243, doi:10.1016/j.tra.2017.01.011.
24. Jiang, S.; Jiang, L.; Han, Y.; Wu, Z.; Wang, N. OpenBIM: An enabling solution for information interoperability. *Appl. Sci.* **2019**, *9*, doi:10.3390/app9245358.
25. Lee, Y.C.; Eastman, C.M.; Solihin, W.; See, R. Modularized rule-based validation of a BIM model pertaining to model views. *Autom. Constr.* **2016**, *63*, 1–11, doi:10.1016/j.autcon.2015.11.006.
26. Pasetto, M., Partl, M. N., & Tebaldi, G. The BIM (building information modeling)-based approach for road pavement maintenance. In Proceedings of the Proceedings of the 5th International Symposium on

Asphalt Pavements & Environment (APE). Lecture Notes in Civil Engineering.; 2020.
27. Blanco, J. L., Mullin, A., Pandya, K., Parsons, M., & Ribeirinho, M.J. Seizing opportunity in today's construction technology ecosystem.
28. Eastman, C., Fisher, D., Lafue, G., Lividini, J., Stoker, D., & Yessios, C. *An outline of the building description system.*; 1974;
29. van Nederveen, G.A.; Tolman, F.P. Modelling multiple views on buildings. *Autom. Constr.* **1992**, *1*, 215–224, doi:10.1016/0926-5805(92)90014-B.
30. Eastman, C.; Teicholz, P.; Sacks, R.; Liston, K. *BIM Handbook: A guide to Building Information Modeling for owners, managers, designers, engineers and contractors*; 2008; ISBN 9780470185285.
31. Liebich, T.; Schweer, C.-S.; Wernik, S. Die Auswirkungen von Building Information Modeling auf die Leistungsbilder und Vergütungsstrukturen für Architekten und Ingenieure sowie auf die Vertragsgestaltung. *buildingSMART* **2011**, 6–9.
32. Jernigan, F.E. *BIG BIM – Little BIM: The practical approach to building information modeling: Integrated practice done the right way!*; (2nd ed.).; Salisbury, 2008;
33. Gallaher, M.P.; O'Connor, A.C.; Dettbarn, J.L.; Gilday, L.T. Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry. National Institute of Standards and Technology (NIST). *Natl. Inst. Stand. Technol. (NIST), Gaithersburg, MD, USA, Tech. Rep.* **2004**, 04–867.
34. (BIM), G.C.C.G.B.I.M. A report for the Government Construction Client Group Building Information Modelling (BIM) Working Party Strategy Paper. **2011**.
35. Wong, A.K.D.; Wong, F.K.W.; Nadeem, A. Attributes of Building Information Modelling Implementations in Various Countries. *Archit. Eng. Des. Manag.* **2010**, *6*, 288–302, doi:10.3763/aedm.2010.IDDS6.
36. Phang, T. Beyond BIM: What's next for the industry? Available online: https://www.constructionglobal.com/equipment-and-it/beyond-bim-whats-next-industry .
37. Cheng, J.C.P.; Lu, Q. A review of the efforts and roles of the public sector for BIM adoption worldwide. *J. Inf. Technol. Constr.* **2015**, *20*, 442–478.
38. EU BIM TASK GRUOP Available online: http://www.eubim.eu/.
39. Ullah, K.; Lill, I.; Witt, E. An overview of BIM adoption in the construction industry: Benefits and barriers. *Emerald Reach Proc. Ser.* **2019**, *2*, 297–303, doi:10.1108/S2516-285320190000002052.
40. Beetz, J. Structured Vocabularies in Construction: Classifications, Taxonomies and Ontologies. In *Building Information Modeling: Technology Foundations and Industry Practice*; Borrmann, A., König, M., Koch, C., Beetz, J., Eds.; Springer International Publishing: Cham, 2018; pp. 155–165 ISBN 978-3-319-92862-3.
41. Borrmann, A.; König, M.; Koch, C.; Beetz, J. *Building Information Modeling:*

Technology Foundations and Industry Practice; Springer International Publishing AG, part of Springer Nature 2015, 2018, 2018; ISBN ISBN 978-3-319-92861-6.
42. Saygi, G.; Agugiaro, G.; Hamamcloğlu-Turan, M.; Remondino, F. Evaluation of GIS and BIM roles for the information management of historical buildings. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2013**, *2*, 283–288, doi:10.5194/isprsannals-II-5-W1-283-2013.
43. Borrmann, A.; Muhic, S.; Hyvärinen, J.; Chipman, T.; Jaud, S.; Castaing, C.; Dumoulin, C.; Liebich, T.; Mol, L. The IFC-Bridge project – Extending the IFC standard to enable high-quality exchange of bridge information models. *Proc. 2019 Eur. Conf. Comput. Constr.* **2019**, *1*, 377–386, doi:10.35490/ec3.2019.193.
44. AIA *AIA contract document G202-2013, building information modeling protocol form.*; Washington, DC:, 2013;
45. BIMforum *Level of development specification.*; 2013;
46. Building smart Information Delivery Manual Guide to Components and Development Methods. *buildingSMART* **2010**, 1–84.
47. Baldwin, M. *The BIM Manager. A Practical Guide for BIM Project Management.*; GmbH, B.V., Ed.; 2019;
48. Tomczak, A.; van Berlo, L.; Krijnen, T.; Borrmann, A.; Bolpagni, M. A review of methods to specify information requirements in digital construction projects. *Proc. 2022 World Build. Conf.* **2022**, doi:10.1088/1755-1315/1101/9/092024.
49. J. Messner et al. *BIM Project Execution Planning Guide-Version 2.2*; 2019;
50. Khattra, S.K. GENERATING STRUCTURAL MODEL THROUGH AUTOMATIC DATA EXTRACTION. **2020**, *11*, 602–613, doi:10.34218/IJARET.11.7.2020.0.
51. Lai, H.; Zhou, C.; Deng, X. Exchange requirement-based delivery method of structural design information for collaborative design using industry foundation classes. *J. Civ. Eng. Manag.* **2019**, *25*, 559–575, doi:10.3846/jcem.2019.9870.
52. Xu, Z.; Rao, Z.; Gan, V.J.L.; Ding, Y.; Wan, C.; Liu, X. Developing an Extended IFC Data Schema and Mesh Generation Framework for Finite Element Modeling. *Adv. Civ. Eng.* **2019**, *2019*, 1–19, doi:10.1155/2019/1434093.
53. Collao, J.; Lozano-galant, F.; Lozano-galant, J.A. BIM Visual Programming Tools Applications in Infrastructure Projects : A State-of-the-Art Review. *Appl. Sci.* **2021**.
54. Biancardo, S.A.; Capano, A.; de Oliveira, S.G.; Tibaut, A. Integration of BIM and procedural modeling tools for road design. *Infrastructures* **2020**, *5*, 1–14, doi:10.3390/infrastructures5040037.
55. Andriamamonjy, A.; Saelens, D.; Klein, R. An automated IFC-based workflow for building energy performance simulation with Modelica. *Autom. Constr.* **2018**, *91*, 166–181, doi:10.1016/j.autcon.2018.03.019.

56. Ramaji, I.J.; Memari, A.M. Interpretation of structural analytical models from the coordination view in building information models. *Autom. Constr.* **2018**, *90*, 117–133, doi:10.1016/J.AUTCON.2018.02.025.
57. Park, S.I.; Lee, S.H.; Almasi, A.; Song, J.H. Extended IFC-based strong form meshfree collocation analysis of a bridge structure. *Autom. Constr.* **2020**, *119*, 103364, doi:10.1016/j.autcon.2020.103364.
58. Muller, M.F.; Garbers, A.; Esmanioto, F.; Huber, N.; Loures, E.R.; Canciglieri, O. Data interoperability assessment though IFC for BIM in structural design–a five-year gap analysis. *J. Civ. Eng. Manag.* **2017**, *23*, 943–954, doi:10.3846/13923730.2017.1341850.
59. Macit İlal, S.; Günaydın, H.M. Computer representation of building codes for automated compliance checking. *Autom. Constr.* **2017**, *82*, 43–58, doi:10.1016/j.autcon.2017.06.018.
60. Li, B.; Schultz, C.; Dimyadi, J.; Amor, R. Defeasible reasoning for automated building code compliance checking. In *ECPPM 2021–eWork and eBusiness in Architecture, Engineering and Construction*; CRC Press, 2021; pp. 229–236 ISBN 1003191479.
61. Temel, B.A.; Başağa, H.B. Investigation of IFC file format for BIM based automated code compliance checking. *J. Constr. Eng. Manag. Innov.* **2020**, *3*, 113–130, doi:10.31462/jcemi.2020.02113130.
62. Liu, Z.-Q.; Zhang, F.; Zhang, J. The building information modeling and its use for data transformation in the structural design stage. **2016**, *19*, 273–284, doi:10.6180/jase.2016.19.3.05.
63. Shin, T. Building Information Modeling (BIM) Collaboration from the Structural Engineering Perspective. **2017**, *17*, 205–214, doi:10.1007/s13296-016-0190-9.
64. Vitiello, U.; Ciotta, V.; Salzano, A.; Asprone, D.; Manfredi, G.; Cosenza, E. BIM-based approach for the cost-optimization of seismic retrofit strategies on existing buildings. *Autom. Constr.* **2019**, *98*, 90–101, doi:10.1016/j.autcon.2018.10.023.
65. Zhao, P.; He, X. Research on dynamic data monitoring of marine bridge steel structure building information based on BIM model. *Arab. J. Geosci.* **2021**, *14*, doi:10.1007/s12517-021-06601-w.
66. Science, E. A Study of BIM Combined with ETABS in Reinforced Concrete Structure Analysis A Study of BIM Combined with ETABS in Reinforced Con- crete Structure Analysis. **2019**, doi:10.1088/1755-1315/233/2/022024.
67. Santos, R.; Costa, A.A.; Grilo, A. Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015. *Autom. Constr.* **2017**, *80*, 118–136, doi:10.1016/j.autcon.2017.03.005.
68. Hu, Z.Z.; Zhang, X.Y.; Wang, H.W.; Kassem, M. Improving interoperability between architectural and structural design models: An industry foundation classes-based approach with web-based tools. *Autom. Constr.* **2016**, *66*, 29–42, doi:10.1016/j.autcon.2016.02.001.

69. Fedorik, F.; Makkonen, T.; Heikkilä, R. Integration of BIM and FEA in Automation of Building and Bridge Engineering Design. **2016**.
70. Ren, R.; Zhang, J.; Dib, H. BIM Interoperability for Structure Analysis. **2018**, doi:10.1061/9780784481264.046.
71. Xiangyu, H.C.; Yi, W. BIM-Enabled Structural Design : Impacts and Future Developments in Structural Modelling , Analysis and Optimisation Processes. **2015**, 135–151, doi:10.1007/s11831-014-9127-7.
72. Lee, Y.C.; Eastman, C.M.; Solihin, W. An ontology-based approach for developing data exchange requirements and model views of building information modeling. *Adv. Eng. Informatics* **2016**, *30*, 354–367, doi:10.1016/j.aei.2016.04.008.
73. Akcamete, A.; Akinci, B.; Garrett, J.H. Potential utilization of building information models for planning maintenance activities. *EG-ICE 2010 - 17th Int. Work. Intell. Comput. Eng.* **2019**.
74. Delgado, J.M.D.; Brilakis, I.; Middleton, C. Modelling, management, and visualisation of structural performance monitoring data on BIM. In Proceedings of the Transforming the Future of Infrastructure through Smarter Information - Proceedings of the International Conference on Smart Infrastructure and Construction, ICSIC 2016; ICE Publishing, 2016; pp. 543–549.
75. Artus, M.; Koch, C. State of the art in damage information modeling for RC bridges – A literature review. *Adv. Eng. Informatics* **2020**, *46*, doi:10.1016/j.aei.2020.101171.
76. Ji, Y.; Beetz, J.; Katz, C.; Nisbet, N.; Bonsma, P.; Borrmann, A. *Integration of Parametric Geometry into IFC-Bridge*; 2011;
77. Monteiro, A.; Martins, J.P. Automation in Construction A survey on modeling guidelines for quantity takeoff-oriented BIM-based design. *Autom. Constr.* **2013**, *35*, 238–253, doi:10.1016/j.autcon.2013.05.005.
78. Choi, J.; Kim, H.; Kim, I. Open BIM-based quantity take-off system for schematic estimation of building frame in early design stage $. *J. Comput. Des. Eng.* **2015**, *2*, 16–25, doi:10.1016/j.jcde.2014.11.002.
79. Faghihi, V.; Reinschmidt, K.F.; Kang, J.H. Automation in Construction Objective-driven and Pareto Front analysis : Optimizing time , cost , and job-site movements. *Autom. Constr.* **2016**, *69*, 79–88, doi:10.1016/j.autcon.2016.06.003.
80. Cheung, F.K.T.; Rihan, J.; Tah, J.; Duce, D.; Kurul, E. Automation in Construction Early stage multi-level cost estimation for schematic BIM models. *Autom. Constr.* **2012**, *27*, 67–77, doi:10.1016/j.autcon.2012.05.008.
81. Sepasgozar, S.M.E.; Hui, F.K.P.; Shirowzhan, S.; Foroozanfar, M.; Yang, L.; Aye, L. Lean practices using building information modeling (Bim) and digital twinning for sustainable construction. *Sustain.* **2021**, *13*, 1–22, doi:10.3390/su13010161.
82. Zou, Y.; Kiviniemi, A.; Jones, S.W. A review of risk management through BIM and BIM-related technologies. *Saf. Sci.* **2017**,

doi:10.1016/j.ssci.2015.12.027.
83. Shim, C.S.; Yun, N.R.; Song, H.H. Application of 3D bridge information modeling to design and construction of bridges. *Procedia Eng.* **2011**, *14*, 95–99, doi:10.1016/j.proeng.2011.07.010.
84. León-Robles, C.A.; Reinoso-Gordo, J.F.; González-Quiñones, J.J. Heritage building information modeling (H-BIM) applied to a stone bridge. *ISPRS Int. J. Geo-Information* **2019**, *8*, doi:10.3390/IJGI8030121.
85. Lu, R.; Brilakis, I. Digital twinning of existing reinforced concrete bridges from labelled point clusters. *Autom. Constr.* **2019**, *105*, 102837, doi:10.1016/j.autcon.2019.102837.
86. Scherer, R.J.; Katranuschkov, P. BIMification: How to create and use BIM for retrofitting. *Adv. Eng. Informatics* **2018**, *38*, doi:10.1016/j.aei.2018.05.007.
87. Barazzetti, L.; Banfi, F.; Brumana, R.; Previtali, M.; Roncoroni, F. Bim From Laser Scans… Not Just for Buildings: Nurbs-Based Parametric Modeling of a Medieval Bridge. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2016**, *III–5*, 51–56, doi:10.5194/isprsannals-iii-5-51-2016.
88. Salamak, M.; Januszka, M. Brim bridge inspections in the context of industry 4.0 trends. *Maintenance, Safety, Risk, Manag. Life-Cycle Perform. Bridg. - Proc. 9th Int. Conf. Bridg. Maintenance, Saf. Manag. IABMAS 2018* **2018**, 2260–2267, doi:10.1201/9781315189390-307.
89. Sánchez-Rodríguez, A.; Esser, S.; Abualdenien, J.; Borrmann, A.; Riveiro, B. From point cloud to IFC: A masonry arch bridge case study. *EG-ICE 2020 Work. Intell. Comput. Eng. Proc.* **2020**, 422–431.
90. Pan, Y.; Dong, Y.; Wang, D.; Chen, A.; Ye, Z. Three-dimensional reconstruction of structural surface model of heritage bridges using UAV-based photogrammetric point clouds. *Remote Sens.* **2019**, *11*, doi:10.3390/rs11101204.
91. Popescu, C.; Täljsten, B.; Blanksvärd, T.; Elfgren, L. 3D reconstruction of existing concrete bridges using optical methods. *Struct. Infrastruct. Eng.* **2019**, *15*, 912–924, doi:10.1080/15732479.2019.1594315.
92. Borin, P.; Cavazzini, F. CONDITION ASSESSMENT of RC BRIDGES. INTEGRATING MACHINE LEARNING, PHOTOGRAMMETRY and BIM. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. - ISPRS Arch.* **2019**, *42*, 201–208, doi:10.5194/isprs-archives-XLII-2-W15-201-2019.
93. Barazzetti, L.; Banfi, F.; Brumana, R.; Gusmeroli, G.; Previtali, M.; Schiantarelli, G. Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans. *Simul. Model. Pract. Theory* **2015**, *57*, 71–87, doi:10.1016/j.simpat.2015.06.004.
94. Lu, R.; Brilakis, I. Generating bridge geometric digital twins from point clouds. *Proc. 2019 Eur. Conf. Comput. Constr.* **2019**, *1*, 367–376, doi:10.35490/ec3.2019.182.
95. Isailović, D.; Stojanovic, V.; Trapp, M.; Richter, R.; Hajdin, R.; Döllner, J. Bridge damage: Detection, IFC-based semantic enrichment and

visualization. *Autom. Constr.* **2020**, *112*, 103088, doi:10.1016/j.autcon.2020.103088.
96. Sacks, R.; Kedar, A.; Borrmann, A.; Ma, L.; Singer, D.; Kattel, U. SeeBridge information delivery manual (IDM) for next generation bridge inspection. *ISARC 2016 - 33rd Int. Symp. Autom. Robot. Constr.* **2016**, 826–834, doi:10.22260/isarc2016/0100.
97. López, F.J.; Lerones, P.M.; Llamas, J.; Gómez-García-Bermejo, J.; Zalama, E. A review of heritage building information modeling (H-BIM). *Multimodal Technol. Interact.* **2018**, *2*, doi:10.3390/mti2020021.
98. Fonnet, A.; Alves, N.; Sousa, N.; Guevara, M.; Magalhães, L. Heritage BIM integration with mixed reality for building preventive maintenance. *EPCGI 2017 - 24th Encontro Port. Comput. Graf. e Interacao* **2017**, *2017-January*, 1–7, doi:10.1109/EPCGI.2017.8124304.
99. McKenna, T.; Minehane, M.; O'Keeffe, B.; O'Sullivan, G.; Ruane, K. Bridge information modelling (BrIM) for a listed viaduct. *Proc. Inst. Civ. Eng. Bridg. Eng.* **2017**, doi:10.1680/jbren.16.00007.
100. Banfi, F.; Barazzetti, L.; Previtali, M.; Roncoroni, F. Historic bim: A new repository for structural health monitoring. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. - ISPRS Arch.* **2017**, *42*, 269–274, doi:10.5194/isprs-Archives-XLII-5-W1-269-2017.
101. Zou, Y.; Kiviniemi, A.; Jones, S.W.; Walsh, J. Risk Information Management for Bridges by Integrating Risk Breakdown Structure into 3D/4D BIM. *KSCE J. Civ. Eng.* **2019**, *23*, 467–480, doi:10.1007/s12205-018-1924-3.
102. Zhao, Z.; Gao, Y.; Hu, X.; Zhou, Y.; Zhao, L.; Qin, G.; Guo, J.; Liu, Y.; Yu, C.; Han, D. Integrating BIM and IoT for smart bridge management. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *371*, doi:10.1088/1755-1315/371/2/022034.
103. Welch, D.P.; Sullivan, T.J.; Filiatrault, A. Potential of Building Information Modelling for seismic risk mitigation in buildings. *Bull. New Zeal. Soc. Earthq. Eng.* **2014**, *47*, 253–263, doi:10.5459/bnzsee.47.4.253-263.
104. Abualdenien, J.; Pfuhl, S.; Braun, A. Development of an MVD for checking fire-safety and pedestrian simulation requirements. *Proc. 2019 Sep 17 (p. 191). Univ. der TU Berlin.* **2019**, 1–8.
105. Messaoudi, M.; Nawari, N.O. BIM-based Virtual Permitting Framework (VPF) for post-disaster recovery and rebuilding in the state of Florida. *Int. J. Disaster Risk Reduct.* **2020**, *42*, 101349, doi:10.1016/j.ijdrr.2019.101349.
106. Christodoulou, S.E.; Vamvatsikos, D.; Georgiou, C. A BIM-based framework for forecasting and visualizing seismic damage, cost and time to repair. *eWork Ebus. Archit. Eng. Constr. - Proc. Eur. Conf. Prod. Process Model. 2010* **2010**, 33–38, doi:10.1201/b10527-8.
107. Lu, R.; Brilakis, I.; Middleton, C.R. Detection of Structural Components in Point Clouds of Existing RC Bridges. *Comput. Civ. Infrastruct. Eng.* **2019**,

34, 191–212, doi:10.1111/mice.12407.
108. Hüthwohl, P.; Brilakis, I.; Borrmann, A.; Sacks, R. Integrating RC Bridge Defect Information into BIM Models. *J. Comput. Civ. Eng.* **2018**, *32*, doi:10.1061/(ASCE)CP.1943-5487.0000744.
109. Hüthwohl, P.; Brilakis, I. Detecting healthy concrete surfaces. *Adv. Eng. Informatics* **2018**, *37*, 150–162, doi:10.1016/j.aei.2018.05.004.
110. Davila, M.; Butler, L.J.; Manuel Davila Delgado, J.; Brilakis, I.; Reader, R.; ZEB Elshafie, M.; Senior Lecturer, R.; Middleton, C.R.; Professor, R. Structural Performance Monitoring Using a Dynamic Data-Driven BIM Environment Data-Centric Bridge Assessment View project Evaluation of Recycled Concrete Aggregate Performance in Structural Concrete View project Structural performance monitoring using a dynamic data-driven BIM environment. **2018**, doi:10.1061/(ASCE)CP.1943.
111. Lu, X.; Gu, D.; Xu, Z.; Zeng, X. Seismic loss assessment for buildings with multiple LOD BIM data. *13th Int. Conf. Appl. Stat. Probab. Civ. Eng. ICASP 2019* **2019**, 1–8.
112. Scherer, R.J.; Katranuschkov, P. BIMification: How to create and use BIM for retrofitting. *Adv. Eng. Informatics* **2018**, *38*, 54–66, doi:10.1016/j.aei.2018.05.007.
113. Panah, R.S.; Kioumarsi, M. Application of building information modelling (BIM) in the health monitoring and maintenance process: A systematic review. *Sensors (Switzerland)* **2021**, *21*, 1–26, doi:10.3390/s21030837.
114. Theiler, M.; Dragos, K.; Smarsly, K. BIM-based design of structural health monitoring systems. *Struct. Heal. Monit. 2017 Real-Time Mater. State Aware. Data-Driven Saf. Assur. - Proc. 11th Int. Work. Struct. Heal. Monit. IWSHM 2017* **2017**, *1*, 829–836, doi:10.12783/shm2017/13941.
115. Jeong, S.; Hou, R.; Lynch, J.P.; Sohn, H.; Law, K.H. An information modeling framework for bridge monitoring. *Adv. Eng. Softw.* **2017**, *114*, doi:10.1016/j.advengsoft.2017.05.009.
116. Theiler, M.; Smarsly, K. *IFC Monitor – An IFC schema extension for modeling structural health monitoring systems*;
117. Kang, K.; Lin, J.; Zhang, J. BIM- and IoT-based monitoring framework for building performance management. *J. Struct. Integr. Maint.* **2018**, *3*, 254–261, doi:10.1080/24705314.2018.1536318.
118. Deng, L.; Lai, S.; Ma, J.; Lei, L.; Zhong, M.; Liao, L.; Zhou, Z. Visualization and monitoring information management of bridge structure health and safety early warning based on BIM. *J. Asian Archit. Build. Eng.* **2021**, *00*, 1–12, doi:10.1080/13467581.2020.1869013.
119. Valinejadshoubi, M.; Bagchi, A.; Moselhi, O. Development of a BIM-Based Data Management System for Structural Health Monitoring with Application to Modular Buildings: Case Study. *J. Comput. Civ. Eng.* **2019**, *33*, doi:10.1061/(ASCE)CP.1943-5487.0000826.
120. Jensen, J.S. Innovative and sustainable operation and maintenance of

bridges. *Struct. Infrastruct. Eng.* **2020**, *16*, 72–83, doi:10.1080/15732479.2019.1604772.
121. Smarsly, K.; Tauscher, E. *IFC-BASED MONITORING INFORMATION MODELING FOR DATA MANAGEMENT IN STRUCTURAL HEALTH MONITORING*;
122. Rio, J.; Ferreira, B.; Poças-Martins, J. Expansion of IFC model with structural sensors. *Inf. la Constr.* **2013**, *65*, 219–228, doi:10.3989/ic.12.043.
123. Sacks, R.; Barak, R. Impact of three-dimensional parametric modeling of buildings on productivity in structural engineering practice. *Autom. Constr.* **2008**, *17*, 439–449, doi:10.1016/j.autcon.2007.08.003.
124. Marmo, R.; Nicolella, M.; Polverino, F.; Tibaut, A. A methodology for a performance information model to support facility management. *Sustain.* **2019**, *11*, 1–25, doi:10.3390/su11247007.
125. Construction, M.H. *The Business Value of BIM for Construction in Major Global Markets: How Contractors Around the World Are Driving Innovation With Building Information Modeling.*; 2014;
126. Eirinaki, M.; Dhar, S.; Mathur, S.; Kaley, A.; Patel, A.; Joshi, A.; Shah, D. A building permit system for smart cities: A cloud-based framework. *Comput. Environ. Urban Syst.* **2018**, *70*, 175–188, doi:10.1016/j.compenvurbsys.2018.03.006.
127. Shahi, K.; McCabe, B.Y.; Shahi, A. Framework for automated model-based e-permitting system for municipal jurisdictions. *J. Manag. Eng.* **2019**, *35*, 04019025, doi:10.1061/(ASCE)ME.1943-5479.0000712.
128. Muto, M. *e-submission common guidelines for introduce BIM to building process - Technical Report No. RR-2020-1015-TR*; 2020;
129. Whitell, M., Cao, Y., McCabe, B. Y., & Shahi, A. Standardizing Ontario's permitting process for e-permitting implementation. In Proceedings of the Construction Research Congress 2020: Project Management and Controls, Materials, and Contracts; 2020; pp. 1339–1348.
130. Robert K. Reitherman *Earthquakes and engineers: An international history*; ASCE Press, 2002;
131. Borrmann, André; König, M.K.J.B. *Building Information Modeling: Technology Foundations and Industry Practice*; Springer International Publishing AG, part of Springer Nature 2015, 2018, 2018; ISBN 9783319928623.
132. Kim, K.P.; Freda, R.; Nguyen, T.H.D. Building Information Modelling Feasibility Study for Building Surveying. *Sustainability* **2020**, *12*, 4791, doi:10.3390/su12114791.
133. Noardo, F.; Wu, T.; Arroyo Ohori, K.; Krijnen, T.; Stoter, J. IFC models for semi-automating common planning checks for building permits. *Autom. Constr.* **2022**, *134*, 104097, doi:10.1016/j.autcon.2021.104097.
134. Ullah, K.; Raitviir, C.; Lill, I.; Witt, E. BIM ADOPTION IN THE AEC/FM INDUSTRY – THE CASE FOR ISSUING BUILDING PERMITS. *Int. J. Strateg. Prop. Manag.* **2020**, *24*, 400–413, doi:10.3846/ijspm.2020.13676.

135. Noardo, F.; Malacarne, G.; Mastrolembo Ventura, S.; Tagliabue, L.C.; Ciribini, A.L.C.; Ellul, C.; Guler, D.; Harrie, L.; Senger, L.; Waha, A.; et al. Integrating expertises and ambitions for data-driven digital building permits – the EUNET4DBP. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2020**, *XLIV-4/W1-*, 103–110, doi:10.5194/isprs-archives-XLIV-4-W1-2020-103-2020.
136. Noardo, F.; Wu, T.; Arroyo Ohori, K.; Krijnen, T.; Tezerdi, H.; Stoter, J. Geobim for digital building permit process: Learning from a case study in Rotterdam. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences; 2020; Vol. 6, pp. 151–158.
137. buildingSMART International Information Delivery Manual: Guide to Components and Development Methods. **2010**, 1–84.
138. International Organization for Standardization ISO 16739-1:2018 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries — Part 1: Data schema Available online: https://www.iso.org/standard/70303.html (accessed on Mar 1, 2022).
139. Sanguinetti, P.; Abdelmohsen, S.; Lee, J.; Lee, J.; Sheward, H.; Eastman, C. General system architecture for BIM: An integrated approach for design and analysis. *Adv. Eng. Informatics* **2012**, *26*, 317–333, doi:10.1016/j.aei.2011.12.001.
140. N. Nawari BIM Standardization and Wood Structures. *J. Comput. Civ. Eng.* **2012**, 32.
141. Ramaji, I.J.; Memari, A.M.; Solnosky, R.L. Integrated BIM platform for multi-story modular building industry. *2nd Resid. Build. Des. Constr. Conf.* **2014**, 230–244.
142. Panushev, I.; Eastman, C.; Sacks, R.; Venugopal, M.; Aram, V. Development of the National BIM Standard (NBIMS) for precast/prestressed concrete. *Proc. 27th Int. Conf. Inf. Technol. Constr. CIB W78* **2010**, 16–18.
143. Ran Ren; and Jiansong Zhang Model Information Checking to Support Interoperable BIM Usage in Structural Analysis. *J. Comput. Civ. Eng.* **2019**, 105–113.
144. Lai, H.; Zhou, C.; Deng, X. Exchange requirement-based delivery method of structural design information for collaborative design using Industry Foundation Classes. *J. Civ. Eng. Manag.* **2019**, *25*, 559–573, doi:10.3846/jcem.2019.9870.
145. Lee, Y.-C.; Eastman, C.M. The Validation Logic and Structures of a Building Information.; 2015.
146. Lee, Y.C.; Solihin, W.; Eastman, C.M. The Mechanism and Challenges of Validating a Building Information Model regarding data exchange standards. *Autom. Constr.* **2019**, *100*, 118–128, doi:10.1016/j.autcon.2018.12.025.

147. Lee, Y.C.; Eastman, C.M.; Solihin, W.; See, R. Modularized rule-based validation of a BIM model pertaining to model views. *Autom. Constr.* **2016**, *63*, 1–11, doi:10.1016/j.autcon.2015.11.006.
148. Lee, Y.-C.; Eastman, C.M.; Solihin, W. Rules and validation processes for interoperable BIM data exchange. *J. Comput. Des. Eng.* **2021**, *8*, 97–114, doi:10.1093/jcde/qwaa064.
149. Technical, I.D.M.; January, T. Quick Guide Business Process Modeling Notation. *Event (London)* **2007**.
150. buildingSMART International IfcDoc Tool Available online: https://github.com/buildingSMART/ifcdoc (accessed on Oct 1, 2021).
151. Chipman, T.; Liebich, T.; Weise, M.; Chipman, T.;; Liebich, T.; Specification of standardized format to define and exchange Model Biew Definitions with Exchange Requirements and Validation Rules. *BuildingSMART* **2016**, *1*, 49.
152. Karlshøj, J.; See, R.; Davis, D. An Integrated Process for Delivering IFC Based Data Exchange. *Build. Int.* **2012**, 53.
153. Liu, R.; Issa, R.R.A. Survey: Common Knowledge in BIM for Facility Maintenance. *J. Perform. Constr. Facil.* **2016**, *30*, 04015033, doi:10.1061/(asce)cf.1943-5509.0000778.
154. Eastman, C.; Teicholz, P.; Sacks, R.; Liston, K. *BIM Handbook. A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*; John Wiley & Sons, I., Ed.; Second Edi.; 2021;
155. Daniotti, B.; Della Torre, S.; Gianinetto, M. *Digital Transformation of the Design, Processes of the Built Management Construction and Environment*; 2020; ISBN 9783030335694.
156. Latiffi, A.A.; Mohd, S.; Kasim, N.; Fathi, M.S. Building Information Modeling (BIM) Application in Malaysian Construction Industry. *Int. J. Constr. Eng. Manag. 2013*, doi:10.5923/s.ijcem.201309.01.
157. Latiffi, A.A.; Mohd, S.; Brahim, J. Application of Building Information Modeling (BIM) in the Malaysian Construction Industry: A Story of the First Government Project. *Appl. Mech. Mater.* **2015**, *773–774*, 996–1001, doi:10.4028/www.scientific.net/amm.773-774.996.
158. Latiffi, A.A.; Brahim, J.; Fathi, M.S. Roles and Responsibilities of Construction Players in Projects Using Building Information Modeling (BIM). In Proceedings of the Product Lifecycle Management in the Era of Internet of Things; Bouras, A., Eynard, B., Foufou, S., Thoben, K.-D., Eds.; Springer International Publishing: Cham, 2016; pp. 173–182.
159. Pasetto, M.; Giordano, A.; Borin, P.; Giacomello, G. Integrated railway design using Infrastructure-Building Information Modeling. the case study of the port of Venice. In Proceedings of the Transportation Research Procedia; Elsevier B.V., 2020; Vol. 45, pp. 850–857.
160. Bensalah, M.; Elouadi, A.; Mharzi, H. Overview: the opportunity of BIM in railway. *Smart Sustain. Built Environ.* **2019**, *8*, 103–116, doi:10.1108/SASBE-11-2017-0060.

161. Pakhale, P.D.; Pal, A. Digital project management in infrastructure project: a case study of Nagpur Metro Rail Project. *Asian J. Civ. Eng.* **2020**, *21*, 639–647, doi:10.1007/s42107-020-00224-4.
162. Arashpour, M.; Bai, Y.; Kamat, V.; Hosseini, R.; Martek, I. Project production flows in off-site prefabrication: BIM-enabled railway infrastructure. In Proceedings of the ISARC 2018 - 35th International Symposium on Automation and Robotics in Construction and International AEC/FM Hackathon: The Future of Building Things; International Association for Automation and Robotics in Construction I.A.A.R.C), 2018.
163. Wang, G.; Zhang, Z. BIM implementation in handover management for underground rail transit project: A case study approach. *Tunn. Undergr. Sp. Technol.* **2021**, *108*, doi:10.1016/j.tust.2020.103684.
164. Kwon, T.H.; Park, S.I.; Jang, Y.H.; Lee, S.H. Design of railway track model with three-dimensional alignment based on extended industry foundation classes. *Appl. Sci.* **2020**, *10*, doi:10.3390/app10103649.
165. Liu, B.; Sun, X. Application Analysis of BIM Technology in Metro Rail Transit. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *128*, doi:10.1088/1755-1315/128/1/012028.
166. Xu, X.; Wang, G.; Cao, D.; Zhang, Z. BIM Adoption for Facility Management in Urban Rail Transit: An Innovation Diffusion Theory Perspective. *Adv. Civ. Eng.* **2020**, *2020*, doi:10.1155/2020/8864221.
167. Ait-Lamallam, S.; Yaagoubi, R.; Sebari, I.; Doukari, O. Extending the IFC Standard to Enable Road Operation and Maintenance Management through OpenBIM. *ISPRS Int. J. Geo-Information* **2021**, *10*, 496, doi:10.3390/ijgi10080496.
168. Yin, X.; Liu, H.; Chen, Y.; Wang, Y.; Al-Hussein, M. A BIM-based framework for operation and maintenance of utility tunnels. *Tunn. Undergr. Sp. Technol.* **2020**, *97*, 103252, doi:10.1016/j.tust.2019.103252.
169. Floros, G.S.; Boyes, G.; Owens, D.; Ellul, C.; Engineering, G.; Street, G.; Park, V.B.; Management, A. DEVELOPING IFC FOR INFRASTRUCTURE : A CASE STUDY OF THREE HIGHWAY ENTITIES. **2019**, *IV*, 24–27.
170. Gao, G.; Liu, Y.; Wu, J.; Gu, M.; Yang, X.; Li, H.; Third, T.; Survey, R.; Third, T.; Survey, R.; et al. IFC Railway : A Semantic and Geometric Modeling Approach for Railways based on. **2014**, 1188–1195.
171. Costin, A.; Adibfar, A.; Hu, H.; Chen, S.S. Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations. *Autom. Constr.* **2018**, *94*, 257–281, doi:10.1016/j.autcon.2018.07.001.
172. Soilán, M.; Nóvoa, A.; Sánchez-Rodríguez, A.; Justo, A.; Riveiro, B. Fully automated methodology for the delineation of railway lanes and the generation of IFC alignment models using 3D point cloud data. *Autom. Constr.* **2021**, *126*, doi:10.1016/j.autcon.2021.103684.

173. Shalabi, F.; Turkan, Y. IFC BIM-Based Facility Management Approach to Optimize Data Collection for Corrective Maintenance. *J. Perform. Constr. Facil.* **2017**, *31*, 04016081, doi:10.1061/(asce)cf.1943-5509.0000941.
174. Takikawa, M. Innovation in Railway Maintenance utilizing Information and Communication Technology (Smart Maintenance Initiative). **2016**, 22–35.
175. Cavka, H.B.; Staub-French, S.; Poirier, E.A. Developing owner information requirements for BIM-enabled project delivery and asset management. *Autom. Constr.* **2017**, *83*, 169–183, doi:10.1016/j.autcon.2017.08.006.
176. Neves, J.; Sampaio, Z.; Vilela, M. A case study of BIM implementation in rail track rehabilitation. *Infrastructures* **2019**, *4*, doi:10.3390/infrastructures4010008.
177. Biancardo, S.A.; Viscione, N.; Cerbone, A.; Dessì, E. BIM-Based Design for Road Infrastructure: A Critical Focus on Modeling Guardrails and Retaining Walls. *Infrastructures* **2020**, *5*, doi:10.3390/infrastructures5070059.
178. Caldera, S.; Mostafa, S.; Desha, C. Exploring the Role of Digital Infrastructure Asset Management Tools for Resilient Linear Infrastructure Outcomes in Cities and Towns : A Systematic Literature Review. **2021**.
179. Santos, E.T. *Lecture Notes in Civil Engineering Proceedings of the 18th International Conference on Computing in Civil and Building Engineering*; 2020; ISBN 9783030512941.
180. Shim, C.S.; Dang, N.S.; Lon, S.; Jeon, C.H. Development of a bridge maintenance system for prestressed concrete bridges using 3D digital twin model. *Struct. Infrastruct. Eng.* **2019**, *15*, 1319–1332, doi:10.1080/15732479.2019.1620789.
181. Shirowzhan, S.; Sepasgozar, S.M.E.; Edwards, D.J.; Li, H.; Wang, C. BIM compatibility and its differentiation with interoperability challenges as an innovation factor. *Autom. Constr.* **2020**, *112*, 103086, doi:10.1016/j.autcon.2020.103086.
182. Byun, N.; Han, W.S.; Kwon, Y.W.; Kang, Y.J. Development of bim-based bridge maintenance system considering maintenance data schema and information system. *Sustain.* **2021**, *13*, doi:10.3390/su13094858.
183. Wan, C.; Zhou, Z.; Li, S.; Ding, Y.; Xu, Z.; Yang, Z.; Xia, Y.; Yin, F. Development of a bridge management system based on the building information modeling technology. *Sustain.* **2019**, *11*, 1–17, doi:10.3390/su11174583.
184. Shim, C. su; Kang, H.; Dang, N.S.; Lee, D. Development of BIM-based bridge maintenance system for cable-stayed bridges. *Smart Struct. Syst.* **2017**, *20*, 697–708, doi:10.12989/sss.2017.20.6.697.
185. McGuire, B.; Atadero, R.; Clevenger, C.; Ozbek, M. Bridge Information Modeling for Inspection and Evaluation. *J. Bridg. Eng.* **2016**, *21*,

doi:10.1061/(ASCE)BE.1943-5592.0000850.
186. MIT Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio dei Ponti Esistenti. Ministero delle Infrastrutture e dei Trasporti. Consiglio Superiore dei Lavori Pubblici. **2020**.
187. Santarsiero, G.; Masi, A.; Picciano, V.; Digrisolo, A. The Italian Guidelines on Risk Classification and Management of Bridges : Applications and Remarks on Large Scale Risk Assessments. **2021**.
188. Esser, S.; Aicher, K. IfcBridge Model Generation using Visual Programming. *Forum Bauinformatik 2019* **2019**, 101–108.
189. Ding, L.; Li, K.; Zhou, Y.; Love, P.E.D. An IFC-inspection process model for infrastructure projects: Enabling real-time quality monitoring and control. *Autom. Constr.* **2017**, *84*, 96–110, doi:10.1016/j.autcon.2017.08.029.
190. Tanaka, F.; Hori, M.; Onosato, M.; Date, H.; Kanai, S. Bridge Information Model Based on IFC Standards and Web Content Providing System for Supporting an Inspection Process. **2015**.
191. Borrmann, A.; Muhic, S.; Hyvärinen, J.; Chipman, T.; Jaud, S.; Castaing, C.; Dumoulin, C.; Liebich, T.; Mol, L. The IFC-Bridge project – Extending the IFC standard to enable high-quality exchange of bridge information models. In Proceedings of the Proceedings of the 2019 European Conference for Computing in Construction; University College Dublin, 2019; Vol. 1, pp. 377–386.
192. Isailović, D.; Petronijević, M.; Hajdin, R. The future of BIM and Bridge Management Systems. *IABSE Symp. Guimaraes 2019 Towar. a Resilient Built Environ. Risk Asset Manag. - Rep.* **2019**, 1673–1680, doi:10.2749/guimaraes.2019.1673.
193. Dang, N.S.; Shim, C.S. Bridge assessment for PSC girder bridge using digital twins model. *Lect. Notes Civ. Eng.* **2020**, *54*, 1241–1246, doi:10.1007/978-981-15-0802-8_199.
194. Cheng, J.C.P.; Lu, Q.; Deng, Y. Analytical review and evaluation of civil information modeling. *Autom. Constr.* **2016**, *67*, 31–47, doi:10.1016/j.autcon.2016.02.006.
195. Girardet, A.; Boton, C. Automation in Construction A parametric BIM approach to foster bridge project design and analysis. *Autom. Constr.* **2021**, *126*, 1–23, doi:10.1016/j.autcon.2021.103679.
196. Blanco Rávena, R.; Martínez García, J.; Mozas González, B.; García Alberti, M.; Arcos Álvarez, A.A. Uso de la metodología BIM en la remodelación de un puente existente = Use of BIM methodology in the re-modelling of an existing bridge. *An. Edif.* **2019**, *5*, 100, doi:10.20868/ade.2019.4376.
197. Hui, W.; Xu, H.; Li, Z.; Ma, C. Parametric Design and Application of Assembled Steel Plate Composite Beam Bridge Based on BIM Technology. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *371*, doi:10.1088/1755-1315/371/2/022074.

198. Biancardo, S.A.; Intignano, M.; Viscione, N.; Guerra De Oliveira, S.; Tibaut, A. Procedural Modeling-Based BIM Approach for Railway Design. *J. Adv. Transp.* **2021**, *2021*, doi:10.1155/2021/8839362.
199. Biancardo, S.A.; Intignano, M.; Abramović, B.; Abbondati, F.; Dell'Acqua, G. Horizontal Building Information Modeling: the Croatian railway Gradec-Sveti Ivan Žabno case study. *Ing. Ferrov.* **2021**, *76(12)*, 979–994.
200. Abbondati, F.; Biancardo, S.A.; Sicignano, G.; de Oliveira, S.; Tibaut, A.; Dell'Acqua, G. Bim parametric modelling of a railway underpass. *Ing. Ferrov.* **2020**, *75*, 443–459.
201. Pasetto, M.; Giordano, A.; Borin, P.; Giacomello, G. Integrated railway design using Infrastructure-Building Information Modeling. the case study of the port of Venice. *Transp. Res. Procedia* **2020**, *45*, 850–857, doi:10.1016/j.trpro.2020.02.084.
202. Davila Delgado, J.M.; Oyedele, L.O. BIM data model requirements for asset monitoring and the circular economy. *J. Eng. Des. Technol.* **2020**, *18*, 1269–1285, doi:10.1108/JEDT-10-2019-0284.
203. Floros, G.S.; Ellul, C. LOSS of INFORMATION during DESIGN & CONSTRUCTION for HIGHWAYS ASSET MANAGEMENT: A GEOBIM PERSPECTIVE. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2021**, *8*, 83–90, doi:10.5194/isprs-annals-VIII-4-W2-2021-83-2021.
204. Dang, N.S.; Shim, C.S. BIM authoring for an image-based bridge maintenance system of existing cable-supported bridges. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *143*, doi:10.1088/1755-1315/143/1/012032.
205. Chan, B.; Guan, H.; Hou, L.; Jo, J.; Blumenstein, M.; Wang, J. Defining a conceptual framework for the integration of modelling and advanced imaging for improving the reliability and efficiency of bridge assessments. *J. Civ. Struct. Heal. Monit.* **2016**, *6*, 703–714, doi:10.1007/s13349-016-0191-6.
206. Nordestgaard, P.M.; Jensen, J.; Mortensen, P.; Wyrtz, M.; Mikulenas, M.; Trifan, A.E. Application of Parametric Design in Project Containing Steel Structures: Parametric Light-Rail Steel Bridge. *Ce/Papers* **2019**, *3*, 767–772, doi:10.1002/cepa.1166.
207. Park, S.I.; Lee, S.H.; Almasi, A.; Song, J.H. Extended IFC-based strong form meshfree collocation analysis of a bridge structure. *Autom. Constr.* **2020**, *119*, 103364, doi:10.1016/j.autcon.2020.103364.
208. Chang, K.M.; Dzeng, R.J.; Wu, Y.J. An automated IoT visualization BIM platform for decision support in facilities management. *Appl. Sci.* **2018**, *8*, doi:10.3390/app8071086.
209. Dang, N.S.; Rho, G.T.; Shim, C.S. A master digital model for suspension bridges. *Appl. Sci.* **2020**, *10*, 1–22, doi:10.3390/app10217666.
210. Eastman, C.M.; Jeong, Y.-S.; Sacks, ; R; Kaner, I. Exchange Model and Exchange Object Concepts for Implementation of National BIM Standards., doi:10.1061/ASCE0887-3801201024:125.
211. Zhang, P.; Portillo, L.; Kezunovic, M. Compatibility and interoperability

evaluation for all-digital protection system through automatic application test. *2006 IEEE Power Eng. Soc. Gen. Meet. PES* **2006**, 1–7, doi:10.1109/pes.2006.1709286.
212. Mark Lutz *Learning Python*; 2008; ISBN 9780874216561.
213. Xu, X.; Huang, Q.; Ren, Y.; Zhao, D.Y.; Zhang, D.Y.; Sun, H. Bin Condition evaluation of suspension bridges for maintenance, repair and rehabilitation: a comprehensive framework. *Struct. Infrastruct. Eng.* **2019**, *15*, 555–567, doi:10.1080/15732479.2018.1562479.
214. Boje, C.; Guerriero, A.; Kubicki, S.; Rezgui, Y. Towards a semantic Construction Digital Twin: Directions for future research. *Autom. Constr.* **2020**, *114*, 103179, doi:10.1016/j.autcon.2020.103179.
215. Nuttens, T.; Breuck, V.D.E.; Cattoor, R.; Decock, K.; Hemeryck, I. Using bim models for the design of large rail infrastructure projects: Key factors for a successful implementation. *Int. J. Sustain. Dev. Plan.* **2018**, *13*, 73–83, doi:10.2495/SDP-V13-N1-73-83.
216. Abrishami, S.; Goulding, J.S.; Rahimian, F.P.; Ganah, A. Integration of BIM and generative design to exploit AEC conceptual design innovation. *J. Inf. Technol. Constr.* **2014**, *19*, 350–359.
217. Zheng, Y.; Xu, C. Application of BIM in Bridge Engineering and Its Risk Analysis. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *526*, doi:10.1088/1755-1315/526/1/012223.
218. Bartholomew, M.; Blasen, B.; Koc, A. Bridge Information Modeling (BrIM) Using Open Parametric Objects. *Us Dep. Transp.* **2015**, *1*, 296.
219. Sacks, R.; Kedar, A.; Borrmann, A.; Ma, L.; Brilakis, I.; Hüthwohl, P.; Daum, S.; Kattel, U.; Yosef, R.; Liebich, T.; et al. SeeBridge as next generation bridge inspection: Overview, Information Delivery Manual and Model View Definition. *Autom. Constr.* **2018**, *90*, 134–145, doi:10.1016/j.autcon.2018.02.033.