INFORMATION LIFECYCLE MANAGEMENT IN STRUCTURAL ENGINEERING

BIM, OPEN BIM AND BLOCKCHAIN TECHNOLOGY TO DIGITISE AND RE-ENGINEER STRUCTURAL SAFETY INFORMATION MANAGEMENT PROCESSES

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Index

Index of figures

Index of tables

THESIS OUTLINE

I. Context

Over the past decade, the *building information modelling (BIM) approach* has increasingly been used in both professional practice and research relating to the fields of civil and structural engineering. Indeed, it has been adopted across the globe [1], with some governments demanding its use in public projects involving bridges, tunnels and railways, as well as for strategic facilities like hospitals and schools. In Europe, most countries comply with *Directive 2014/24/EU of the European Parliament and of the Council* [2] on public procurements, which allows such clients to demand the use of BIM methodologies. Some countries, meanwhile, have decided to enforce digital delivery; for example, the United Kingdom has required the use of BIM in all government projects since 2016, while the Italian government published a timeline in 2018 mandating the use of BIM methodologies in all construction work by 2025. As a consequence, companies involved in the AEC sector are embracing the BIM approach by employing new tools and workflows, even though they face obstacles in relation to issues like training costs and time or low initial productivity [3].

BIM-based workflows, innovative tools and collaboration platforms can be employed throughout the lifecycle of an asset [4], and have been the catalyst for innovation in the entire architecture, engineering and construction (AEC) industry [5]. However, the BIM approach does not have its own agenda for research purposes only, but this has one in applied research with the purpose of aiding professional practice. Thus, this thesis will address the use of BIM in structural engineering not for the sake of the research itself, but with the practical intent of summarizing and presenting the current experience of the use of BIM in structural engineering and then contributing to expanding knowledge about the possible uses of BIM in this regard.

II. Approach

This thesis proposes innovative processes for the lifecycle information management of information that refers to the discipline of structural engineering. The proposed processes are based on the BIM approach, an information management framework that allows to standardise information flows using processes that implement tools such as BIM-authoring software, BIM tools and collaboration platforms. More precisely, BIM is a collaborative methodology for information management during the entire lifecycle of a facility, as Figure I depicts.

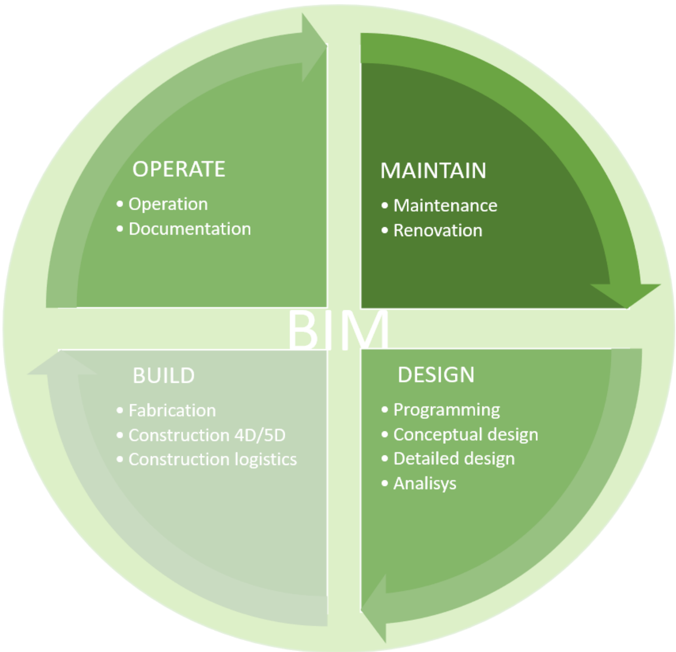


Figure I: The lifecycle of facilities in the Architectural, Engineering and Construction sector.

In detail, the BIM-based processes here proposed are in the number of three and refer, respectively, to the authorization phase, the testing and closeout phase, and the operation and maintenance phase of the lifecycle of a facility. A further novelty of this work is investigating the use of the open format *industry foundation classes (IFC)* in the processes that refer to the authorization phase and the operation and maintenance phase, and the use of blockchain technology in the testing and closeout phase.

The author has also taken part in the *Structural E-Permit (Str.E.Pe) research project* and *BIM-to-CIM research project*, literally '*from the building information modelling to the city information modelling'*, on behalf of the University of Naples Federico II - Department of Structures for Engineering and Architecture (DIST). The work that the author has carried out in these research projects is presented in this thesis and relates, respectively, to the BIM-based process for the authorization phase and the BIM-based operation and maintenance phase of a facility. In detail, the Str.E.Pe. project concerns the digitalization and dematerialization (no more paper documentation) of the application process for the seismic authorization permit using Open BIM standards. The project was conducted between 2018 and 2019 by the University of Naples Federico II in collaboration with ACCA Software, the Campania region, the Avellino BAB, and the Municipality of Montemarano. The BIM-to-CIM project is a multidisciplinary (i.e. it includes structural engineering, architecture, acoustic, systems engineering and urban planning disciplines) research project that aims to develop, implement and simulate the use of interoperable collaborative platforms, using non-proprietary open formats (Open BIM), in BIM-based processes for the management, maintenance and monitoring of buildings. The project is currently in its closing phase and has involved six partners: University of Naples – DIST, that was responsible for the structural engineering discipline; the software house ACCA Software; the Politecnico di Milano (PoliMi); the Politecnico di Torino (PoliTo); the Università IUAV di Venice is responsible for the systems engineering discipline; the Consiglio Nazionale delle Ricerche (CNR) - Instituto di Metodologie per l’Analisi Ambientale.

III. Objectives

The fields of civil engineering, i.e. structural engineering, have increasingly used the building information modelling (BIM) approach in both professional practice and as the focus of research. However, the field of structural engineering, which can be seen as a sub-discipline of civil engineering, misses, as far as the author is aware, a real state-of-the-art or an account of the current experience on the use of BIM in this regard. The first aim of this thesis, therefore, is to start bridging that gap by 1) providing the first state-of-the-art on the use of BIM in structural engineering.

Additionally, this thesis is original in that it addresses the production, management, and storage of information that pertains to structural engineering. Accordingly, this work aims at:

2) Proposing an open BIM-based process for the application for seismic authorization, in Italian ‘autorizzazione sismica’ (authorization phase).
3) Proposing a proof-of-concept for the integration of blockchain technology and smart contract into information flows among common data environments (CDEs) in the construction process of structural systems (testing and closeout phase).

4) Proposing an open BIM-based process for the operation and maintenance phase of structures.

IV. Structure of the thesis

This thesis is divided into seven chapters. Chapter 1 introduces the BIM approach that will be the reference framework of the entire thesis. This is also the place where the international and Italian regulatory context concerning the BIM approach is presented.

Chapter 2 presents the state-of-the-art on the BIM approach in structural engineering; this preliminary study aims to present current experience of BIM I structural engineering both in Accademia and industry, from a structural engineering perspective.

Chapters 3 to 5 deal with salient moments of the life cycle of a facility where information that pertains to structural safety is produced, managed, exchanged and archived. More precisely, chapters 3 to 5 contain an introduction to the process currently in use, a proposal for an innovative BIM-based process, a review of the novel technologies used (if necessary), and a case study that presents an implementation of the proposed innovative process.

Chapter 3 the focuses on the authorization phase and presents a BIM-based process to apply for seismic authorization (in Italian, ‘autorizzazione sismica’).

Chapter 4 focuses on the testing and close-out phase of structures anp proposes a proof-of-concept for the integration of blockchain technology and smart contract into information flows among common data environments (CDEs) in the construction process of structural systems.

Chapter 5 focuses on the operation and maintenance phase of structures and proposes an open BIM-based process for the operation and maintenance phase of structures.

Chapter 6 is the place where the discussion section is addressed.

Chapter 7 is left for conclusions.

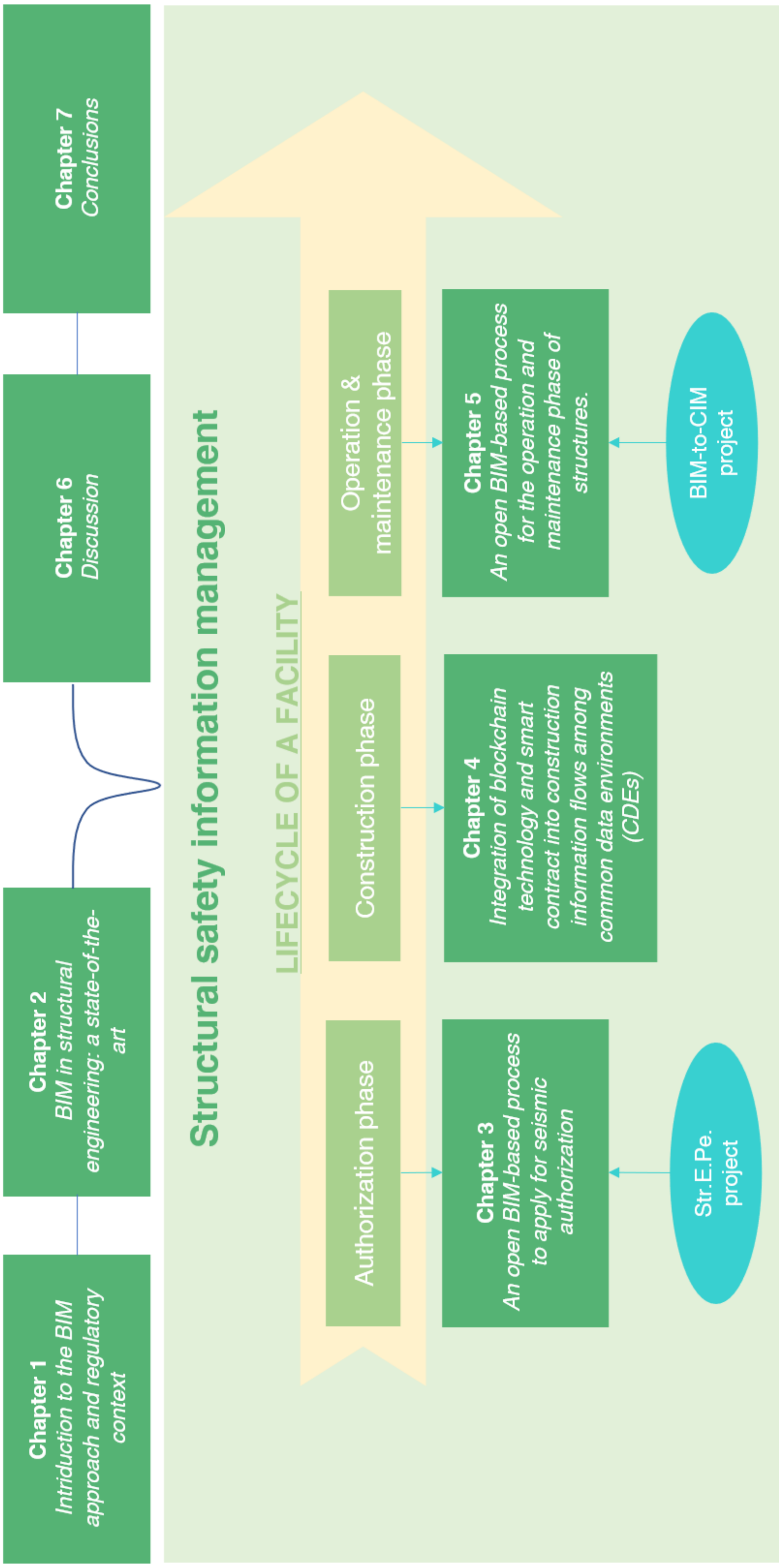


Figure II: Overall structure of the thesis.

V. Results

The work presented in this thesis has proven to be valuable for both scientific and industrial communities. In fact, a revised version of Chapter 2 has been currently accepted by the scientific journals CivilEng (MDPI)[1]; moreover, a revised version of Chapter 3 and Chapter 4 is currently under review at, respectively, the Journal of Civil Engineering Management (JCEM)[2] and Automation in Construction (AutCon)[3]. This highlights the scientific community's interest in the work presented in this thesis. Additionally, the Str.E.Pe. research project won a *buildingSMART® International award* at a ceremony held in Beijing in 2019. The author would like to thank Antonio Cianciulli, Guido Cianciulli and all the ACCA Software development team for their support in the production of the Str.E.Pe. platform.

Chapter 2 presents a traditional literature review on the utilisation of BIM in structural engineering, which has enabled me to perform a detailed content analysis in relation to both of these fields. My qualitative investigation of the literature has highlighted six main BIM uses in structural engineering: 1. structural analyses; 2. production of shop drawings; 3. optimised structural design: early identification of constructability issues and comparison of different structural solutions; 4. seismic risk assessments; 5. existing-condition modelling and retrofitting of structures; and 6. structural health monitoring. Each of these is discussed in relation to their: reference workflows; use of information models; information exchanges; and main limitations.

Chapter 3 investigates the creation and use of integrated IFC models to modernise traditional processes for applications to building authorities for structural-engineering approvals and permits. First, I provide a brief overview of e-permit systems in the AEC sector, with the focus on solutions that implement openBIM standards like IFC, MVD, and IDM. Second, I conduct a study on the information requirements of Italy's seismic-authorisation processes relating specifically to the field of structural engineering. Third, I describe preliminary research on defining the structural-engineering information that needs to be incorporated in the IFC format for e-permitting scopes. Fourth, I illustrate the reference workflow of the Str.E.Pe. project and propose a proof-

[1]A revised version of Chapter 2 has been currently *accepted* (July 2021) by the journal CivilEng-MDPI (Manuscript ID: civileng-1219077).

[2]A revised version of Chapter 3 is currently *under review* with the Journal of Civil Engineering and Management (Manuscript ID SCEM-2021-0075).

[3]A revised version of chapter 4 is currently *under review* with the journal Automation in Construction (Manuscript Number: AUTCON-D-21-00551)

of-concept of that makes use of an IFC model, which has been integrated with structural information to support the activities of the building authority in Avellino. The officers there have developed a SWOT analysis using IFC models to assist them in assessing the compliance of structural projects with seismic requirements.

Chapter 4 focuses on the process of constructing structural systems, which produces a huge amount of documentation that traces human activities on a construction site. While the building information modelling approach introduces common data environments (CDEs) to support document management, communication between them is limited, mainly involving the use of email and activities susceptible to human error. This chapter proposes a proof-of-concept for the integration of blockchains and smart contracts into information flows used in various CDEs. The focus of the proposal is on reducing human error and increasing the reliability and transparency of decision-making processes on construction sites pertaining to the structural system. To this end, the proof-of-concept introduces smart contracts that have different levels of complexity, with the advanced version comparing information exchanged with data gathered by IoT sensors on site. A first implementation of the proposal is also presented.

Finally, Chapter 5 presents a novel process to manage information in the operation and maintenance phase of structures. The process belongs to a wider framework that has been developed within the BIM-to-CIM research project. The chapter focuses on the structural engineering discipline, presents the work of the Department of Structures of Engineering and Architecture (DIST) of the Università di Napoli Federico II (UniNa), and depicts an application of BIM-based process and platforms for the maintenance of the bearing structure of a building.

VI. Implications and limitations

The academic implication of this work is prominent in almost every chapter. Chapter 2 proposes a reference for all academics involved in structural engineering who want to approach the BIM world for the first time. Chapters 3 and 4 open specialized research paths that need further developments: in the first case, the University of Naples is already working on the development of a special MVD for the structural discipline; in the second case, the University of Naples is working on the implementation of an advanced smart contract combining BIM and IoT. This would allow to develop a novel process that could replace the construction manager for structural elements made by 3D printing on site. Finally, chapter 5 proposes an open BIM-based approach for maintenance whose implications for the management of the operation and maintenance phase of infrastructures could also be explored.

However, since BIM falls under the domain of applied research, the processes that both the academic and industrial communities propose must be validated by an audience of industry experts in order to be widely implemented in current practice. In addition, the audience must be composed of industry experts with very heterogeneous backgrounds to account for the multidisciplinary nature of the BIM approach. This may represent a limitation for the transfer of the processes proposed in this thesis into professional practice. However, the author is striving to give more prominence to the work done and has made contact with the Italian IBIMI chapter of buildingSMART International (the University of Naples is a corporate member of this association). Since 2021 the author is part of the *working group Ri.Di.PE (Rilascio Digitale Permessi Edilizi)* for which the author is working to develop a case study that schematizes the work presented in chapter 3 so that it can become (after approval) a reference for the whole building smart international community, in particular for the regulatory room. The author also recently presented the results of Chapter 3 at the IBIMI Italian international conference to raise awareness of the topic among the Italian public administration.

The author is also a member of the Italian commission UNI/CT 033/SC 05 for the working groups GL 2, GL 4 and GL 7, which respectively focus on parts 3, 5, and 9 of the UNI 11337 series. The author hopes to be able to bring his contribution by proposing some insights from Chapter 5 in GL 07, which deals with Part 9, focused on the use of bim for the building logbook (this work has not yet started). However, the work conducted in Chapter 4 may also be of value to the UNI 11337 series, recently expanded to also contain a Part 11 on the topic of blockchain and smart.

References

[1] R. Edirisinghe and K. London, "Comparative Analysis of International and National Level BIM Standardization Efforts and BIM adoption," in *Proc. of the 32nd CIB W78 Conference 2015, 27th-29th October 2015, Eindhoven, The Netherlands*, 2015, pp. 149–158.

[2] European Union, "Directive 2014/23/EU of the European Parliament and of the Council of 26 February 2014 on the award of concession contracts," *Off. J. Eur. Union*, vol. L 94/1, no. 28.3.2014, pp. 1–64, 2014.

[3] F. Muñoz-La Rivera, J. C. Vielma, R. F. Herrera, and J. Carvallo,

"Methodology for Building Information Modeling (BIM) Implementation in Structural Engineering Companies (SECs)," *Adv. Civ. Eng.*, vol. 2019, pp. 1–16, Feb. 2019.

[4] A. Grilo and R. Jardim-Goncalves, "Value proposition on interoperability of BIM and collaborative working environments," *Autom. Constr.*, vol. 19, no. 5, pp. 522–530, 2010.

[5] S. Azhar, "Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry," *Leadersh. Manag. Eng.*, vol. 11, no. 3, pp. 241–252, Jul. 2011.

1 An introduction to building information modelling

1.1 Introduction

The building information modelling (BIM) approach fosters collaboration between the stakeholders in a project. It also uses the unique sources of data available in multidisciplinary, integrated, verifiable and updatable information models to streamline the exchange of information [1]. Moreover, BIM-based workflows, innovative tools and collaboration platforms can be employed throughout the lifecycle of an asset [2], and have been the catalyst for innovation in the entire architecture, engineering and construction (AEC) industry [3]. Over the past decade, the BIM approach has increasingly been used in both professional practice and research relating to the fields of civil and structural engineering. Indeed, it has been adopted across the globe [4], with some governments demanding its use in public projects involving bridges, tunnels and railways, as well as for strategic facilities like hospitals and schools. In Europe, most countries comply with *Directive 2014/24/EU of the European Parliament and of the Council* [5] on public procurements, which allows such clients to demand the use of BIM methodologies. Some countries, meanwhile, have decided to enforce digital delivery; for example, the United Kingdom has required the use of BIM in all government projects since 2016, while the Italian government published a timeline in 2018 mandating the use of BIM methodologies in all construction work by 2025. As a consequence, companies involved in The AEC sector are embracing the BIM approach by employing new tools and workflows, even though they face obstacles in relation to issues like training costs and time or low initial productivity [6]. The focus of academic research on the benefits and limitations of the BIM approach in the production of construction deliverables for new buildings [7], [8] has also evolved in the last decade. The emphasis is now on potential new uses, as well as interoperability issues between BIM-authoring software and that used in finite element analyses (FEA) to conduct structural assessments [9]–[12]. It is worth noting that the current trend in relation to existing buildings is orientated towards employing the accurate and reliable information-management and visualization processes of information models to improve structural refurbishment and retrofit interventions [13], [14]. The use of these models as high-performing repositories has paved the way for a completely new research field that combines their benefits with the advantages of diagnostic approaches like structural health monitoring (SHM) [15]–[17]. As far as I am aware, there is currently no real state-of-the-art available for consultation on the use of BIM in structural engineering, and so one of the goals of this thesis is to fill this lacuna. It is worth noting that the bibliometric review by Vilutiene *et al.* (2019) [18] is the only relevant example of similar research, even though this is more a quantitative literature review. However, before I get into that, this chapter provides and introduction to the BIM approach in general and its regulatory context both at international and national level.

1.1.1 Advantages in adopting the BIM approach

The BIM approach brings a fundamental change in traditional methodologies adopted in the building process life cycle from design phase to operation phase. The change can be better understood by observing Figure 1.1, which shows two diagrams: the one on the left illustrates the relationships that arise between the stakeholders of the construction process when traditional methodology is adopted; the one on the right illustrates the relationships that arise between the stakeholders of the construction process when the BIM approach is adopted. The stakeholders of a construction project may include the client, structural engineer, architect, contractor, project manager, among others.

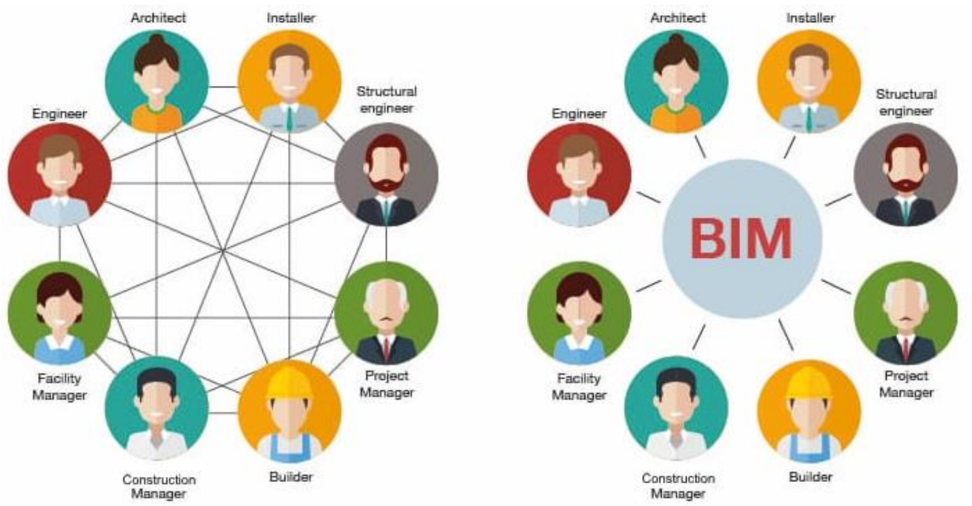


Figure 1.1: Relationships between stakeholders in the building process: traditional methodology (left) and BIM methodology (right).

The traditional methodology requires stakeholders to establish multiple relationships, which means that there are a number of 1-to-1 exchanges of information related to a building during the construction process. In the absence of coordination, the information transferred between the parties is often redundant and makes communication inefficient as well as laborious, since it is essentially based on 2D representations of the work. The BIM methodology, on the other hand, introduces a digital and shared representation of the asset whose creation all stakeholders contribute to, and which, concurrently, they use as a means to exchange information. As a result, communication between the various parties is much more efficient, relying as it does on a common, single, and centralized source of information.

The BIM approach consists of methodologies that rely on technological solutions (i.e. tools) in order to: create digital representations of assets; manage, coordinate and control the information content of digital representations; and create common environments for stakeholders where they can share the digital representations of works. Several studies have been conducted in order to identify and quantify the benefits of adopting BIM as a replacement for traditional methods. Among the earliest is the study conducted by Patrick MacLeamy in 2004, effectively summarized in the graph in Figure 1.2, which is also commonly known as the 'MacLeamy curve' [2].

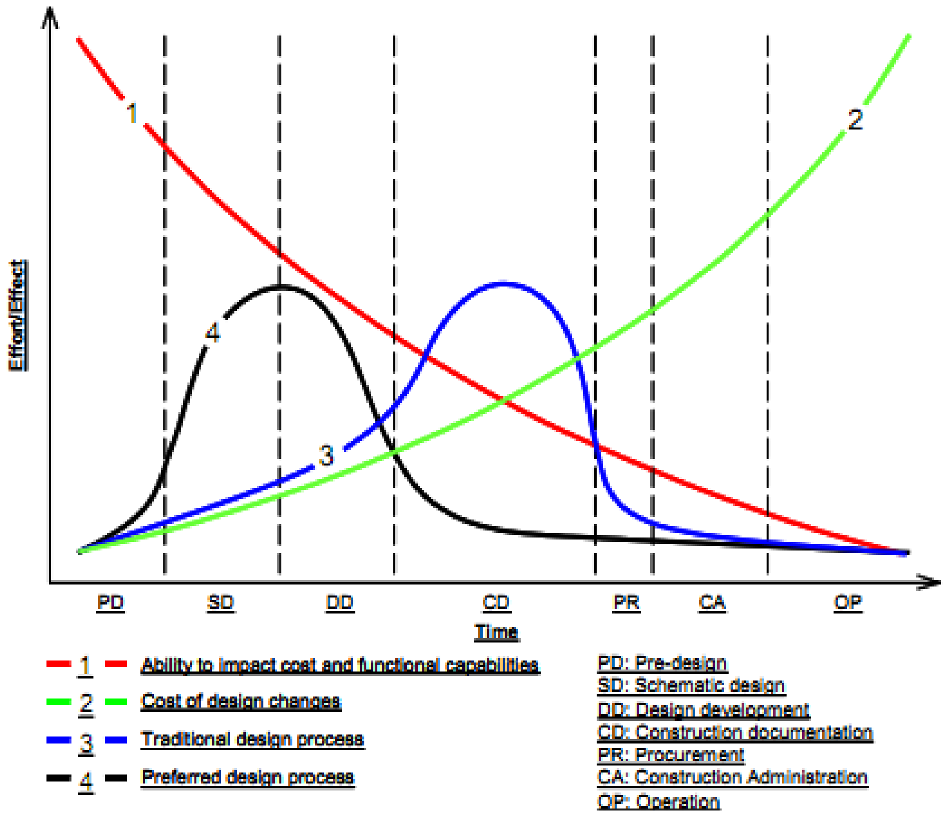


Figure 1.2: The MacLeamy curve.

In Figure 1.2, curve 4 (in black) represents the construction process when the BIM approach is implemented, while curve 3 (in blue) represents the traditional design process. The y-axis shows the effort, in terms of costs and labour, that is required to implement the construction process, while the x-axis shows time. MacLeamy's study shows that adopting the BIM approach means the peak effort occurs earlier, in the concept and design phases, whereas for the traditional methodology the peak effort occurs in the construction phase. It follows that if an organization adopts the BIM approach, it should be prepared to incur higher costs and workmanship in the concept and design phases than it does with the traditional approach. The advantage, for a firm, of adopting the BIM approach is an increase in the efficiency of the design process: using digital representations of projects allows stakeholders to highlight in advance problems that are typically encountered in the construction phase, for example clashes between the structural project and architectural project (i.e., a column that crosses a window). The cost of changes is lower in the initial phases, as curve 2 (in green) shows, because there are fewer constraints, and, at the same time, it is possible to have a more effective impact on the total cost and functionality of the work (curve 1, coloured red). The traditional methodology presents maximum effort in the construction phase because, typically, construction issues are addressed at this point, and changes are therefore made on a project whose design phase has already concluded. For the traditional methodology, changes to the project are characterized by higher costs, in terms of both time and money, because when the construction phase starts, approvals and permits have already been issued for the project, and changes to the project must therefore be communicated to and approved by the authorities that have issued the permits and approvals.

The first estimates of the financial benefits associated with the digitization of design, construction and management processes were conducted in 2016 by the Boston Consulting Group (BCG) [3]. According to this study, adoption of the BIM approach results in project lifecycle cost savings of between 10% and 20%, both in the context of point construction (buildings) and infrastructure works. The savings, however, require engineering and construction companies to make a change by introducing new skills, business models and processes; at the same time, software vendors should produce tools that address new industry needs, while at the governmental level, policies that promote innovation are essential. These assessments spurred the creation of a European Union BIM working group, the EU BIM Task Group (EUBIMTG), which, in 2018, drafted a handbook [4] for the introduction of BIM by public demand in Europe. The study points out that using even the lower threshold proposed by the BCG would result in a 10% improvement in the productivity of the European construction industry, with savings of €130 billion.

In 2017, the McKinsey Global Institute conducted a study on productivity growth in the construction industry over the past two decades [5]. In economics, productivity can be defined as the ratio of the quantity of output to the weighted average of inputs used in the production process. Figure 1.3 depicts an interesting chart from the McKinsey report showing trends in overall productivity growth in the construction and manufacturing industries. A comparison between these two trends highlights that the construction sector has had largely constant productivity over time, while the manufacturing sector has managed, in the same time span, to double its productivity. The study identifies the main causes that have prevented the greater growth of productivity in the AEC sector; specifically, among the main obstacles, there is a lack of standardization in production processes, which is due to the very nature of the construction industry's products, since these are mostly one-of-a-kind, on-site manufactured goods.

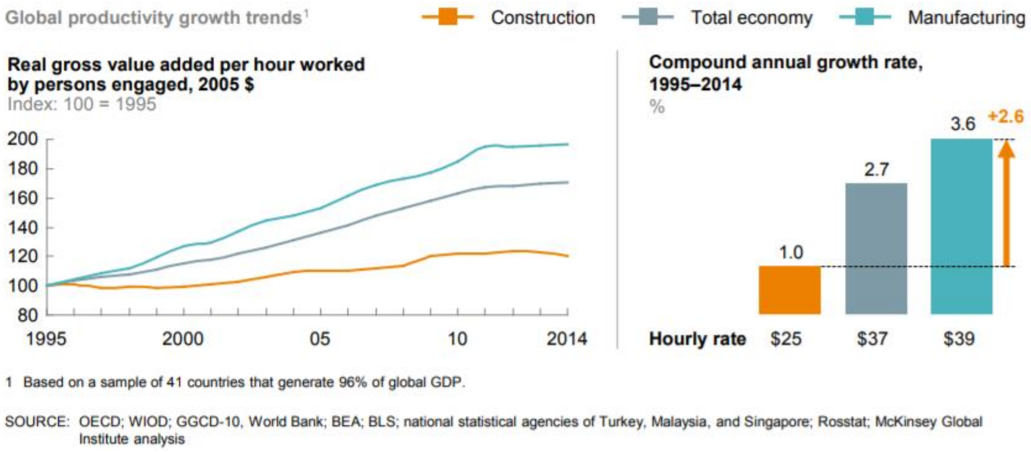


Figure 1.3: Overall productivity trends in the construction and manufacturing sectors.[4]

Finally, the study identifies seven ‘levers’ that can drive productivity gains in the construction industry: changing industry regulations; redefining the contractual framework; rethinking design and engineering processes and encouraging standardization; improving (on-site) procurement and supply chain management; improving on-site work execution; encouraging the adoption of digital technologies, innovative materials and advanced automation tools; and training the workforce to learn new skills. The BIM methodology integrates almost all these elements, so its adoption has a positive impact on the productivity of the construction industry. Indeed, according to the study, the lack of standardization in production processes means that construction professionals spend 30% of their time designing a solution, and the remaining 70% creating and updating two-dimensional representations (2D tables, but also reports, etc.) of the solution, the intention being, fundamentally, to communicate and transfer the designed solution to other stakeholders. On the other hand, members of the workforce who adopt the BIM approach may be able to spend 70% of their time designing a solution for a project, while using the remaining 30% of their time to prepare the material to communicate their solution.

1.1.2 Fundamental pillars of the BIM approach

The BIM approach can be better understood by identifying three fundamental pillars:

- Information models.
- Informative processes (workflows).

[4] McKinsey Global Institute, *Reinventing Construction: a route to higher productivity*, 2017.

- Collaboration platforms.

Informative processes in the form of workflows are used to develop an information model of an asset throughout a project, ensuring the coherence and accuracy of the data stored in it. A model's contents, obviously, change and expand during an asset's lifecycle. However, a collaboration platform enables all the stakeholders involved in a project to work together in the same environment using the information stored in such a model. Each pillar of the BIM approach is described in detail below.

1.1.2.1 Information models

An information model is created with BIM-authoring software. This can sculpt 3D parametric objects that contain many kinds of data, including information about costs, mechanical properties and thermal characteristics. Suitable BIM tools can be used to process the information stored in these models to support tasks like quantity take-offs, economic estimates, and structural and thermal analyses. An information model can also take the form of several models merged in a centralised and integrated version known as a federated model [6]. In this scenario, each model is typically produced by different project teams from disciplines like architecture, structural engineering, mechanical, electrical, and plumbing (MEP) systems, and heating, ventilation and air conditioning (HVAC).

1.1.2.2 Informative processes (workflows)

Information models enable the storage of information from all the disciplines involved in a project. However, it is essential to define well-conceived processes to ensure that this data is consistent and coherent [7]. The BIM approach tackles this by employing standardised work processes instead of stakeholder interactions, and also supports codified information exchanges by way of both proprietary and open-format software. An explanatory process based on an information model therefore produces standardised and streamlined information flows in relation to the following components:

- The information requirements based on project goals.
- The stakeholders involved.
- The activities to be developed.
- The outputs to be delivered.

Of course, the definitions of these elements differ depending on the goals. Furthermore, as the BIM approach can be used throughout the lifecycle of an asset, its processes start from the design phase and foster the integration of information from different disciplines. As an example, the reliability of a model's information relating to 3D coordination, clash-detection, modelling and code-checking can be tested automatically throughout a project's lifecycle using specific BIM tools. These are computerised and sophisticated ways of performing activities that were once conducted using only the human eye. Moreover, because information models are virtualisations rather than simply representations, the creation of design outputs like shop drawings, schedules and bills of quantities is supported by automatic updating procedures. Finally, due to the high quality of the information they store, information models can be used in the facility-management phase, as well as for maintenance, monitoring and decision-making.

1.1.2.3 Collaboration platforms

Collaboration platforms are local or cloud environments with access rules and privileges for each stakeholder; they are also where project documentation (information models, structural analysis models, reports, documents, schedules, plans, etc.) is stored. Known worldwide as a common data environment (CDE), the ISO 19650 series of standards defines the requirement to use a CDE to collect, manage and disseminate information during BIM projects. Consequently, a collaboration platform supports BIM processes and underpins collaborative approaches.

1.1.2.4 Dichotomy between model and process in the BIM approach

Unfortunately, the BIM acronym is often, and improperly, thought to be synonymous with BIM-authoring software, creating the misleading impression that it is more performance software than computer aided design (CAD). In reality, there is a dichotomy between model and process in the BIM approach, with each being essential to the other. In our view, having good knowledge of the technology and tools used to create information models is unproductive if the information stored is not the result of informative processes that ensure its consistency and integrity. Information is crucial in the BIM approach, and so its quality is the key factor in determining whether a project will be successful. In other words, BIM tools and methodologies are a way to safeguard the quality of the information provided by the AEC industry throughout the lifecycle of a facility and in relation to all the disciplines involved in a project. The resulting information models and related information containers contribute to the definition of both a project information model (PIM), from the concept stage to the handover and close-out phases, and an asset information model (AIM) in the operation and management stage.

1.2 A brief introduction to openBIM®

The Institution of Civil Engineers (ICE) defines interoperability as *the ability of computer systems or software to exchange and make use of information* [8]. In the BIM approach, stakeholders generally choose their tools according to internal necessities rather than collaboration criteria, meaning that informative processes often deploy software that is produced by different software houses. Commonly, a software house always ensures the interoperability of its own products. Those by different vendors can become interoperable with plug-ins, which software houses use to collaborate to ensure the compliance of products with vendor-neutral formats like IFC, PDF, BCF, COBie, CityGML, gbXML, and .cvs. In this regard, buildingSMART International not only fosters the diffusion of 'openBIM®', *a collaborative process that is vendor-neutral* (source: https://www.buildingsmart.org/about/openbim, 2020), but also develops and maintains openBIM® industry standards such as IFC, IDM, bSDD and BCF. For the sake of brevity, and to facilitate the reader's understanding of the sections that follow, a brief introduction to IFC and IDM is set out below.

The Industry Foundation Classes (IFC) format is an open, vendor-neutral data model schema that is currently standardised in ISO 16739-1:2018 [9], while the Information Delivery Manual (IDM) is a methodology with which to *facilitate interoperability between software applications used in the construction process, promote digital collaboration between actors in the construction process and provide a basis for accurate, reliable, repeatable and high quality information exchanges* [10]. The IDM methodology is currently standardised in ISO 29481-1:2016 and ISO 29481-2:2012 [11], and includes process maps, interaction maps and exchange requirements. A process map describes the sequence of activities within a particular topic, the stakeholders' roles, and the information required, created and consumed [12]. An interaction map defines roles and transactions for a specific purpose, while exchange requirements identify a *set of information that needs to be exchanged to support a particular business requirement* [10]. This information exchange is based on the IFC format, via the IFC model view definition format (MVD), which is a subset of the IFC schema needed to satisfy one or many exchange requirements. Various MVDs have been certified by buildingSMART®, for example, the: Coordination View; Structural Analysis View; Basic FM Handover View; Space Boundary Add-on View; and Reference View (source: https://technical.buildingsmart.org/, 2020). These are already on the list of MVD options available in the IFC export user interfaces of BIM-authoring software, but it is also possible to develop new

MVDs, with one such possibility being mvdXML (source: https://technical.buildingsmart.org/standards/ifc/mvd/, 2020).

1.3 BIM standards

BIM standardization has three levels: international, European, and national. The *International Organization for Standardization (ISO)* operates at the international level with a dedicated committee on BIM: the TC 59/SC 13 – *Organization and digitization of information about buildings and civil engineering works, including building information modelling*. The *European Committee for Standardization (CEN)* operates at European level with a dedicated committee on BIM: the CT 442 – *Building Information Modelling*. The *Ente Nazionale Italiano di Unificazione (UNI)* is the local standardization body for Italy and has a dedicated committee on BIM, the CT 033/SC 05 – *BIM e gestione digitale dei processi informativi delle costruzioni.*

1.3.1 ISO 19650

BIM-based information management in the AEC industry refers to the ISO 19650 series, which provides international standard procedures for the creation of *information models*, management of *information containers*, and development of procedures for addressing *information exchanges* and *delivery*. In detail, ISO 19650 comprises:

- ISO 19650-1:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling -- Information management using building information modelling: Concepts and principles.
- ISO 19650-2:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling -- Information management using building information modelling: Delivery phase of the assets.
- ISO 19650-3:2020 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 3: Operational phase of the assets.
- ISO/CD 19650-4 *(Under development)* Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 4: Information exchange.
- EN ISO 19650-5:2020 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM). Information management using building

information modelling. Security-minded approach to information management.

Briefly, part 1 introduces concepts and principles of information management through BIM methodology. Part 2 focuses on information management during the design phase of the work, while part 3 focuses on information management during the operation phase of the work. Part 4, which is still in progress, will focus on information exchange; finally, part 5 focuses on information management from the point of view of information security. Information management according to ISO 19650 is closely connected to the concepts of:

- Project information model (PIM) and asset information model (AIM).
- Information requirements (OIR, AIR, PIR, EIR).
- Level of information need.
- Information process management.
- Common data environment (CDE).
- Stages of maturity.

1.3.1.1 Project information model (PIM) and asset information model (AIM)

According to the ISO 19650 series, the information that relates to a project should be managed (*information management*) throughout the entire lifecycle of the project, which, according to ISO 19650-1:2018, is divided into a delivery phase and an operational phase. The delivery phase encompasses the part of the lifecycle in which a real estate asset is designed, built, and put into service; the information managed there constitutes the PIM, short for project information model. The managerial phase encloses the part of the lifecycle in which the work is used and submitted to maintenance; the information managed there constitutes the AIM, an abbreviation of asset information model. Figure 1.4 shows an excerpt from ISO 19650-1:2018 that schematizes information management in the lifecycle of a project.

Key

AIM Asset Information Model
PIM Project Information Model
A Start of delivery phase (see 3.2.11) – transfer of relevant information from AIM to PIM
B Progressive development of the design intent model into the virtual construction model (see 3.3.10 Note 1)
C End of delivery phase – transfer of relevant information from PIM to AIM

Figure 1.4: Generic lifecycle management of information inherent to the project and the asset.

The PIM and AIM will develop progressively as information is produced. The PIM will converge into the AIM, although only in part, in general, because the latter contains information that is specifically needed for the operation and maintenance phase, whereas the PIM contains information specific to the design and construction phase, such as construction models and fabrication models. However, this information will be archived so that it is available in the event of renovation and retrofitting works. Information management in the two phases of the lifecycle of a project, identified by ISO 19650-1:2018, is specifically addressed in ISO 19650 part 2 and ISO 19650 part 3.

Considering the above, it is easier to understand why the ISO 19650 series, the current reference standard for information management methodology in BIM, frames the BIM approach within the broader framework of organization management, which has ISO 9001 as its reference standard: the goal is to ensure greater quality in the construction process. Indeed, by adopting BIM, it is finally possible to manage the exchange of information in a high-quality manner, through the use of standardized procedures for exchanging information (such as file naming), thereby avoiding misunderstandings, and the use of BIM-authoring software and BIM tools to check production and management of information order, in order to prevent stakeholders from sharing partial or redundant information.

1.3.1.2 Information exchanges: OIR, AIR, PIR, EIR

Information management in BIM involves organizing and managing a large amount of information. The appointing party is whoever requests this information, and usually coincides with the client, the operator of the project, or the owner of the project. The appointing party (there are usually multiple appointing parties) produces and delivers the requested information.

According to ISO 19650, information is required in the form of information requirements: *the actual specifications of what, when, how and for whom the information is produced* [1]. The definition of information requirements follows the hierarchical approach of Figure 1.5, which provides strategic-level information requirements (OIR), high-level information requirements (AIR and PIR), and detailed information requirements (EIR). This approach promotes more informed requests for information, oriented towards meeting a goal, purpose, or need.

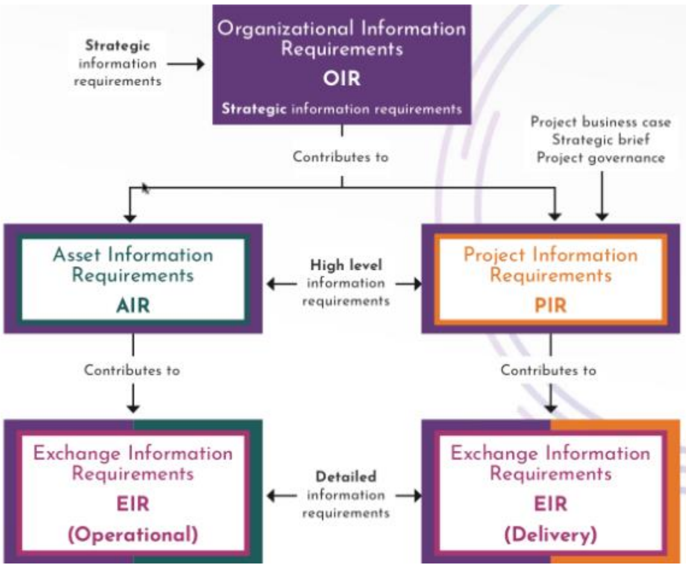


Figure 1.5: Hierarchical organization of information requirements, extracted from Guidance part D of the UK BIM framework.

Moving from the top to the bottom of Figure 1.5, an organization defines its *organization information requirements (OIR)* on the basis of strategic objectives such as: reducing emissions, managing the property, or meeting legal requirements. The OIR help to define high-level information requirements, which divide into project information requirements (PIR) specific to the delivery phase of the work, and asset information requirements (AIR), specific to the operation phase of the work. These are used in the *appointment* phase to prepare the *exchange information requirements (EIR),* which must be defined for each supplier. The information requirements expressed in the EIRs contribute to defining the information deliverables that the suppliers will deliver to the appointing party; these will flow into the project information model (PIM) and then into the asset information model (AIM). Figure 1.6 shows an extract from ISO 19650-1:2018 that schematically summarizes the flow from OIR to AIM.

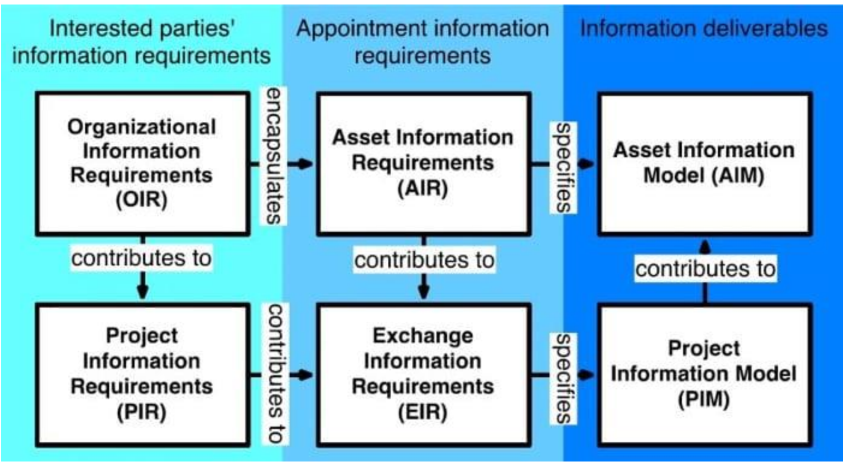


Figure 1.6: Relationships between information requirements and information models.

1.3.1.3 The level of information need

The *level of information need* is the new reference framework that the EN 17412-1:2020 has introduced to define information exchange requirements. The novelty consists in explicitly including documentation in the information exchange requirements.

Figure 1.7: The level of information need framework, extracted from UK BIM FRAMEWORK guidance D to ISO 19650.

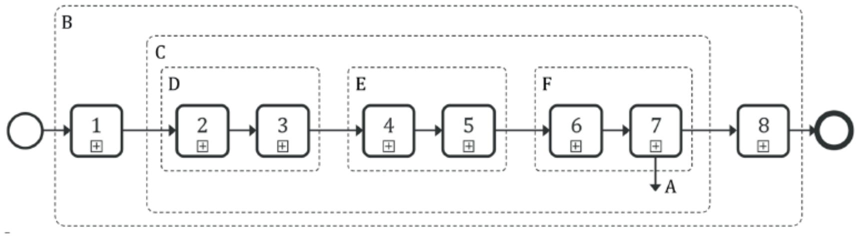
The level of information need is defined according to the objectives of the information models and the objectives and uses of the BIM models and objects, as well as the AEC documents. The proponent, i.e., the person drafting the EIR, defines the Information Requirement Level of the information models, BIM models and objects, and AEC documents according to its needs. However, it is possible that the client lacks the skills and knowledge to establish the Information Requirement Level of the assignment, so the task is performed by the contractor who drafts the BEP.

1.3.1.4 The information management process

ISO 19650-2:2018 identifies the main activities of a project's information management process in relation to the *delivery phase*:

- Assessment and need
- Invitation to tender
- Tender response
- Appointment
- Mobilization
- Collaborative production of information
- Information model delivery
- Project close-out

Figure 1.8 shows the information management process of ISO 19650-2:2018. The process begins with an *assessment and need* by the client, which makes its own evaluations and defines its own needs in terms of information management for the project it intends to implement. This activity, which can be compared to the Italian '*studio di fattibilità tecnico-economico'*, leads the client to define the EIR of the project.



Key

Activity

1	Assessment and need	A	Information model progressed by subsequent delivery team(s)
2	Invitation to tender	B	Activities undertaken per project
3	Tender response	C	Activities undertaken per appointment
4	Appointment	D	Activities undertaken during the procurement stage (of each appointment)
5	Mobilization		
6	Collaborative production of information	E	Activities undertaken during the planning stage (of each appointment)
7	Information model delivery		
8	Project close-out (End of delivery phase)	F	Activities undertaken during the production stage (of each appointment)

Figure 1.8: The information management process from ISO 19650-2:2018.

This is followed by the tender stage, divided into *invitation to tender* (activity two) and *tender response* (activity three). In order to meet the client's needs as defined in the EIR, prospective bidders submit their bid for information management through the *pre-appointment BIM execution plan* (pre-BEP), in which they attest to their ability and capacity in relation to the information management of a project. The *lead appointed party*, in collaboration with the other members of the *delivery team*, reviews and updates the (pre-appointment) *BEP*. More precisely, they specify the names of all the appointed parties that the delivery team includes, the hardware and software tools that will be used, as well as the responsibility matrix, and prepare additional information management planning documents such as the *master information delivery plan (MIDP)* and the *task information delivery plan (TIDP).* The strategy also includes defining the common data environment (CDE), which is made explicit in the BEP in terms of technology, structure, and processes. In the stage of production of information, the delivery team carries out activities six, *collaborative production of information*, and seven, *information model delivery*. In detail, the appointed parties produce the information collaboratively by exploiting the CDE and the information exchange and delivery processes defined in the BEP, while the lead appointed party is responsible for ensuring the coordination of the information produced by the appointed parties and for delivering the project deliverables to the client. In the end, the project ends with the *close-out* activity, which can take place only at the end of all appointments related to the project.

1.3.1.5 The common data environment (CDE)

The *common data environment (CDE)* is introduced in ISO 19650-1:2018, where it is defined as "an agreed source of information for a given job or asset, used to collect, manage and share (in the sense of to disseminate, communicate) each information container through a management process (predefined)". The standard emphasizes the dual nature of the CDE, consisting of CDE workflow, i.e. the processes, and CDE solutions, i.e. the technology(s). The CDE leverages technology solutions from the marketplace to implement processes that ensure information is managed and made readily available to those who need it when they need it. More precisely, a CDE facilitates a dynamic environment where 'information containers' move between different stages based on a particular workflow. As is shown in Figure 1.9, an information container normally starts with a *work-in-progress* stage, before moving to a *shared* stage. The *published* stage is achieved after several exchanges back and forth between the first two phases. The final step occurs when the information container is *archived*. Moving from one stage to the next requires the deployment of a process consisting of checks, approvals, and authorisations. In this regard, CDE solutions today all contain valuable tools for use in process design and management.

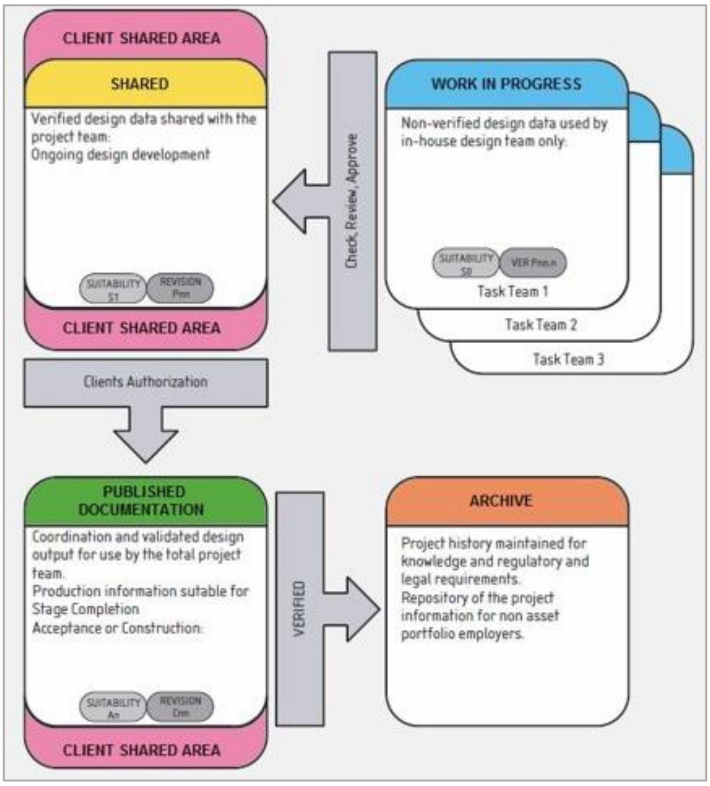


Figure 1.9: The structure of the common data environment (CDE) according to ISO 19650.

1.3.1.6 Stages of maturity

Before the publication of the ISO 19650 series, BIM digital maturity levels were typically described with respect to the Bew-Richards triangle that Figure 1.10 depicts.

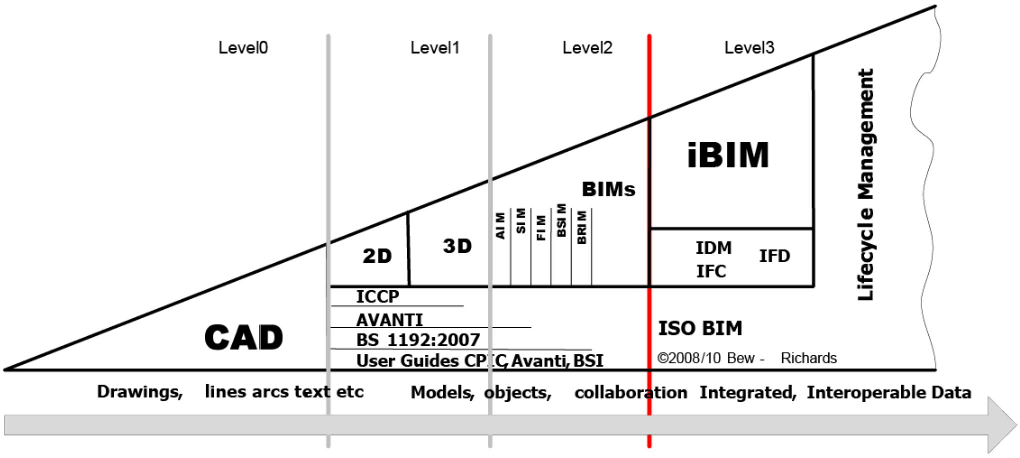


Figure 1.10: BIM digital maturity levels - the Bew-Richards triangle.

The triangle helps us to understand the progressive change introduced by the BIM approach in the construction industry: proceeding from level 0 to level 3, it increases the digital maturity of the project, which entails the availability of structured information and adequate tools that enable collaboration between actors. Level 0 corresponds to the traditional approach based on the use of CAD (construction aided design) to create 2D drawings of the project (plans, elevations, carpentry, etc.) that the actors exchange on paper if necessary. In Level 1, BIM is used to complement 2D drawings with 3D digital models to improve understanding of the project, especially in the case of architecture. The real ‘collaborative revolution’ occurs at Level 2, where an information-sharing environment is defined for the first time to truly enable collaboration among stakeholders. Each discipline (structures, architecture, systems, etc.) has its 3D digital model that will be federated (merged to form a single model) with the other models. Level 3 concludes, characterized by stakeholders collaborating through a single project model (i.e., valid for all design disciplines) that is shared, since it is stored in a centralized repository.

Currently, the ISO 19650 series has introduced the stages of maturity of BIM and proposes the new reference framework that Figure 1.11 depicts. The scheme identifies on the horizontal axis three stages (phases) of progression articulated in four layers: normative, technological, informative and business. For the normative layer, phase 1 requires the use of national standards (in Italy, for example, UNI 11337), phase 2 requires ISO 19650 as the reference standard, and phase 3 foresees standards that have not been produced yet. The technological layer requires the support of a CDE in all phases: in phases 1 and phase 2 the CDE can manage files and models, in other words, informative containers, but in phase 3 the CDE can manage the data and is no longer limited to simple containers. However, this is a hypothetical scenario because technologies that can support such an approach are currently lacking. The information layer follows the trend of the technological layer: in phase 1 it requires the use of structured and unstructured data, in phase 2 it opens to the use of federated information models as well, but in phase 3 it includes the possibility of using servers able to manage the BIM objects directly. Moving from phase 1 to phase 3, the information layer is accompanied by an increase in benefits from collaboration. In the end, the business layer benefits more by proceeding from phase 1 to phase 3 as it increases its ability to implement digital processes.

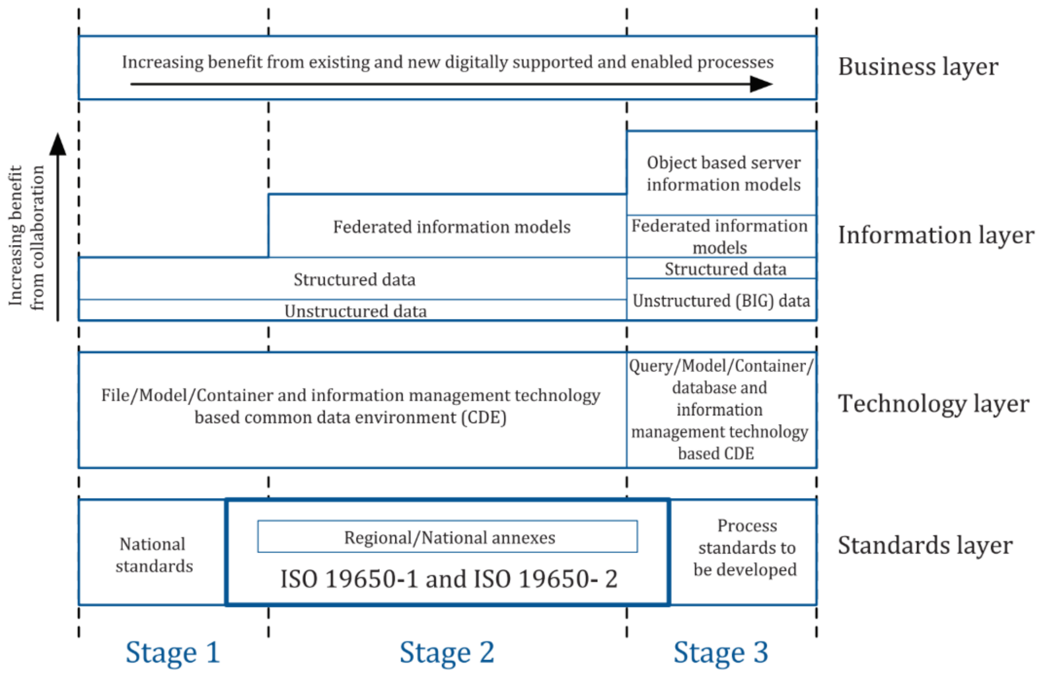


Figure 1.11: Stages of maturity of analogue and digital information management according to ISO 19650-1:2018.

1.3.2 UNI 11337

In 2019, following the publication of ISO 19650, the UNI 11337 series become the Italian national annex to the international standard (ISO 19650), according to the Vienna Agreement signed between ISO and CEN in 1991. The Italian technical committee UNI/CT 033 is currently reviewing and updating UNI 11337:2017 to harmonise the Italian national annex with the novelties that the ISO 19650 has introduced. At the moment, the UNI 11337 series comprises twelve parts, which are summarized in Table 1.1.

Table 1.1: The UNI 11337 series.

UNI 11337 – Gestione digitale dei processi informativi delle costruzioni (BIM)		
Part	**Subject**	**Status**
Part 1	Concetti e principi: sistemi informativi per le costruzioni, modelli, elaborati e oggetti	Under review
Part 2	Classi e oggetti digitali	Under review
Part 3	Attributi informativi, schede di prodotto e smart CE	Under review
Part 4	Livelli di fabbisogno informativo	Under review
Part 5	Ambiente di condivisione dei dati (ACDat)	Under review
Part 6	Capitolato informativo	Under review
Part 7	Figure professionali	Under review
Part 8	Flussi informativi per la gestione della commessa	Under development
Part 9	Fascicolo del costruito	Under development
Part 10	Verifica amministrativa	Under development
Part 11	Sicurezza dei dati	Under development
Part 12	Sistemi di gestione BIM (PdR 74/2020)	Under development

1.3.2.1 UNI 11337 part 1

UNI 11337 part 1 introduces concepts and principles of information management in BIM. This is intended also to guide the reader in understanding the subject that each part focuses on. One of the fundamental concepts that the standard introduces is *building information systems*. In general, an information system comprises *components of an organization to acquire, elaborate, archive, retrieve, share and transfer information* (Chianese et al., 2015). The components consist of human resources, data, automatic and non-automatic procedures, automatic and non-automatic tools, and organizational and management rules. Interactions between these components create *information flows*, which pass through organizations' processes (*production or decision-making processes*, commonly), conditioning their efficiency and effectiveness.

The information system of an organization includes the *computer system*, which is *the technology/s supporting an information system* [13]; a computer system therefore belongs to the field of Information and Communication Technology (ICT). On the other hand, an information system belongs to the organization system, which could also exist, in the past, without a supporting computer system.

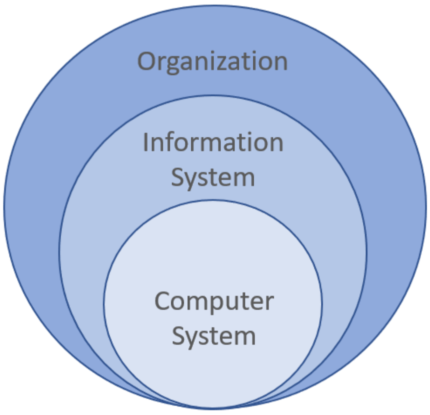


Figure 1.12: Organization, information and computer system.

UNI 11337 part 1 states that "*organizations operating in the AEC (Architecture, Engineering, Construction) sector shall have, for the purposes of product and process information management, AEC information systems to manage data, information and information containers*". This also states that an AEC information system manages information models through:

- coordination platforms
- sharing environments (CDEs)
- libraries
- software.

The information models of the AEC sector are virtualizations or digital simulations (i.e. simplified versions) of the real world, created, with respect to the AEC domain, through machine-readable data and information. Data, information and digital information contents are collected in a structured manner and placed in information containers (files, directories and databases (DB)) that can be managed by AEC information systems. More specifically, information contents include:

- GIS models;
- BIM models;
- BIM objects;

- AEC and non-AEC documentation.

BIM Authoring software allows us to produce BIM models that are made up of a structured set of graphical/geometric BIM objects (3D) of construction products. BIM objects of the AEC sector are 3D parametric representations of construction products (in other words, they relate to structures, architecture, electrical system, etc.). Information can be added to BIM objects in the form of attributes to the object: for example, its mechanical performance, thermal performance, cost, etc. Examples of AEC documents are 2D documents, i.e., two-dimensional representations of the design solution, but also calculation reports, material reports, etc.

1.3.2.2 UNI 11337 part 4

UNI 11337 part 4 focuses on determining the information complexity of BIM models and objects. In particular, part 4 will incorporate the principles defined in EN 17412:2020 regarding the Level of Information Need framework. While the level of information need will be specific to the assignment, current systems refer to the Level of Development (LOD) of objects' scale, a pre-established scale for qualifying and quantifying information needs. Table 1.2 summarises the LOD scale according to the UNI 11337 series.

Table 1.2: LOD according to the UNI 11337.

	LOD	
LOD A	Oggetto Simbolico	**Entità:** rappresentate graficamente attraverso un sistema geometrico simbolico. **Caratteristiche:** qualitative e quantitative sono indicative
LOD B	Oggetto Generico	**Entità:** rappresentate graficamente attraverso un sistema geometrico generico o una geometria di ingombro. **Caratteristiche:** quantitative e qualitative sono approssimate.
LOD C	Oggetto Definito	**Entità:** rappresentate con un sistema geometrico definito. **Caratteristiche:** quantitative e qualitative sono definite in via generica entro e nel rispetto dei limiti della legislazione vigente e delle norme tecniche di riferimento
LOD D	Oggetto Dettagliato	**Entità**: rappresentate come sistema geometrico definito. **Caratteristiche**: quantitative e qualitative sono specifiche di una pluralità definita di prodotti

LOD E	Oggetto Specifico	**Entità**: rappresentate come sistema geometrico definito. **Caratteristiche**: quantitative e qualitative sono specifiche di ogni singolo sistema produttivo legato ad un prodotto definito. Dettagli di fabbricazione e montaggio
LOD F	Oggetto Eseguito	**Entità**: rappresentano la virtualizzazione verificata sul luogo dello specifico sistema produttivo (as-built). **Caratteristiche:** quantitative e qualitative sono specifiche di ogni singolo sistema produttivo legato ad un prodotto posato o installato. Dettagli di manutenzione, riparazione e sostitutizione legato al ciclo di vita dell'opera
LOD G	Oggetto Aggiornato	**Entità:** rappresentano la virtualizzazione aggiornata dello stato di fatto di un'entità in un tempo definito. Rappresentazione storicizzata dello scorrere della vita utile di uno specifico sistema produttivo. **Caratteristiche:** quantitative e qualitative aggiornate rispetto al ciclo di vita.

1.3.2.3 UNI 11337 part 5

UNI 11337 part 5 introduces information flows and the general architecture of data sharing environments (ACDat), which is the Italian version of CDE.

1.3.2.4 UNI 11337 part 6

UNI 11337 part 6 is a guideline for drafting the '*Capitolato Informativo*' (CI), the Italian term for the EIR of ISO 19650. The client drafts the CI, to which aspiring project teams respond with an '*Offerta di Gestione Informativa*' (oGI), the Italian for pre-BEP. After the tender stage, the winning project team prepares the '*piano di gestione informativa*' (pGI), the Italian for BEP of ISO 19650.

1.3.2.5 UNI 11337 part 7

UNI 11337 part 7 introduces roles for practitioners who are involved in the production and management of information for the AEC sector. Specifically, these roles are divided into two categories:

- Roles at organization level: BIM Manager and PLT Manager.
- Roles at the project or asset level: BIM Coordinator, BIM Specialist and CDE Manager (single or distributed; job/asset).

Part 7 identifies and lists, for each role, the knowledge, skill, and competency requirements. More precisely, the BIM Manager has a strategic role in an AEC organization: he/she knows the business processes and therefore the information flows of the organization; he/she manages tools, budgets and human resources; he/she produces the BIM-related guidelines of the organization. The PLT Manager regulates and manages coordination information systems and has IT skills in data analysis (big data, blockchain, etc.). The BIM Coordinator has an operational role at the job order level, and therefore: manages and coordinates job or asset information flows; manages work groups; has expertise on specific information tools for classification, coordination and verification of information; manages information models; and collaborates with the BIM Manager in the production of the Information Specifications and/or bid and Information Management plan. The BIM Specialist is distinguished according to the discipline of competence, for instance BIM Specialist for structure, for architecture, for MEP, and so on. He/she is responsible for the production of information flows, has expertise in specific information production tools and data production, BIM Models and Objects, and AEC Documents. The CDE Manager is responsible for managing collaborative information systems and has expertise in data management information technology (DBMS, etc.).

References

[1] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons, 2011.

[2] A. Grilo and R. Jardim-Goncalves, "Value proposition on interoperability of BIM and collaborative working environments," *Autom. Constr.*, vol. 19, no. 5, pp. 522–530, 2010.

[3] S. Azhar, "Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry," *Leadersh. Manag. Eng.*, vol. 11, no. 3, pp. 241–252, Jul. 2011.

[4] R. Edirisinghe and K. London, "Comparative Analysis of International and National Level BIM Standardization Efforts and BIM adoption," in *Proc. of the 32nd CIB W78 Conference 2015, 27th-29th October 2015, Eindhoven, The Netherlands*, 2015, pp. 149–158.

[5] European Union, "Directive 2014/23/EU of the European Parliament and of the Council of 26 February 2014 on the award of concession contracts," *Off. J. Eur. Union*, vol. L 94/1, no. 28.3.2014, pp. 1–64, 2014.

[6] F. Muñoz-La Rivera, J. C. Vielma, R. F. Herrera, and J. Carvallo, "Methodology for Building Information Modeling (BIM) Implementation in Structural Engineering Companies (SECs)," *Adv. Civ. Eng.*, vol. 2019, pp. 1–16, Feb. 2019.

[7] I. Kaner, R. Sacks, W. Kassian, and T. Quitt, “Case studies of BIM adoption for precast concrete design by mid-sized structural engineering firms,” *J. Inf. Technol. Constr.*, vol. 13, no. 21, pp. 303–323, 2008.

[8] D. Schinler and E. Nelson, “BIM and the structural engineering community,” *Structure*, vol. 12, pp. 10–12, 2008.

[9] F. Fedorik, T. Makkonen, and R. Heikkilä, “Integration of BIM and FEA in automation of building and bridge engineering design,” in *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, 2016, vol. 33, p. 1.

[10] R. Pukl, P. Pálek, and J. Červenka, “The possibility of using BIM for nonlinear life-cycle analysis of concrete structures,” in *The Fifth International Symposium on Life-Cycle Civil Engineering (IALCCE 2016), Oct. 16–20, Delft, Netherlands*, 2016, pp. 655–661.

[11] R. Ren, J. Zhang, and H. N. Dib, “BIM Interoperability for Structure Analysis,” in *Construction Research Congress 2018*, 2018, pp. 470–479.

[12] A. M. M. Hasan, A. A. Torky, and Y. F. Rashed, “Geometrically accurate structural analysis models in BIM-centered software,” *Autom. Constr.*, vol. 104, no. December 2018, pp. 299–321, 2019.

[13] S. Bruno, M. De Fino, and F. Fatiguso, “Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management,” *Autom. Constr.*, vol. 86, no. December 2017, pp. 256–276, 2018.

[14] U. Vitiello, V. Ciotta, A. Salzano, D. Asprone, G. Manfredi, and E. Cosenza, “BIM-based approach for the cost-optimization of seismic retrofit strategies on existing buildings,” *Autom. Constr.*, vol. 98, pp. 90–101, Feb. 2019.

[15] F. Banfi, L. Barazzetti, M. Previtali, and F. Roncoroni, “HISTORIC BIM: A NEW REPOSITORY FOR STRUCTURAL HEALTH MONITORING,” *ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. XLII-5/W1, no. 5W1, pp. 269–274, May 2017.

[16] A. N. Ede, O. M. Olofinnade, and J. O. Sodipo, “Use of building information modelling tools for structural health monitoring,” in *2017 International Conference on Computing Networking and Informatics (ICCNI)*, 2017, pp. 1–4.

[17] M. Theiler, K. Dragos, and K. Smarsly, “BIM-based Design of Structural Health Monitoring Systems,” in *Structural Health Monitoring 2017*, 2017, vol. 0, no. shm.

[18] T. Vilutiene, D. Kalibatiene, M. R. Hosseini, E. Pellicer, and E. K. Zavadskas, “Building Information Modeling (BIM) for Structural Engineering: A Bibliometric Analysis of the Literature,” *Adv. Civ. Eng.*, vol. 2019, pp. 1–19, Aug. 2019.

[19] P. MacLeamy, “MacLeamy curve,” *Collab. Integr. Information, Proj. Lifecycle Build. Des. Constr. Oper.*, 2004.

[20] P. Gerbert, S. Castagnino, C. Rothballer, A. Renz, and R. Filitz, “Digital in Engineering and Construction: The Transformative Power of Building Information Modeling,” *Bost. Bost. Consult. Gr. Inc*, 2016.

[21] EUBIM Task Group, “Handbook for the introduction of Building Information Modelling by the European Public Sector,” *EU BIM Task Gr.*, p. 84, 2016.

[22] F. Barbosa, J. Woetzel, and J. Mischke, “Reinventing Construction: A Route of Higher Productivity,” McKinsey Global Institute, 2017.

[23] “19650-1: 2018 - Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 1: Concepts and principles.” 2018.

[24] C. Eastman, P. Teicholz, R. Liston, and K. Liston, *BIM Handbook A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, Second Edition*. 2012.

[25] R. Sacks, M. Treckmann, and O. Rozenfeld, “Visualization of Work Flow to Support Lean Construction,” *J. Constr. Eng. Manag.*, vol. 135, no. 12, pp. 1307–1315, Dec. 2009.

[26] “Interoperability: The ability of computer systems or software to exchange and make use of information.” [Online]. Available: https://www.ice.org.uk/getattachment/news-and-insight/the-civil-engineer/june/overcome-interoperability-challenge/Interoperability-Information-Sheet-(1).pdf.aspx. [Accessed: 26-Apr-2021].

[27] “ISO 16739-1:2018 - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries -- Part 1: Data schema.” .

[28] “ISO 29481-1: 2016 - Building Information Modeling—Information Delivery Manual—Part 1: Methodology and Format.” ISO, Geneva, Switzerland, 2016.

[29] “ISO 29481-2:2012 - Building information models–information delivery manual–part 2: interaction framework.” 2012.

[30] R. Volk, J. Stengel, and F. Schultmann, “Building Information Modeling (BIM) for existing buildings - Literature review and future needs,” *Automation in Construction*, vol. 38. Elsevier, pp. 109–127, 01-Mar-2014.

[31] A. Chianese, *Sistemi di basi di dati e applicazioni*. Maggioli Editore, 2015.

2 BIM in Structural Engineering: The State-of-the-Art

2.1 Introduction

Over the past decade, the fields of civil engineering, i.e. structural engineering, have increasingly used the building information modelling (BIM) approach in both professional practice and as the focus of research. However, the field of structural engineering, which can be seen as a sub-discipline of civil engineering, misses, as far as I am aware, there is no real state-of-the-art on the use of BIM in this regard. The aim of this chapter, therefore, is to start bridging that gap. In particular, I have conducted a traditional literature review on the utilization of BIM in structural engineering, enabling me to perform a detailed content analysis of publications. The qualitative investigation of the literature has highlighted six main BIM uses in structural engineering: 1. structural analyses; 2. production of shop drawings; 3. optimized structural design: early identification of constructability issues and comparison of different structural solutions; 4. seismic risk assessments; 5. existing-condition modelling and retrofitting of structures; and 6. structural health monitoring. Each of these is discussed in relation to their: reference workflows; use of information models; information exchanges; and main limitations. In the conclusions, I identify current gaps in knowledge, likely developments and improvements in the utilization of BIM in structural engineering. I also outline the possible significance of this work more broadly.

2.2 Methodology

The methodology adopted to develop this state-of-the-art on the use of BIM in structural engineering both in industry and research had three key steps:

1. A traditional literature search on the use of BIM in structural engineering. This has enabled a thorough analysis of the content uncovered in order to identify: 1. the topics addressed by relevant publications pertaining to structural engineering (i.e., structural analyses, structural type, structural design, damage assessment, performance-based earthquake engineering (PBEE), post-earthquake assessments, SHM, etc.)); 2. the phase(s) of a building’s lifecycle

considered by these publications; and 3. the availability of reference BIM workflows (or process maps). The results are presented in Table 2.1.

2. A qualitative analysis of the content relating to structural engineering uncovered in Step 1. This highlighted six main areas where BIM tools and methodologies are used in structural engineering, i.e., ‘BIM uses in structural engineering’. These six uses are described in detail in Table 2.2, which also contains the outputs of a comparison with the ‘25 BIM-uses’ documentation produced by Penn State University. In this regard, I defined three matching criteria in relation to the list of BIM uses and their description given in the Penn State University guide:
   - Weak: there is no BIM use with the same title proposed by the Authors nor is there a BIM use that, in its description, focuses on the structural engineering area that the Authors identified.
   - Medium: there is either a BIM use with the same title identified by the Authors or there is a BIM use (or more than one) that focuses on the same topic proposed by the Authors, even if the description in the guide is too general and never directly relates to the structural engineering discipline.
   - Strong: there is a BIM use with the same title identified by the Authors and its description goes into detail about the structural engineering area that the Authors identified.
3. A detailed description of the identified BIM uses in structural engineering, highlighting their reference workflows in contemporary experience, use of information models and information exchanges, and their main limitations.

2.2.1 Literature search on the use of BIM in structural engineering and analysis of the content uncovered

Search engines like Google Scholar, Scopus and ASCE were used to conduct a literature search for articles, conference reports and books relating to BIM and structural engineering concurrently. After a preliminary analysis of the title, keywords, and abstract, many papers were excluded from any further analysis, because their focus was mainly on disciplines like architecture, energy performance, and sustainability, or their purpose was to explain the BIM strategies adopted by construction companies, engineering firms and educators. Some of these studies may, nonetheless, be valuable for those wanting a comprehensive literature review on the BIM approach more generally [1], [2]. However, papers with mixed topics were considered where this preliminary analysis highlighted relevant structural engineering content. My final bibliography references 45 journal articles, conference reports and books, and is summarised in Table 2.1 below.

2.3 Results

Table 2.1 presents the results of the literature search on the use of BIM in structural engineering and the Authors' analysis of the content uncovered. The final bibliography references 45 journal articles, conference reports and books.

I conducted a thorough analysis of the content uncovered in these 45 publications in order to identify:

- Topics pertaining to structural engineering (i.e., structural analyses, structural type, structural design, damage assessment, performance-based earthquake engineering (PBEE), post-earthquake assessments, structural health monitoring (SHM), etc.) addressed in the publications.
- The building lifecycle phase(s) considered.
- The BIM content of the publications was analysed from a methodological and technological perspective. In the first case, the Authors identified the availability of reference BIM workflows (or process maps) by answering the question: 'Is there any BIM workflow or process map in this publication?'. In addition, the Authors highlighted the possible collaborative characteristic of the implemented processes by answering the question, 'is integration with one or more disciplines addressed?'. From a technological perspective, the Authors preferred to neglect details about the technologies used in the publications. However, the Authors highlighted whether a publication specifically addressed interoperability (and issues that may be related to this) among the implemented technologies by answering the question, 'is interoperability addressed in this publication?'.

The year and type of publication are also specified.

Table 2.1: Results of literature search on the use of BIM in structural engineering.

				Building lifecycle				BIM content		
Reference	**Year**	**Type of publication**	**Structural engineering content**	**Plan**	**Design**	**Construction**	**Operate**	**Is there any BIM workflow or process map in this publication?**	**Is integration with one or more disciplines addressed?**	**Is interoperability addressed in this publication?**
[3]	2012	Journal article	Structural safety; structural analyses; comparison of different structural design solutions (set-base analysis); early-stage optimisation of structural design choices with respect to constructability criteria (cost-estimations and quantity take-offs); outrigger systems (high-rise buildings).		X			Yes	Yes	Yes
[4]	2014	Conference paper	Structural safety; structural analyses.		X			No	Yes	Yes
[5]	2015	Journal article	Structural analyses; structural design optimisation; early-stage optimisation of structural design choices with respect to constructability criteria.		X			Yes	No	No
[6]	2016	Journal article	Structural analyses.		X			Yes	No	Yes
[7]	2016	Conference paper	Structural analyses; bridge engineering.		X			Yes	No	Yes
[8]	2017	Journal article	Structural analyses; BIM collaboration processes in structural engineering.		X	X		No	Yes	Yes
[9]	2016	Journal article	Non-linear FEM analysis; structural analyses; lifecycle reliability of structures and structural elements; concrete and reinforced concrete structures; bridge engineering.		X			Yes	No	Yes
[10]	2018	Journal article	Structural analyses.		X			No	No	Yes
[11]	2018	Conference paper	Structural analyses.		X			No		Yes
[12]	2018	Book	Structural design; structural analyses; production of structural engineering deliverables from structural building information modelling (S-BIM).		X	X		Yes	Yes	Yes
[13]	2019	Journal article	Structural analyses.		X			No	No	Yes
[14]	2009	Journal article	Production of structural engineering deliverables; optimisation of structural design choices on constructability criteria; pre-cast concrete; pre-stressed concrete; structural engineering.		X	X		Yes	Yes	Yes
[15]	2012	Book	Production of structural engineering deliverables from S-BIM.		X	X	X	No	Yes	Yes
[16]	2009	Journal article	S-BIM; fabrication model; precast concrete; steel and cast-in place reinforced concrete members.		X	X		No	Yes	Yes
[17]	2011	Journal article	4D structural information model; time-dependent structural models; structural analyses; optimisation of structural design choices on safety criteria.		X	X		Yes	Yes	Yes
[18]	2011	Journal article	4D structural information model; time-dependent structural models; structural analyses; optimisation of structural design choices on safety criteria.		X	X		Yes	Yes	Yes
[19]	2016	Journal article	Early-stage optimisation of structural design choices on constructability criteria.		X	X		Yes	No	No
[20]	2012	Journal article	Early-stage optimisation of structural design choices on economic criteria.		X	X		Yes	No	No
[21]	2013	Journal article	Quantity take-off-oriented BIM-based design; optimisation of structural design choices.		X			Yes	No	No
[22]	2015	Journal article	Early-stage optimisation of structural design choices on quantity take-off criteria.		X			Yes	No	No

[23]	2010	Journal article	Pacific Earthquake Engineering Research (PEER) Centre's performance-based earthquake engineering (PBEE) methodology; assembly-based vulnerability (ABV); damage analysis; structural and non-structural components; scheduling of 3D/4D visualisations for post-earthquake building rehabilitation.	X		Yes	No	No
[24]	2014	Journal article	Seismic risk assessment; seismic risk mitigation; PEER Centre's PBEE methodology; damage analysis assessment; existing structures; structural and non-structural components; structural health monitoring; post-earthquake inspections.	X	X	No	No	No
[25]	2017	Journal article	PBEE; automated seismic design; FEMA P-58 method; structural and non-structural components.	X		Yes	No	No
[26]	2016	Journal article	Existing structures; post-earthquake damage assessment; strength analysis; reinforced concrete.		X	Yes	No	No
[27]	2016	Conference paper	PBEE; structural analyses; earthquake-loading conditions; damage analysis; lifecycle environmental assessment (LCA); environmental impact of damaged building; seismic retrofit.	X	X	Yes	No	No
[28]	2019	Journal article	PBEE; FEMA P-58 method; seismic loss assessment; structural and non-structural components.	X		No	No	No
[29]	2020	Journal article	Seismic risk assessment; non-structural elements.	X		Yes	No	No
[30]	2019	Journal article	PEER Centre's PBEE methodology; lifecycle costing (LCC); optimisation of seismic retrofit strategies; damage analysis; structural and non-structural components; existing structures.	X	X	Yes	No	No
[31]	2019	Journal article	Seismic structural analysis; seismic damage simulation and analysis; octree algorithm for discretisation; complex geometries.	X		Yes	No	No
[32]	2015	Journal article	Existing structures; building condition assessment (structural survey); as-built modelling of structures; access to and integration of maintenance information and knowledge.		X	No	No	No
[33]	2015	Journal article	Existing structures; building condition assessment (structural survey); as-built modelling of structures; finite element analysis (FEM); structural analysis; complex geometries.		X	Yes	No	No
[34]	2016	Journal article	Existing structures; building condition assessment (structural survey); as-built modelling of structures; structural analysis; timber roof structures; complex geometries.		X	Yes	No	No
[35]	2017	Journal article	Existing structures; building condition assessment (structural survey); structural analysis; seismic vulnerability.		X	Yes	No	Yes
[36]	2018	Journal article	Existing structures; building condition assessment (structural survey); management of diagnostic tests; structural analysis; diagnostics and monitoring for structural reinforcement.		X	Yes	No	No
[37]	2018	Journal article	Existing bridges; reinforced concrete bridges; defect modelling.		X	Yes	No	Yes
[38]	2014	Journal article	Existing structures; building condition assessment (structural survey); retrofitting.		X	Yes	Yes	Yes
[39]	2017	Journal article	BIM-based bridge management system; bridge maintenance; inspection system using 3D models; existing cable-stayed bridge.		X	Yes	No	No
[40]	2019	Conference paper	Existing structures; building condition assessment (structural survey); as-built modelling of structures; management of diagnostic tests.		X	No	No	No
[41]	2015	Conference paper	Structural health monitoring (SHM); as-built modelling of infrastructures; existing infrastructures.		X	No	No	Yes

[42]	2017	Conference paper	SHM; modelling of structural performance monitoring systems; pre-stressed concrete bridge.	X	No	No	Yes
[43]	2017	Conference paper	SHM; modelling of structural performance monitoring systems.	X	No	No	Yes
[44]	2017	Conference paper	SHM; archiving and visualising SHM data; existing bridges.	X	Yes	No	No
[45]	2018	Journal article	SHM; bridges.	X	Yes	No	Yes
[46]	2018	Journal article	SHM; damage visualization.	X	Yes	No	Yes
[47]	2018	Journal article	SHM; modelling of structural performance monitoring systems.	X	No	No	Yes

2.1.1 The BIM approach in structural engineering: the main BIM uses

The qualitative analysis of the structural engineering content described in Table 2.1 identified six main areas in the field where BIM tools and methodologies can be employed, i.e., BIM uses:

(1) Structural analyses.

(2) Production of shop drawings.

(3) Optimised structural design: early identification of constructability issues and comparison of different structural solutions.

(4) Seismic risk assessments.

(5) Existing-condition modelling and retrofitting of structures.

(6) Structural health monitoring.

The term 'BIM use' was first coined in 2013 by Penn State University, which defines it as a unique task or procedure on a project which can benefit from the integration of BIM into that process [48]. Although only some of the publications summarised in, address the employment of the BIM approach throughout a project, all of those listed aimed to both describe the integration of BIM tools and methodologies in very specific aspects (or purposes) of structural engineering and explain the benefits and limitations of the BIM approach [48]. Table 2.2 sets out a detailed account of six BIM uses I identified, clarifying the ways in which the methodology can be applied in structural engineering. The table also includes a comparison with the list of 25 BIM uses contained in the BIM Project Execution Planning Guide [48]. This reveals strong correspondence for BIM use (1); medium correspondences for (2), (3) and (5) and weak correspondence for (4) and (6). The medium correspondences originate from the broad nature of the BIM-use descriptions produced by Penn State University and from the absence of any reference to the structural engineering discipline. Meanwhile, the weak correspondences for BIM uses (4) and (6) originate from the very specific structural engineering functions of these BIM uses.

I have also considered the possibility of similarly referring to the specific 'Model Uses' defined by Succar *et al.* as a way 'to identify and collate the Information Requirements that need to be delivered as – or embedded within – 3D digital models' [49]. Unfortunately, most of the publications in Table 2.2 fail to identify clear information requirements, with their focus instead mainly on workflows and interoperability; this makes it very difficult to distinguish any specific model uses. What I have, however, done is to identify applications described in Succar's general and domain lists of model uses that could relate to structural engineering: from the former - brick structure modelling, concrete structure modelling, timber structure modelling and steel frame modelling; and from the latter - 2D documentation, finite element analyses, structural analyses and wind studies [49].

Table 2.2. Detailed description of BIM uses in relation to structural engineering and a comparison with those of Penn State University.

BIM uses	**Description of BIM use in relation to structural engineering**	**Correspondence with Penn State's BIM uses**
(1) Structural analyses.	A structural analysis is the method used by structural engineers to assess the structural behavior of structures under different load conditions. It is typically performed following the concept structural-design stage, and so materials and geometries are broadly assigned [12]. If a structural information model is available after the design stage, a structural analytical model can be generated from it and exported to computational software in order to define the FEM and conduct the structural analyses (Messner et al., 2019). The quality of this export-import operation depends on the interoperability of the BIM-authoring and computational software used.	Strong correspondence with (13) - Engineering Analysis – b. structural analysis.
(2) Production of shop drawings.	The structural solution designed and verified by the structural engineer is typically translated into 2D representations dubbed shop drawings. The use of BIM-authoring software enables this step to be automated (or at least, semi-automated), because shop drawings can be derived from a structural information model, if one is available. Concurrently, the model is used to perform clash detections with respect to other disciplines, meaning that there is high-level integration among project disciplines and time-consuming rework activities are also avoided.	Medium correspondence with (11) 3D coordination, and (12) Design authoring.

(3) Optimized structural design: early identification of constructability issues and comparison of different structural solutions	The construction of the structural solution designed by the structural engineer is typically an issue of construction engineering. However, some products like bridges and other complex designs (e.g., tall buildings or buildings with unconventional geometries) are greatly affected by the construction process identified in the design stage. In addition, these kinds of structure are commonly composed of highly industrialized (and often unique) structural elements made of pre-cast reinforced concrete, pre-stressed reinforced concrete, and steel. Structural engineers maintain communication with manufacturers and suppliers to address production issues with such structural elements (Chi et al., 2015). In this regard, the BIM approach allows the definition of procedures for sharing information with manufacturers right from the start of the design process [50]. Indeed, a structural information model can be both exchanged and used concurrently to manage scheduling, material quantities and costs. In this way, different structural design solutions exchanged with manufacturers can be compared in terms of their construction time and cost, thus optimizing project choices in the design stage.	Medium correspondence with (8) Construction system design, (19) 4D modelling and (20) Cost estimations.
(4) Seismic risk assessments.	The seismic load is considered in general structural analyses, but more sophisticated methods are needed when it comes to the assessment of the damage state of structural and non-structural components and any resulting losses (Welch et al., 2014). Performance-based earthquake engineering (PBEE) is one of these methods. Structural and non-structural components are all included in a (probably federated) information model. This can therefore be used as a repository of inputs to support the PBEE (and other sophisticated analysis methods like LCAs and LCCs for sustainability assessments). Additionally, the results of these sophisticated computations can be stored in information models, potentially improving visualizations and communication with non-experts.	Weak correspondence with Penn State's BIM uses. This can be explained because seismic risk assessment is a specific purposes of structural engineering discipline.
(5) Existing conditions modelling and retrofitting of	Existing conditions modelling of structures represents a stand-alone scope, since there is no design stage and no integration among disciplines; instead, only fragmented	Medium correspondence with (21) – Existing conditions

structures	information is available (Volk et al., 2014). A structural survey is required in most cases and can be performed using in-situ techniques like photogrammetry and 3D laser-scanning. After an elaboration stage, a point cloud from images and scans is imported into a BIM-authoring environment, thereby establishing the pathway upon which the 3D digital model is built. A structural analytical model is then generated and exported to computational software in order to define the FEM and perform the structural analyses. However, further in -situ and laboratory tests are needed to define the mechanical properties of structural materials [40]. Information models and collaborative platforms enable sharing management of all sources of information that come into play in relation to existing structures. These, thus, provide a shared and reliable source of information to perform structural performance assessments and retrofit design.	modelling. There is no mention of structural performance assessments and retrofit design.
(6) Structural health monitoring.	Information models are used as repositories supporting SHM in relation to the modelling and visualizing of structural-performance monitoring systems and managing and visualizing monitoring data (Welch et al., 2014). In more detail, 3D digital models for SHM are enriched with BIM objects representing the sensor-monitoring system and contain a set of informative attributes. Data interpretation and analyses are enabled by purposely developed tools, making them a valuable and reliable way to obtain information for use in decision-making processes concerning refurbishment and maintenance interventions [45].	Weak correspondence with (1) - Building (preventative) maintenance scheduling. There is no mention of structural health monitoring.

Finally, Table 2.3 contains a tabular organisation of my state-of-the-art reference bibliography based on the six BIM uses identified earlier. Also reported are the number of documents considered and their references in the bibliography, although each document may relate to more than one BIM application.

Table 2.3. Organisation of the reference bibliography according to the six identified BIM uses.

BIM use in structural engineering	**Number of reference documents**	**Bibliography reference**
(1) Structural analyses.	11	[3], [4], [5], [6], [7], [8], [10], [11], [12], [13]
(2) Production of shop drawings.	4	[14], [16], [15], [12]
(3) Optimized structural design: early identification of constructability issues and comparison of different structural solutions.	9	[14], [16], [17], [17], [15], [20], [21], [22]
(4) Seismic risk assessments.	9	[23], [24], [27], [26], [30] [25], [28], [31], [29]
(5) Existing conditions modelling and retrofitting of structures.	9	[32], [33], [34], [35], [38] [37], [39], [36], [40]
(6) Structural health monitoring.	8	[41], [42], [43], [44], [36] [45], [46], [47]
Total number of articles, pa pers and books considered.	45	

2.2 The state-of-the-art: presenting the main BIM USES in structural engineering

In this section, the BIM uses identified in Table 2.2 are described in detail to present contemporary experience in relation to the use of BIM tools and methodologies in structural engineering.

2.2.1 BIM-use 1: Structural analyses

Figure 2.1 portrays the reference workflow for the first BIM use, in relation to which I refer to the process map of BIM use (13) in the *BIM Project Execution Planning Guide* [48] because of the strong correspondence between this BIM use and BIM-use (1).

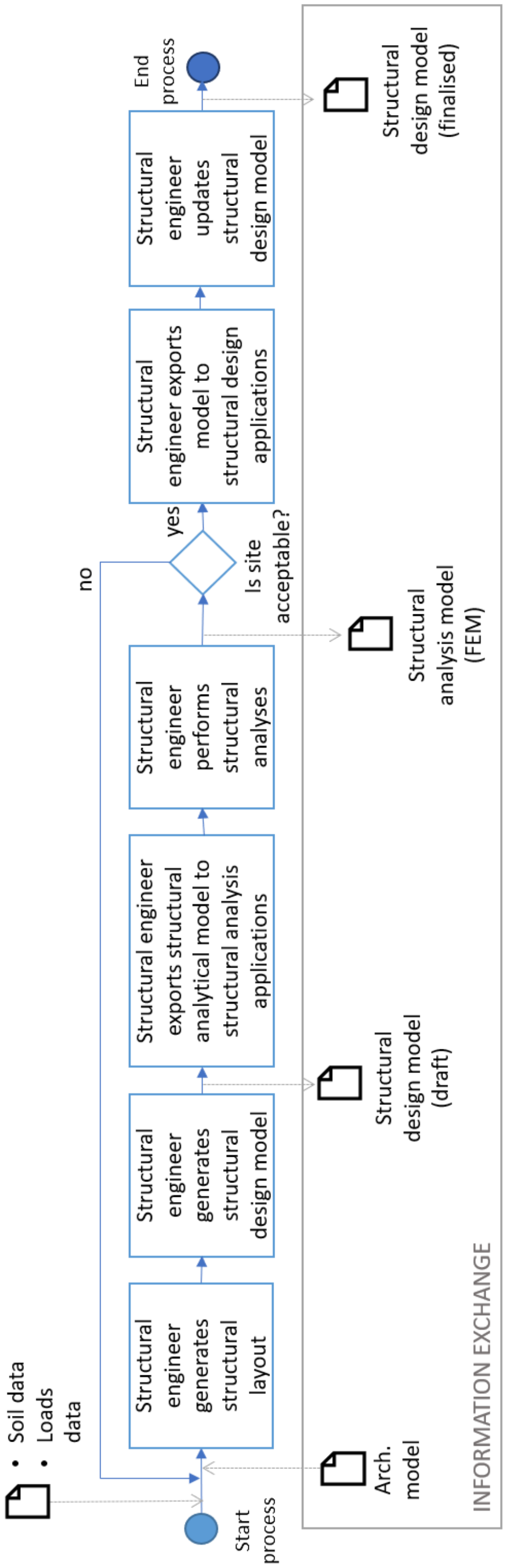


Figure 2.1: Reference workflow of BIM-use (1) – structural analyses.

In detail, the process starts with a concept design of the load-bearing structure, which provides an architectural information model and inputs the foundation soil and loading conditions. In the next step, structural engineers create a draft structural information model; this is then used to define a structural analytical model [12] that can be exported for any following structural analysis applications. These are able to perform finite element analyses calculations on the structural analytical model, which is converted into a finite element model (FEM) (see Figure 2.2). Consequently, the structural engineers have to make a decision: if they detect issues with the site conditions (as well as with the compatibility with the architectural model), they can demand substantial changes that could involve the design concepts of both the structural and architectural models. Accordingly, in these circumstances, the entire process would be repeated, as depicted in Figure 2.1. If no issues are highlighted, the structural design can be completed. This is achieved using post-processing plug-ins or suitable applications with which to complete the ultimate structural design (according to the reference standard) in relation to the structural member assessments, reinforcements and connections [3]. The final step involves updating the structural information model, bringing the process to an end.

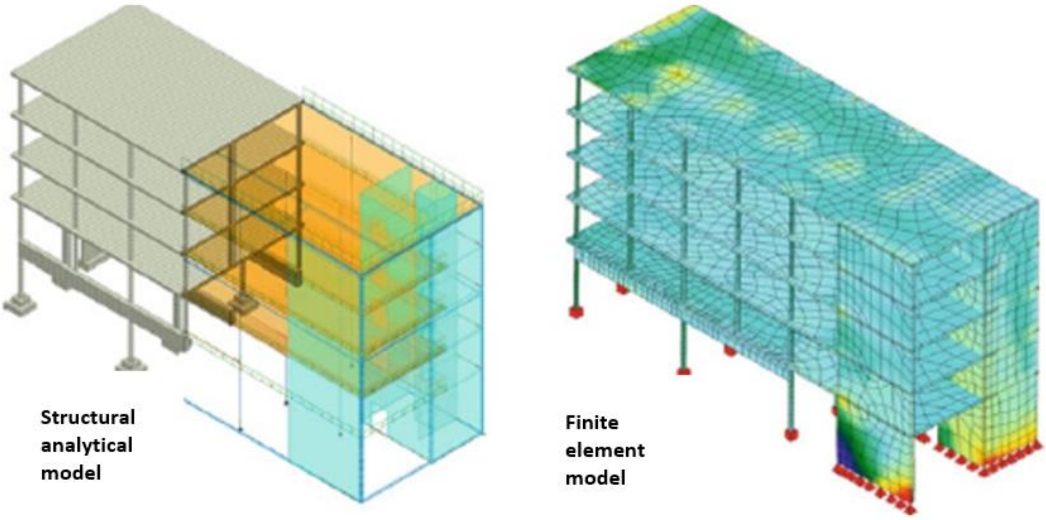


Figure 2.2. Structural analytical model of an office building and the finite element mesh generated from it [12].

However, significant reworking may be required to set the FEM up correctly for the structural analyses; this is because interoperability issues can arise [8], creating a need for further inputs (i.e., the reference standard) [4], [6]. These issues can slow the process down significantly, and so are analysed in more detail in section 2.2.1.1 below.

2.2.1.1 Limitations

Interoperability issues between BIM-authoring and FEA software are common, meaning that much of this discussion is dedicated to analysing this limitation. Developing a structural analytical model from its BIM counterpart, and then importing it into FEA software to produce a FEM, can be achieved by adopting: proprietary format plug-ins, if available, which enable information exchanges between BIM-authoring and FEA software [6], [51], [52]; and openBIM® standards, which involve using the IFC format to support the information exchanges [2], [53]. In such cases, any BIM-authoring and FEA software that allows exports-imports of the IFC format can be used.

A structural analytical model should include:

- Geometry and sections of structural members (i.e., beams, columns, walls and slabs).
- Materials assigned to structural members.
- Loads (it is worth noting that BIM-authoring software is unable to manage reference standards for structural engineering. Therefore, while structural analytical models can include gravity loads like destination use and the weight of non-structural components, they fail to contain load types like wind or seismic action and load combinations in general).
- Constraints (i.e. fixed joint constraint, hinge joint constraint, etc.).

Minor interoperability issues have been detected adopting proprietary format plug-ins. These have been widely investigated in [7], [13], [54], and arise because plug-ins are specifically developed (mainly by software vendors and developers) to ensure that the FEA software interprets the structural analytical models correctly on a semantic level (semantic interoperability is '*the ability of two tools to come to a common understanding of the meaning of a model being exchanged'* [55]). Commonly, plug-ins are available when the BIM-authoring and the FEA software are from the same software house, or if two different houses work together to develop a solution to achieve semantic interoperability. In addition, these allow round-tripping exchanges in relation to the geometry and sections of the structural elements.

Using openBIM® standards is affected by major interoperability issues. This is because exchanges of data between the BIM-authoring and the structural analysis software using the IFC format can be affected by inaccuracies (data losses or misinterpretations), which is due to the limited coverage of a BIM-based language by implementers [53]. BuildingSMART has previously addressed the issue of the delivery of models between the BIM-authoring and the structural analysis software. In particular, with the release of IFC2x3, the company proposed that the MVD dubbed the 'Structural Analysis View', which covers the exchange requirements (i.e., the information listed above), can be used to transfer the structural analytical model to one or many structural analysis applications. Unfortunately, this MVD often leads to poor quality data exchanges that arise from differences in semantics, syntax and information representations between the various structural analysis applications [55]. In addition, this MVD was not conceived to address round-tripping exchanges, which are therefore currently impossible to automate as part of the OpenBIM approach.

Commonly, in both cases, a structural information model cannot be used as a comprehensive contribution to a structural analysis. This is because the FEMs produced may be incomplete and require further inputs that are closely linked to the logic of the FEA software and the reference standard utilised. For example, further efforts to finalise the FEMs could involve: the load model (i.e., wind, soil and seismic action); the load combinations; the masses; the boundary conditions (springs, rigid links, etc.); and the type of structural analysis employed (modal, linear static, linear dynamic, etc.). However, the issues described here, which strictly depend on the features of the tools being implemented, are just some of the problems that can arise relating to the interoperability between BIM-authoring and FEA software (see [53], for further information).

2.2.2 BIM-use 2: Production of shop drawings

The second BIM use concerns the production of shop drawings of structural elements and systems, and Figure 2.3 depicts the reference high-level workflow for producing them. This workflow has been adopted in numerous simulations conducted by students (mainly practitioners) undertaking the advanced professional training course - '*BIM: Sustainable Integrated Design*', which has been offered for the past four years by the University of Naples, Federico II. I preferred to present contemporary experience with a high-level workflow rather than no workflow at all since no publication in Table 2.1 provides a reference process map.

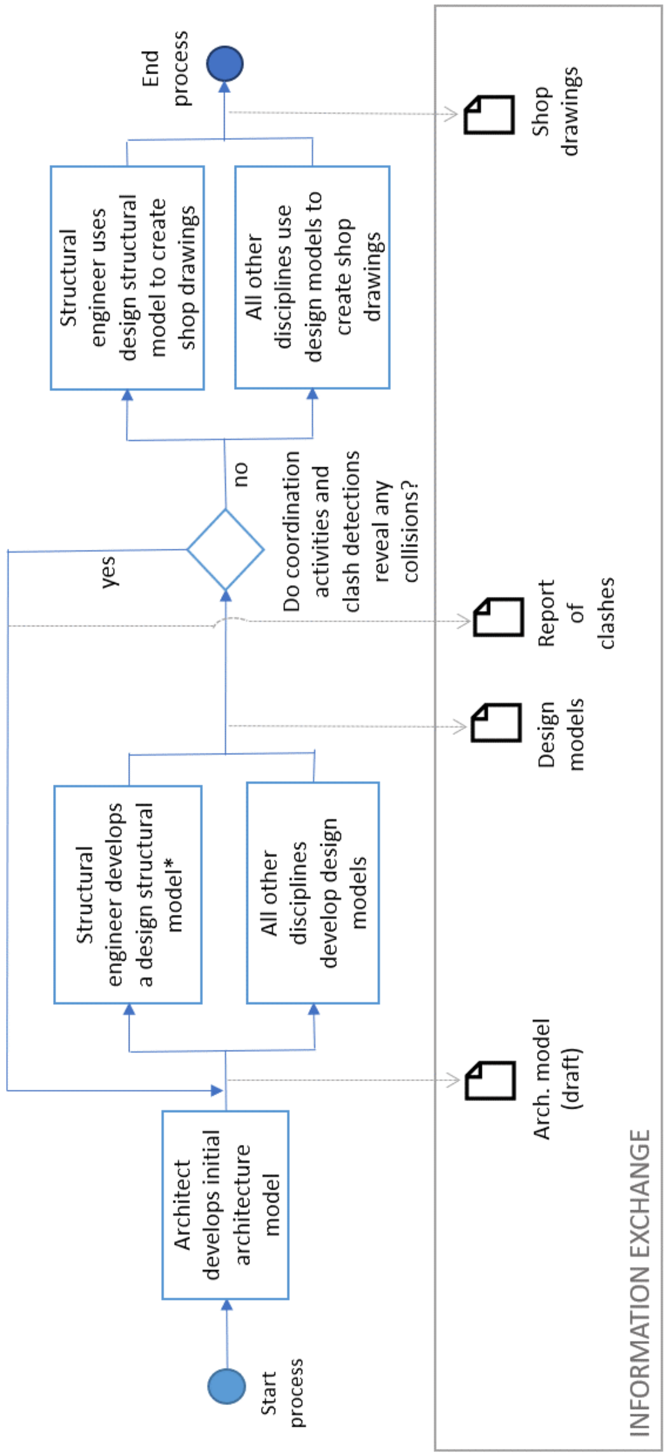


Figure 2.3. Reference workflow of BIM-use 2 – production of shop drawings.

In detail, the BIM workflow for creating shop drawings includes collaborative features that traditional processes often lack [50], [56]. First, an architect develops an initial architecture model, which is used in what follows as a pathway to develop design models of all the other relevant disciplines. The main part of the work involves creating parametric libraries of details, connections and objects, which ensures that the modelling is efficient and there is geometric compatibility between adjacent pieces [14]. Focusing on the structural discipline, a structural engineer develops the design structural model, which should be produced using the process depicted in Figure 2.1(*). The resulting model is composed of 3D objects like beams, columns, and walls, and contains information about their composition. Successively, there is a decision point where this model is integrated with design models of other disciplines to create federated versions (i.e., where the structural and architectural information models, as well as the MEP and HVAC information models, can be merged). Coordination activities and clash-detections are then performed [16], [57] using appropriate applications (interoperability should thus be considered) and collaborative platforms that provide a structured, co-operative environment where information (from different disciplines) can be exchanged and shared. An example of a clash between the structural and the MEP disciplines is depicted in Figure 2.4. If issues arise, clash-detection activity reports are (automatically) produced at the end of the coordination process; these enable conflicts to be discussed to determine the optimal strategy for resolving them. This generally requires adjustments to be made to design models, which are then further developed by returning to the design stage to ensure integration among disciplines and the production of high-quality deliverables. Coordination activities, clash detections and use of collaboration platforms are collaborative features of the BIM approach; these are missing in the traditional process for creating shop drawings [50], [56].

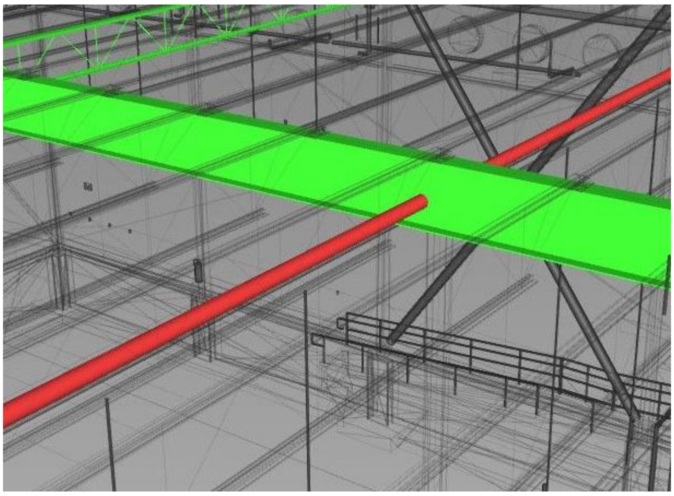


Figure 2.4. Example of a clash between a structure and the MEP discipline.

If no issues arise, the process progresses, and the structural engineer can use an (integrated) design structural model to easily create views, 3D-views and shop drawings. This is also the case for other disciplines. The process then ends. If changes are made later, time-consuming reworks are avoided because amendments to the model are also transferred to the shop drawings. This means that these drawings will always reflect the current status of the model [12].

It is worth noting that a traditional workflow,which is based on computer aided design (CAD), allows the geometry of structural elements and systems to be modelled in a 2D environment; in a BIM-based version, it is possible to create a real-time virtualisation of the structural system, with its geometry and details modelled in a 3D environment. In the former, shop drawings are addressed one by one, while the latter defines a unique BIM structural model from which shop drawings and other construction deliverables, like quantity take-offs and cost estimations, can be derived. The BIM tools and methodologies described thus far are currently, and successfully, used in practice [58].

2.2.2.1 Limitations

Although the BIM approach addresses the issue of time wasted on reworks, produces high-quality deliverables and encourages more collaborative perspectives, it also requires considerable software training [14] and a shift to BIM-based workflows [59]. Both of these changes are time-consuming and expensive, but they are both also essential to having a positive effect on productivity challenges. Of course, the activity of modelling a structural information model is only an addition to other established approaches in the structural engineering field. Moreover, reinforcement drawings generated by the model can themselves require significant reworking (see Figure 2.5) to ensure that they resemble what the participants in the process are used to seeing [12].

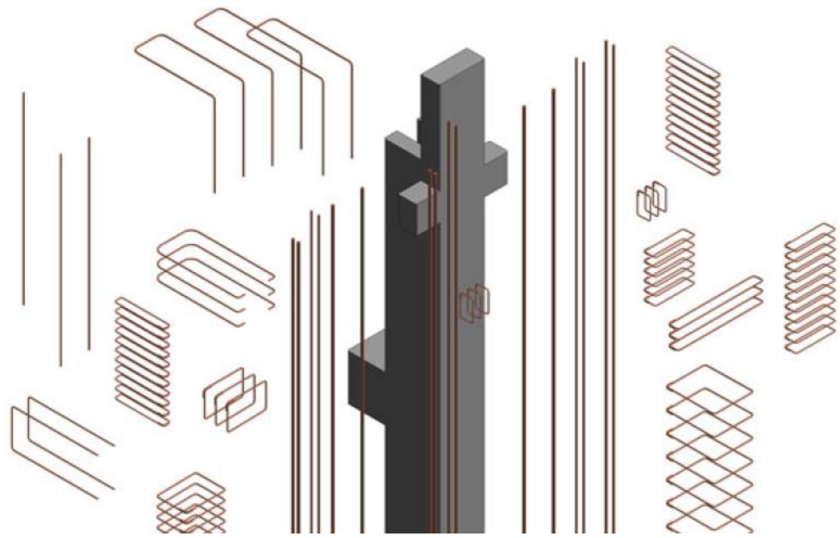


Figure 2.5. Exploded drawing of a reinforcement model for a column [12].

2.2.3 BIM-use 3: Optimized structural design: early identification of constructability issues and comparison of different structural solutions.

BIM use-3 focuses on the optimisation of project choices in the structural design phase. In fact, BIM tools and methodologies enable both the early identification of some constructability issues and comparisons of different structural design solutions in relation to schedule management, material quantities and costs.

Usually, constructability issues are addressed in the construction phase [5][5]. However, structures like bridges, industrial facilities (e.g., shelters), and tall or unconventional buildings commonly need very industrialised and unique structural elements, meaning that early communication with manufacturers can be crucial from the structural design phase onwards [14], [16]. The BIM approach allows the definition of standardised procedures with which to share information (e.g., geometry, sections and reinforcement of structural members) with manufacturers and receive their feedback during the design process [15]; for example, engineers can deliver a structural information model to manufacturers. They can also visualise and better illustrate the solution proposed, highlight geometrical constraints (curvature, length, etc.) and suggest better design strategies, such as separating structural members into modules to ease and speed up the construction process. This approach is preferable for the types of structure listed above for two main reasons: 1) it avoids the late identification of the constructability issues that can cause major economic losses due to necessary reworks and delays [14]; and 2) as load-bearing structures undergo ongoing development during the construction process, with a consequential effect on structural designs, the intermediate structural assessments required as a result can be produced more easily.

In addition, the BIM approach enables bolder solutions to be considered in the design phase. It also means that a structural information model is available for each solution and can be used to address more purposes at the same time, for example: structural analyses, schedule management, and estimating material quantities and costs. Consequently, it is possible to choose the best solution by comparing construction times, the quantity of the materials that would be used and the costs. In detail, throughout any scheduled simulations, specific BIM tools combine work breakdown structures (WBS) with the objects constituting the structural information model [18]. In this regard, some research has focused on leveraging information models, using automatic open-format BIM technology to extract data [15], [19] and identify optimised scheduling solutions. Quantity take-offs relating to structural elements and materials and reinforcements are automatically produced, because the structural information model is composed of parametric objects [21], [22]. At the same time, cost estimations are produced by specific BIM tools that link pricing to BIM objects [19], [20]. Finally, different structural design solutions can be exchanged with manufacturers to identify constructability issues in advance; thereafter, comparisons are made in terms of construction times, the quantity of the materials used and the costs, thus enabling project choices to be optimised in the design stage.

2.2.3.1 Limitations

The optimisation process closely depends on the optimisation criteria and methodologies adopted. Indeed, engineers define optimal solutions with respect to established parameters, and so it is both meaningless to speak of absolutely optimal proposals and possibly misleading to define a reference (BIM-based) optimisation process. The main limitation arises from defining the optimisation procedure to be used, which may require a collaborative approach among stakeholders right from the start.

2.2.4 BIM-use 4: Seismic risk assessments

The fourth BIM use concerns the employment of BIM tools and methodologies to support seismic risk assessments. It should be noted that if the BIM approach is used throughout the lifecycle of a facility, an asset information model (AIM) will be produced after the construction phase. An AIM is composed of several information containers, at the heart of which is a federated BIM model (structural, architectural, MEP and HVAC). As a result, the BIM model is a unique and centralised source of information on structural and non-structural components (e.g., partitions, wall finishes and facades), equipment, and systems (e.g., HVAC, electrical, plumbing). Specialist tools used in seismic risk assessments can employ an asset's BIM model to collect more reliable data for use as inputs [24]. This is demonstrated in Figure 2.6.

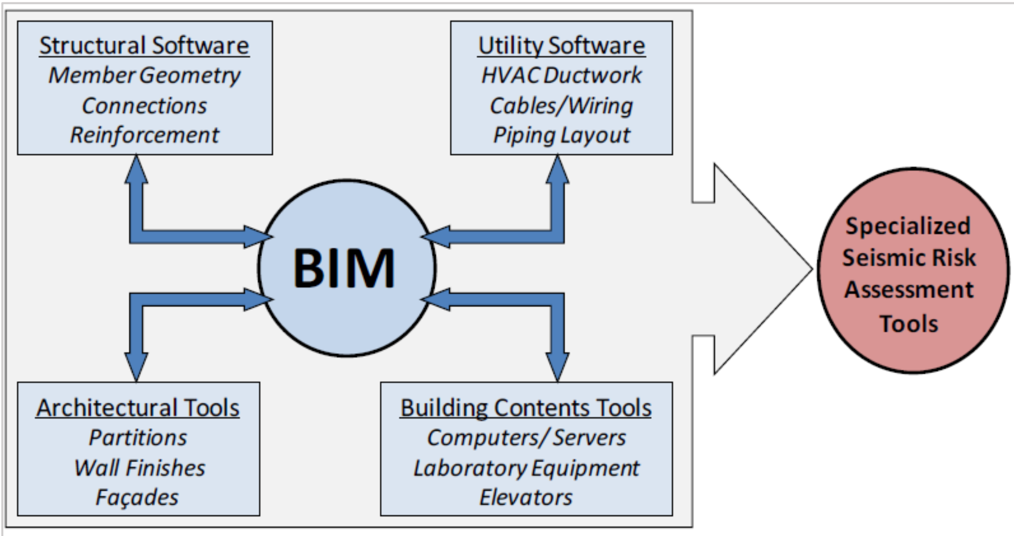


Figure 2.6. BIM models acting as a store for specialist seismic risk assessment tools [24].

The research on assessing the damage state of buildings, i.e., structural, non-structural and contents, contains several examples where 3D digital information models are used to provide inputs for the PEER Centre's PBEE methodology [60]. It should be noted that this seismic design approach involves an iterative procedure that starts with the selection of performance objectives (i.e., damage state) and then checks whether they have been met. In this way, information models can be used to produce inputs for structural analysis models [27], [31] and fragility parameters (according to FEMA; Hamburger *et al*. [61] which can then be added to BIM objects as informative attributes [28], [30]. Researchers often develop their own application programming interfaces (APIs) to automatically collect and then import contributions from BIM models into software that performs structural analyses, damage-state investigations and loss assessments (casualties, repair costs or repair times). Some researchers have also investigated the possibility of using BIM models to visualise the results of damage assessments, thereby improving the communication between non-technical stakeholders [23] and providing support for cost-effective seismic-mitigation strategies [29], as shown in Figure 2.7.

Figure 2.7. Colour-coding of different ranges of seismic-risk scores in a 3D digital model [29].

It is worth noting that scholars have also explored the potential of BIM models as input providers, as well as repositories of information for LCAs and LCC [62].

2.2.4.1 Limitations

The fourth BIM use concerns the employment of multidisciplinary information models to develop reliable data with which to perform seismic-risk assessments and visualise the results. Information exchanges (export/import processes) typically involve elaborate automated (or semi-automated) procedures that use APIs developed for this purpose. However, the value of APIs declines in different ways depending on the BIM-authoring software employed to create the 3D digital model and the structural analysis software used for the calculations. The complexity of this calculation currently hinders the definition of a reference workflow, although further research is ongoing, especially in relation to defining simplified calculation procedures [28], [30].

2.2.5 BIM-use 5: Existing conditions modelling and retrofitting of structures.

The A number of different structural engineering activities can be required for existing structures: defining their geometrical and mechanical features (e.g., via in-situ inspections, non-destructive and destructive tests, analyses of available 2D documentation); assessing the 'as is' structural performance; and designing structural refurbishment interventions. Consequently, the BIM approach can be used to support (see Table 2.3):

- Knowledge management.
- The assessment of structural performance.
- The optimisation, comparison, and design of structural retrofit strategies.

There are major differences between new and existing structures in relation to the conception of information models. While the process of creating a new building is unique and includes inception and production phases, there is more than one option for existing structures (whether or not a pre-existing information model is available), where the focus shifts to maintenance and deconstruction stages. Figure 2.8 depicts the two pathways in detail.

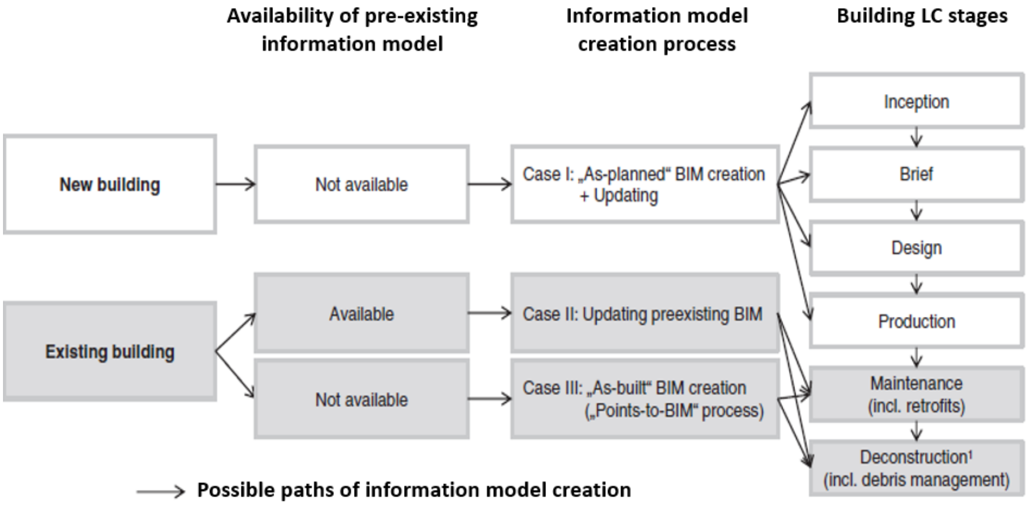


Figure 2.8. Information model creation processes in new or existing buildings depending on available, pre-existing models and their relationship with lifecycle (LC) stages[38].

Structural engineers analyse the performance of existing buildings and infrastructures when structural retrofit interventions are required. This could be due to a change of destination use, evidence of a poor conservation or damage state, or a lack of compliance with up-to-date building codes. In these circumstances, engineers often have to manage uncertainty about the condition of conservation materials and struggle with a lack of project documentation (e.g., shop drawings, reinforcement details, structural calculation reports). Typically, a pre-existing structural information model is unavailable, and project documentation is therefore essential for defining the geometry of a structural model of an existing building. The documents also provide information on materials, reinforcements and connections, which is essential data for any capacity assessments. A lack of documentation and the absence of pre-existing information models mean that a structural survey is required. Clearly, the capacity assessment is key to this process, which is often conditioned by a lack of information. Indeed, limited knowledge of a structure causes very conservative assumptions to be made about geometries, the mechanical properties of materials and structural details, leading to underestimates of actual capabilities and overestimates of any retrofit interventions required.

The BIM approach modifies the traditional process used to gather and expand the information needed to define an accurate FEM and perform capacity assessments. Figure 2.9 shows the reference BIM-based workflow for BIM-use 2 relating to assessments of structural performance. The process was developed and validated as part of the 'BIM to CIM' research project conducted by the University of Naples Federico II in collaboration with the Polytechnic of Milan, the Polytechnic of Turin, the IUAV University of Venice, the National Research Centre and Acca Software.

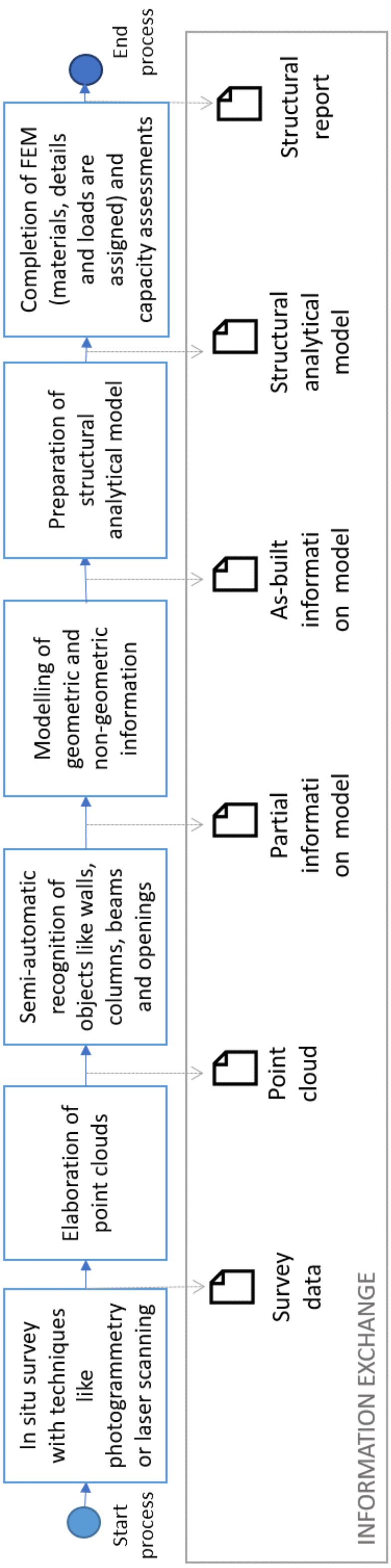


Figure 2.9. BIM-based workflow for BIM-use 5.

The process has six steps: data capture, data processing, object recognition, creation of an as-built information model, preparation of a structural analytical model, completion of a FEM and a capacity assessment of the structure in the FEA software environment. First, a survey is performed using in-situ techniques like photogrammetry and 3D laser-scanning [63]. In step two, the data acquired (i.e., images and scans) are expanded in a BIM-tool environment to obtain point clouds. In step three, the point cloud is imported into a BIM-authoring environment, thereby enabling the preliminary semi-automatic recognition of BIM objects. Further work is then conducted to produce the as-built information model using the point cloud as a pathway. A structural analytical model is then generated in step five and exported to computational software in order to finalise the FEM. Materials and information on structural details, loads and constraints are then assigned. Finally, the model is validated through preliminary checks on the distribution of stresses due to gravity loads and the outputs of a modal analysis (periods of vibration and participating masses). In step six, the capacity assessment of the structure is performed, and safety factors are calculated for each structural member. Commonly, these are collected in a structural report. The process then comes to an end.

The great advantages of this workflow are that the geometry in the structural analytical models is more reliable and the FEMs generated are more accurate. Similar workflows are used in the research I have identified [57], [58], [84]. It is worth noting that these workflows are of particular use in historical (mostly masonry) buildings to enable the easy recreation of their details in the form of a digital representation. This use of BIM techniques is generally known as historical BIM (HBIM) [36], [65], and examples are available of how it has been applied on a wider scale in historical towns (HT-BIM) [35]. However, there are also examples of applications of BIM techniques to existing bridges [37], [39].

Other uncertainties in existing structures, in addition to geometry, relate to the conservation state of the structural materials, which has an obvious impact on the mechanical properties defined in related FEM models. The properties of structural materials are commonly investigated using the in-situ testing of structural elements and the laboratory testing of structural-material samples taken on site. The amount of testing depends on the so-called ‘level of knowledge’ of a building. In this regard, researchers are exploring the possibility of using information models as repositories for data obtained by testing. This would enable both the level of knowledge to be visualised and the information retrieved to be streamlined for further assessments [40]. Figure 2.10 contains an example of the visual representation of levels of knowledge.

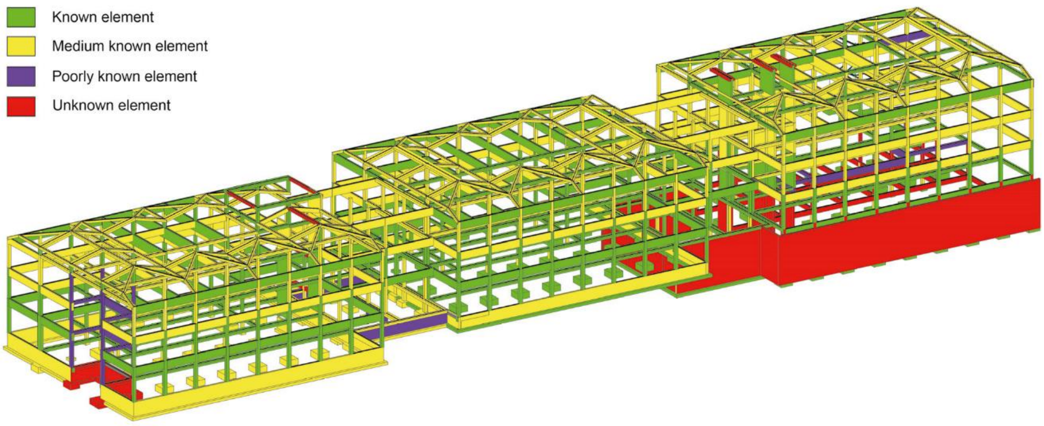


Figure 2.10. Mapping of the overall level of knowledge of a building [40].

Finally, a combination of structural information models and collaboration platforms allows project documentation (in-situ and laboratory tests, pre-existing shop drawings, reinforcement details and structural calculation reports) to be linked to models' objects. In these circumstances, the structural information model becomes a source of reliable, accurate and easily retrievable data for structural engineers to use during structural refurbishments, retrofits and maintenance [36].

2.2.5.1 Limitations

The use of BIM tools and methodologies for existing buildings is somewhat recent from a structural engineering perspective. The content analysis of the reference bibliography has highlighted two main trends in how they are applied in these structures. In particular, information models are used to: 1) define more accurate FEMs with models obtained from point clouds produced for information exchanges; and 2) manage structural engineering data from different sources. The first trend is characterised by a different model creation path to that introduced for BIM-use 1, which researchers are still validating to prove its benefits. The second trend requires further work on defining clear methodologies for visualising the data in information models, combining information models and collaboration platforms to manage data from project documentation, and automating the processes used for knowledge acquisition.

2.2.6 BIM-use 6: Structural health monitoring

The sixth BIM use deals with the employment of BIM tools and methodologies to support structural health monitoring. SHM is the process of implementing a damage detection strategy to assess the structural performances of existing buildings and infrastructures. The goal is to detect early stage damage and optimise maintenance strategies using a condition-based approach, thus extending the functional life of a structure [66]. The content analysis of the reference bibliography has identified that SHM uses structural information models as repositories for three main purposes [42]:

- Modelling and visualising structural performance monitoring systems.
- Managing and visualising monitoring data.
- Data interpretation and decision-making processes.

Although extremely difficult, Figure 2.11 contains an example of a reference BIM-based workflow for BIM-use 6. This was developed in the Department of Structures for Engineering and Architecture at the University of Naples Federico II, thanks to its employment in several Master's degree projects.

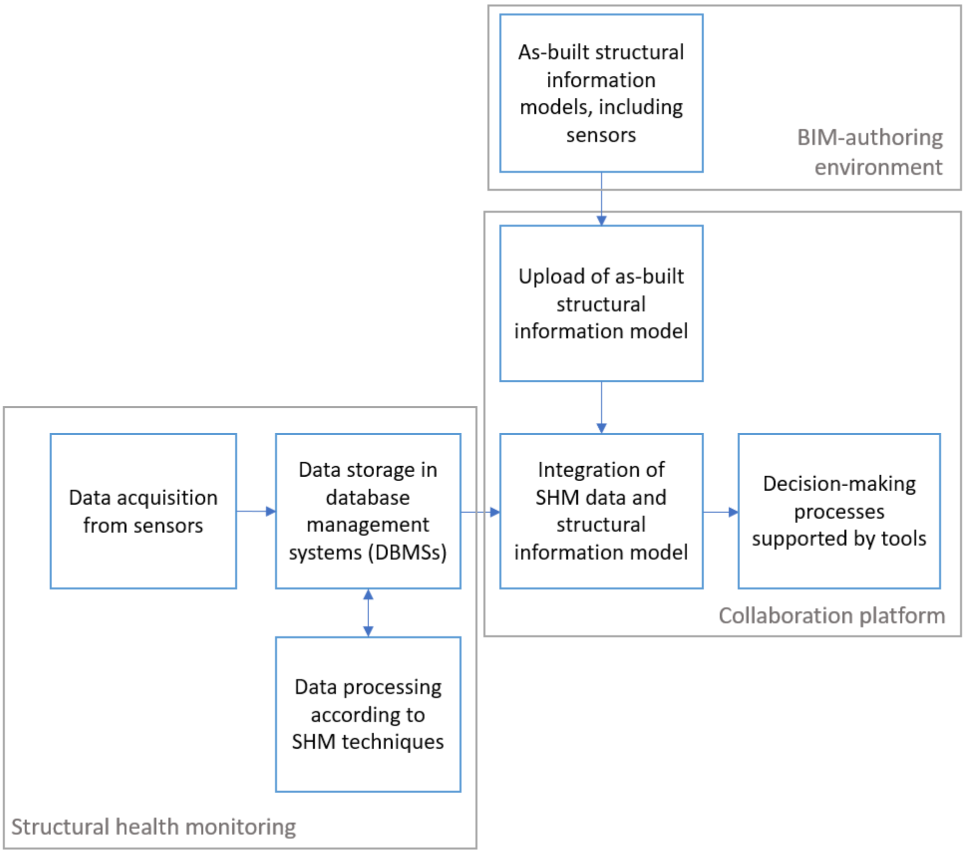


Figure 2.11. Example of reference framework for BIM-use 6.

In more detail, structural information models are enriched in the BIM-authoring environment with BIM objects representing the sensor-monitoring system.

These models contain a set of informative attributes, for example: name, function, properties, materials, openings, composition, representation and relationship parameters, frequency and temperature set-points, date and time of acquisition, and type of relationship between the sensor and relative building component [36], [44]. This as-built structural information model can be exported in the IFC format and uploaded in a cloud-based environment which, in the BIM approach, is essentially a collaboration platform. This environment enables SHM-related data to be integrated into structural information models, although issues arise concerning exchanges of this information and the visualisation of the monitoring process. In this regard, researchers have proposed extending the IFC schema using either a custom property set to retain informative attributes [41], [67], or a real-life IFC-schema extension known as an IFC monitor [47]. Furthermore, in 2018, Davila Delgado *et al.* [41] highlighted that there are no formal directives for managing and visualising sensor data in a BIM environment. As a result, his team developed a dynamic BIM viewer, which is a user-friendly tool that allows the key parameters of a built asset's structural performance to be communicated in a dynamic and interactive manner. Figure 2.12 contains an example of the type of data visualisation proposed. Tools of this kind enable the interpretation and analysis of data, making them a valuable and reliable way to obtain information for use in decision-making processes concerning refurbishment and maintenance interventions.

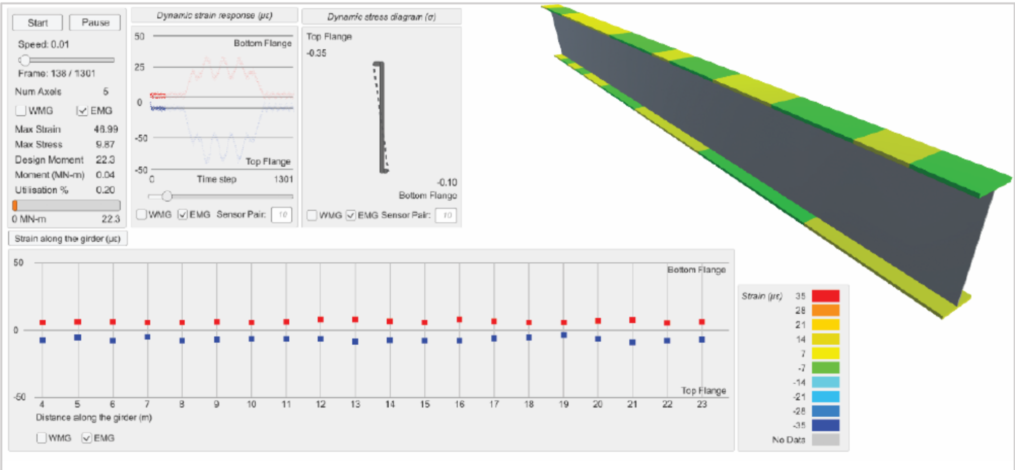


Figure 2.12. Distributed strain visualisations obtained from a dynamic BIM viewer [45].

2.2.6.1 Limitations

Unfortunately, BIM tools and methodologies have only recently been used in relation to the sixth BIM use, meaning that researchers are still focusing on ideal case studies. Further work is therefore required to resolve many interoperability issues, as well as problems with the post-processing and visualisation of data. Accordingly, validated reference workflows still need to be defined.

2.3 Discussion and conclusions

Research on the use of BIM in structural engineering is extremely rare, and no real state-of-the-art is available on the subject. The 2019 bibliometric literature review by Vilutiene *et al.* [68] does examine (automatically) a very large number of publications (over 300), identifying variations in the main topics and keywords over the last decade and adopting clusters to present in-depth analyses of the data obtained. In my view, however, these interesting results do not provide a state-of-the-art on BIM applications in structural engineering, because there is no presentation of detected methodologies and applications, which I regard as essential. Moreover, a preliminary analysis of the papers they examined reveals substantial contamination from fields such as construction engineering and architecture, explaining the significant difference between their methodology and my traditional literature review, which considered just 45 papers in great detail.

My manual approach enabled me to analyse possibly relevant publications in order to highlight content that refers to structural engineering specifically. This has allowed me to identify six main areas of application that correspond to BIM uses in this field. These are exemplified with already validated (in the literature or projects developed by the authors) reference workflows which, although not intended to be exhaustive, are nevertheless illustrative, especially for structural engineers unfamiliar with the BIM approach. My focus is not on the technical features of software tools for use in information modelling and structural analyses for specific reasons: 1) how quickly these tools now change and the high number of applications available, which makes it difficult to produce an exhaustive list; and 2) in an attempt to prevent readers being conditioned with specified opportunities and limitations; instead, my preference is to illustrate workflows and discuss information exchanges to highlight innovations for structural engineering arising from the BIM approach. My conclusions are set out in section 6 below.

In conclusion, there are fundamental differences between the BIM and traditional approaches, with the former enabling the development of standardised information processes and the management of information flows. However, the typical cultural background of structural engineers means that they often lack an aptitude for process identification, multidisciplinary collaboration, and information management. It is my view that research in this field has a prominent role to play in mitigating these shortcomings, fostering the adoption of BIM and other digital technologies via the reference workflows proposed in this chapter, which are a valuable starting point for both practitioners and researchers in structural engineering.

References

1] T. O. Olawumi, D. W. M. Chan, And J. K. W. Wong, "Evolution in the intellectual structure of bim research: a bibliometric analysiS," *J. Civ. Eng. Manag.*, vol. 23, no. 8, pp. 1060–1081, Nov. 2017.

[2] R. Santos, A. A. Costa, and A. Grilo, "Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015," *Automation in Construction*, vol. 80. Elsevier B.V., pp. 118–136, 01-Aug-2017.

[3] S.-I. Lee, J.-S. Bae, and Y. S. Cho, "Efficiency analysis of Set-based Design with structural building information modeling (S-BIM) on high-rise building structures," *Autom. Constr.*, vol. 23, pp. 20–32, May 2012.

[4] A. A. Bhusar and A. R. Akhare, "Application of BIM in structural engineering," *Int. J. Civ. Eng.*, vol. 1, no. 5, pp. 12–20, 2014.

[5] H.-L. Chi, X. Wang, and Y. Jiao, "BIM-Enabled Structural Design: Impacts and Future Developments in Structural Modelling, Analysis and Optimisation Processes," *Arch. Comput. Methods Eng.*, vol. 22, no. 1, pp. 135–151, Jan. 2015.

[6] Z.-Q. Liu, F. Zhang, and J. Zhang, "The building information modeling and its use for data transformation in the structural design stage," *J. Appl. Sci. Eng.*, vol. 19, no. 3, pp. 273–284, 2016.

[7] F. Fedorik, T. Makkonen, and R. Heikkilä, "Integration of BIM and FEA in automation of building and bridge engineering design," in *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, 2016, vol. 33, p. 1.

[8] T. S. Shin, "Building information modeling (BIM) collaboration from the structural engineering perspective," 2017.

[9] R. Pukl, P. Pálek, and J. Červenka, "The possibility of using BIM for nonlinear life-cycle analysis of concrete structures," in *The Fifth International Symposium on Life-Cycle Civil Engineering (IALCCE 2016), Oct. 16–20, Delft, Netherlands*, 2016, pp. 655–661.

[10] R. Ran and Zhang Jiansong, "BIM Interoperability for Structure Analysis," *ASCE*, vol. 1996, pp. 470–479, 2018.

[11] W. Baran and B. Żymańczyk, "Structural Engineering by way of BIM," *MATEC Web Conf.*, vol. 174, p. 04011, Jun. 2018.

[12] T. Fink, "BIM for Structural Engineering," in *Building Information Modeling*, Cham: Springer International Publishing, 2018, pp. 329–336.

[13] A. M. M. Hasan, A. A. Torky, and Y. F. Rashed, "Geometrically accurate structural analysis models in BIM-centered software," *Autom. Constr.*, vol. 104, no. December 2018, pp. 299–321, 2019.

[14] I. Kaner, R. Sacks, W. Kassian, and T. Quitt, "Case studies of BIM adoption for precast concrete design by mid-sized structural engineering firms," *Electron. J. Inf. Technol. Constr.*, vol. 13, no. June, pp. 303–323, 2008.

[15] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons, 2011.

[16] Y.-S. Jeong, C. M. Eastman, R. Sacks, and I. Kaner, "Benchmark tests for BIM data exchanges of precast concrete," *Autom. Constr.*, vol. 18, no. 4, pp. 469–484, Jul. 2009.

[17] Z. Hu and J. Zhang, "BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials," *Autom. Constr.*, vol. 20, no. 2, pp. 167–180, Mar. 2011.

[18] J. P. Zhang and Z. Z. Hu, "BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies," *Autom. Constr.*, vol. 20, no. 2, pp. 155–166, Mar. 2011.

[19] V. Faghihi, K. F. Reinschmidt, and J. H. Kang, "Objective-driven and Pareto Front analysis: Optimizing time, cost, and job-site movements," *Autom. Constr.*, vol. 69, pp. 79–88, Sep. 2016.

[20] F. K. T. Cheung, J. Rihan, J. Tah, D. Duce, and E. Kurul, "Early stage multi-level cost estimation for schematic BIM models," *Autom. Constr.*, vol. 27, pp. 67–77, Nov. 2012.

[21] A. Monteiro and J. Poças Martins, "A survey on modeling guidelines for quantity takeoff-oriented BIM-based design," *Autom. Constr.*, vol. 35, pp. 238–253, Nov. 2013.

[22] J. Choi, H. Kim, and I. Kim, "Open BIM-based quantity take-off system for schematic estimation of building frame in early design stage," *J. Comput. Des. Eng.*, vol. 2, no. 1, pp. 16–25, Jan. 2015.

[23] S. E. Christodoulou, D. Vamvatsikos, and C. Georgiou, "A BIM-based framework for forecasting and visualizing seismic damage, cost and time

to repair," in *8th European Conference on Product and Process Modelling (ECCPM), Cork, Ireland*, 2010.

[24] D. P. Welch, T. J. Sullivan, and A. Filiatrault, "Potential of Building Information Modelling for seismic risk mitigation in buildings," *Bull. New Zeal. Soc. Earthq. Eng.*, vol. 47, no. 4, pp. 253–263, Dec. 2014.

[25] D. Perrone and A. Filiatrault, "Automated seismic design of non-structural elements with building information modelling," *Autom. Constr.*, vol. 84, pp. 166–175, Dec. 2017.

[26] E. B. Anil, B. Akinci, O. Kurc, and J. H. Garrett, "Building-Information-Modeling–Based Earthquake Damage Assessment for Reinforced Concrete Walls," *J. Comput. Civ. Eng.*, vol. 30, no. 4, p. 04015076, Jul. 2016.

[27] M. Alirezaei, M. Noori, O. Tatari, K. R. Mackie, and A. Elgamal, "BIM-based Damage Estimation of Buildings under Earthquake Loading Condition," *Procedia Eng.*, vol. 145, pp. 1051–1058, Jan. 2016.

[28] Z. Xu, X. Lu, X. Zeng, Y. Xu, and Y. Li, "Seismic loss assessment for buildings with various-LOD BIM data," *Adv. Eng. Informatics*, vol. 39, pp. 112–126, Jan. 2019.

[29] M. Valinejadshoubi, A. Bagchi, and O. Moselhi, "Identifying At-Risk Non-Structural Elements in Buildings Using BIM: A Case Study Application," *J. Earthq. Eng.*, vol. 24, no. 5, pp. 869–880, May 2020.

[30] U. Vitiello, V. Ciotta, A. Salzano, D. Asprone, G. Manfredi, and E. Cosenza, "BIM-based approach for the cost-optimization of seismic retrofit strategies on existing buildings," *Autom. Constr.*, vol. 98, pp. 90–101, Feb. 2019.

[31] D. Zou, K. Chen, X. Kong, and X. Yu, "An approach integrating BIM, octree and FEM-SBFEM for highly efficient modeling and seismic damage analysis of building structures," *Eng. Anal. Bound. Elem.*, vol. 104, pp. 332–346, Jul. 2019.

[32] D. Ilter and E. Ergen, "BIM for building refurbishment and maintenance: current status and research directions," *Struct. Surv.*, vol. 33, no. 3, pp. 228–256, Jul. 2015.

[33] L. Barazzetti *et al.*, "BIM FROM LASER CLOUDS AND FINITE ELEMENT ANALYSIS: COMBINING STRUCTURAL ANALYSIS AND GEOMETRIC COMPLEXITY," *ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. XL-5/W4, no. 5W4, pp. 345–350, Feb. 2015.

[34] M. Bassier, G. Hadjidemetriou, M. Vergauwen, N. Van Roy, and E. Verstrynge, "Implementation of Scan-to-BIM and FEM for the

Documentation and Analysis of Heritage Timber Roof Structures," in *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection*, M. Ioannides, E. Fink, A. Moropoulou, M. Hagedorn-Saupe, A. Fresa, G. Liestøl, V. Rajcic, and P. Grussenmeyer, Eds. Cham: Springer International Publishing, 2016, pp. 79–90.

[35] A. Pelliccio, M. Saccucci, and E. Grande, "HT_BIM: Parametric modelling for the assessment of risk in historic centers," *DISEGNARECON*, vol. 10, no. 18, pp. 1–5, 2017.

[36] S. Bruno, M. De Fino, and F. Fatiguso, "Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management," *Autom. Constr.*, vol. 86, no. December 2017, pp. 256–276, 2018.

[37] P. Hüthwohl, I. Brilakis, A. Borrmann, and R. Sacks, "Integrating RC Bridge Defect Information into BIM Models," *J. Comput. Civ. Eng.*, vol. 32, no. 3, p. 04018013, May 2018.

[38] R. Volk, J. Stengel, and F. Schultmann, "Building Information Modeling (BIM) for existing buildings - Literature review and future needs," *Automation in Construction*, vol. 38. Elsevier, pp. 109–127, 01-Mar-2014.

[39] C. S. Shim, H. R. Kang, N. S. Dang, and D. K. Lee, "Development of BIM-based bridge maintenance system for cable-stayed bridges," *Smart Struct. Syst.*, vol. 20, no. 6, pp. 697–708, 2017.

[40] F. M. Ugliotti, A. Osello, C. Rizzo, and L. Muratore, "BIM-based structural survey design," *Procedia Struct. Integr.*, vol. 18, pp. 809–815, Jan. 2019.

[41] D. J. M. Dávila, I. Brilakis, and C. Middleton, "Open data model standards for structural performance monitoring of infrastructure assets," in *Proceedings of the 32nd CIB W78 Conference*, 2015.

[42] J. M. Davila Delgado, L. J. Butler, N. Gibbons, I. Brilakis, M. Z. E. B. Elshafie, and C. Middleton, "Management of structural monitoring data of bridges using BIM," *Proc. Inst. Civ. Eng. - Bridg. Eng.*, vol. 170, no. 3, pp. 204–218, Sep. 2017.

[43] M. Theiler, K. Dragos, and K. Smarsly, "BIM-based design of structural health monitoring systems," in *Proceedings of the 11th International Workshop on Structural Health Monitoring, Stanford, CA, USA*, 2017, vol. 12.

[44] F. Banfi, L. Barazzetti, M. Previtali, and F. Roncoroni, "HISTORIC BIM: A NEW REPOSITORY FOR STRUCTURAL HEALTH MONITORING," *ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. XLII-5/W1, no. 5W1, pp. 269–274, May 2017.

[45] J. M. Davila Delgado, L. J. Butler, I. Brilakis, M. Z. E. B. Elshafie, and C. R. Middleton, “Structural Performance Monitoring Using a Dynamic Data-Driven BIM Environment,” *J. Comput. Civ. Eng.*, vol. 32, no. 3, p. 04018009, May 2018.

[46] M. Valinejadshoubi, A. Bagchi, O. Moselhi, and A. Shakibabarough, “Investigation on the potential of building information modeling in structural health monitoring of buildings,” *CSCE Gen. Conf. 2018, Held as Part Can. Soc. Civ. Eng. Annu. Conf. 2018*, no. June, pp. 407–416, 2018.

[47] M. Theiler and K. Smarsly, “IFC Monitor – An IFC schema extension for modeling structural health monitoring systems,” *Adv. Eng. Informatics*, vol. 37, pp. 54–65, Aug. 2018.

[48] J. Messner *et al.*, “BIM Project Execution Planning Guide-Version 2.2,” *Computer integrated Construction Research Program, Pennsylvania State University*. 2019.

[49] BIMe INITIATIVE, “211in Model Uses Table.” [Online]. Available: https://bimexcellence.org/wp-content/uploads/211in-Model-Uses-Table.pdf. [Accessed: 26-Apr-2021].

[50] R. Sacks and R. Barak, “Impact of three-dimensional parametric modeling of buildings on productivity in structural engineering practice,” *Autom. Constr.*, vol. 17, no. 4, pp. 439–449, May 2008.

[51] R.-J. Tsay, “A Study of BIM Combined with ETABS in Reinforced Concrete Structure Analysis,” in *IOP Conference Series: Earth and Environmental Science*, 2019, vol. 233, no. 2, p. 22024.

[52] M. Aldegeily, J. Zhang, Y. Hu, and X. Shao, “From architectural design to structural analysis: a data-driven approach to study building information modeling (BIM) interoperability.” Western Michigan University, 2018.

[53] Z. Z. Hu, X. Y. Zhang, H. W. Wang, and M. Kassem, “Improving interoperability between architectural and structural design models: An industry foundation classes-based approach with web-based tools,” *Autom. Constr.*, vol. 66, pp. 29–42, Jun. 2016.

[54] R. Ren, J. Zhang, and H. N. Dib, “BIM Interoperability for Structure Analysis,” in *Construction Research Congress 2018*, 2018, pp. 470–479.

[55] J. F. Tchouanguem Djuedja, M. H. Karray, B. K. Foguem, C. Magniont, and F. H. Abanda, “Interoperability Challenges in Building Information Modelling (BIM) BT - Enterprise Interoperability VIII,” in *Proceedings of the I-ESA Conferences book series (IESACON)*, 2019, pp. 275–282.

[56] R. Sacks, M. Treckmann, and O. Rozenfeld, “Visualization of Work

Flow to Support Lean Construction," *J. Constr. Eng. Manag.*, vol. 135, no. 12, pp. 1307–1315, Dec. 2009.

[57] N. Lu and T. Korman, "Implementation of Building Information Modeling (BIM) in Modular Construction: Benefits and Challenges," in *Construction Research Congress 2010*, 2010, pp. 1136–1145.

[58] R. Edirisinghe, "Comparative Analysis of International and National Level BIM Standardization Comparative Analysis of International and National Level BIM Standardization Efforts and BIM adoption," no. October, 2015.

[59] J. Matthews, P. E. D. Love, S. Heinemann, R. Chandler, C. Rumsey, and O. Olatunj, "Real time progress management: Re-engineering processes for cloud-based BIM in construction," *Autom. Constr.*, vol. 58, pp. 38–47, Jul. 2015.

[60] M. S. Günay and K. M. Mosalam, "PEER Performance Based Earthquake Engineering Methodology , Revisited," no. Moehle, 2003.

[61] R. O. Hamburger, C. Rojahn, J. Heintz, and M. G. Mahoney, "FEMA P58: Next-generation building seismic performance assessment methodology," in *15th world conference on earthquake engineering*, 2012, vol. 10, no. 10.

[62] R. Santos, A. A. Costa, J. D. Silvestre, and L. Pyl, "Integration of LCA and LCC analysis within a BIM-based environment," *Autom. Constr.*, vol. 103, pp. 127–149, Jul. 2019.

[63] Y. Arayici, "Towards building information modelling for existing structures," *Struct. Surv.*, vol. 26, no. 3, pp. 210–222, Jul. 2008.

[64] L. Barazzetti *et al.*, "BIM from laser clouds and finite element analysis: combining structural analysis and geometric complexity. The International Archives of the Photogrammetry," *Remote Sens. Spat. Inf. Sci.*, vol. 40, p. 345, 2015.

[65] M. Murphy, E. McGovern, and S. Pavia, "Historic building information modelling (HBIM)," *Struct. Surv.*, vol. 27, no. 4, pp. 311–327, Aug. 2009.

[66] C. R. Farrar and K. Worden, "An introduction to structural health monitoring," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 365, no. 1851, pp. 303–315, 2007.

[67] M. Theiler, K. Dragos, and K. Smarsly, "BIM-based Design of Structural Health Monitoring Systems," in *Structural Health Monitoring 2017*, 2017, vol. 0, no. shm.

[68] T. Vilutiene, D. Kalibatiene, M. R. Hosseini, E. Pellicer, and E. K. Zavadskas, "Building Information Modeling (BIM) for Structural

Engineering: A Bibliometric Analysis of the Literature," *Adv. Civ. Eng.*, vol. 2019, pp. 1–19, Aug. 2019.

3 Structural e-permits: an openBIM, model-based procedure for permit applications pertaining to structural engineering

3.1 Introduction

This chapter investigates the creation and use of integrated IFC models to modernise traditional processes for applications to building authorities for structural-engineering approvals and permits. First, I provide a brief overview of e-permit systems in the AEC sector, with the focus on solutions that implement openBIM standards like IFC, MVD, and IDM. Second, I conduct a study on the information requirements of Italy's seismic-authorisation processes relating specifically to the field of structural engineering. Third, I describe preliminary research on defining the structural-engineering information that needs to be incorporated in the IFC format for e-permitting scopes. Fourth, I illustrate the reference workflow of the Str.E.Pe. project and propose a proof-of-concept of that makes use of an IFC model, which has been integrated with structural information to support the activities of the building authority in Avellino. The officers there have developed a SWOT analysis using IFC models to assist them in assessing the compliance of structural projects with seismic requirements. Finally, in section 5, the chapter sets out additional research that we intend to undertake at the University of Naples Federico II and our conclusions.

In recent years, the Architecture, Engineering and Construction (AEC) sector has undergone a gradual transition from a traditional to a BIM approach. The former deploys processes for the production, exchange and delivery of information which, essentially, consists of 2D representations of construction projects and requires manual human-based checks. Meanwhile, the latter: 1) focuses on 'information management' (i.e., the management and production of information during the life-cycle of a built asset); 2) introduces novel processes for the implementation of information models; and 3) embraces principles of digitisation, collaboration and automation [1]. Automated and semi-automated clash-detection processes, as well as model- and code-checks (performed with suitable software), contribute to the validation of data and guaranteeing the reliability of information models in relation to both interdisciplinary coordination and correspondence with the information requirements specified by clients [2]. Recently, building regulators and Building Authority Bodies (BABs) across the globe have begun to modernise their traditional systems for permit applications [3], [4]. Their proposals generally adopt an information- and document-management system that enables the reliance on paper-based practices to be reduced or, sometimes, replaced with digital submissions of application forms, 2D drawings, and reports containing technical specifications. These have commonly been referred to as 'e-permitting' systems. BABs are currently examining the openBIM approach as a possible strategy for improving their procedures further [5]. This is for good reason, since the use of open model-based processes and automated code-checking tools would streamline and accelerate permit-application practices significantly [6]. In particular, the time spent on labour-intensive reviews would be reduced, misunderstandings arising from poor-quality 2D drawings would be avoided and, in the future, the integration of BIM and GIS technologies could be improved.

3.1.1 Overview of the use of BIM in e-permit systems and procedures in the built-environment sector

The Regulatory Room (RR) of buildingSMART®, an international association that aims to expand the use of openBIM to countries around the world, has recently investigated how e-submission systems (or platforms) and procedures are deployed globally to apply for permits and approvals in the AEC industry. Its study was finalised and released in 2020 as the *E-submission common guidelines for introducing BIM into building processes* [6]. This contains a number of interesting findings. In particular, information exchanges between BABs and AEC stakeholders often relate to more than one phase of the building process. Consequently, applications can be assigned to three main groups: 1) concept approvals and permits; 2) building approvals and permits; and 3) construction approvals and permits. Figure 3.1 portrays the procedure for obtaining approvals in relation to these three elements. It is the first attempt in the field to schematise e-submission procedures within the building process.

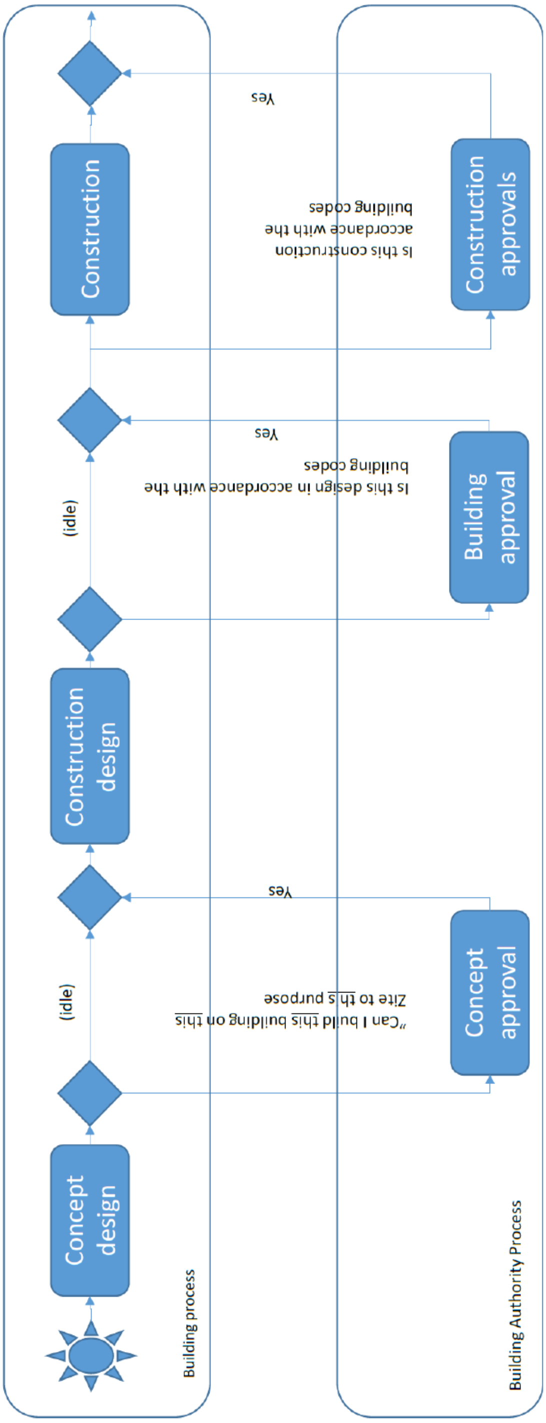


Figure 3.1: Procedure for obtaining permissions during the building process (extracted from [6]*).*

E-submission systems (or platforms) have been in development globally since the early 2000s. However, their use is still limited: the buildingSMART® study has identified only five examples (set out in Table 3.1), and just one of these enables openBIM-based submissions. Unfortunately, however, the guidelines do not contain any insights into this particular procedure.

Table 3.1: E-submission platforms in the AEC sector.

Country	E-submission platforms in the AEC sector		
	Name	**Year came into force**	**Additional information**
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.

The few examples in the buildingSMART® report commonly use the IFC standard [7] to deliver an information model. The study stresses the need to identify: the stakeholders involved (to answer the question 'who?'); the exchange points ('when?'); and the information requirements ('which data?'). Interaction maps are used in the report to depict the exchanges with the e-submission platforms. Particular reference is made to the adoption of the Business Process Model and Notation (BPMN) language (which is also used for Information Delivery Manuals - IDMs) to better describe the processes involved. A gradual transition from a traditional to a BIM-based workflow is essential from a legal perspective. The buildingSMART® study identifies four stages: manual, digital, hybrid and automated. Additionally, the degree to which Industry Foundation Class (IFC) property values are utilised determines three levels of development of BIM e-submission procedures: 1) visualisation - the value of the BIM property is not actively utilised; 2) hybrid/information flow - the value of the BIM property is actively adopted for specific code-checks; in this stage, IFC-based Model View Definitions (MVDs) and IDMs are essential, since information definitions are required to enable the computer program to read and understand the content; and 3) automated code-checking - the value of the BIM property is used for holistic code-checking purposes; e-Low, a machine-readable building code, is required to achieve this. Academic research is also now focusing on e-submission processes and systems. Shahi *et al.*, for example, have defined an e-permit reference framework with four levels of development: traditional permit; basic e-permit; automated model-based e-permit; and fully-integrated (BIM+GIS) e-permit. The Shahi framework considers the impact of each level on the entire life-cycle of a project, i.e., from the submission of permit documentation through to the construction, operation and maintenance of the built facility. Shahi's team also clearly highlights that e-submission systems and procedures are a prolific research field when it comes to the use of automated model-based and fully-integrated BIM+GIS e-permit applications, and proposes a general reference framework for the adoption of openBIM standards in e-permitting [5]. Finally, the buildingSMART® report also contains interesting guidelines for the implementation of openBIM-based procedures.

Problem statement

The buildingSMART® report and the Shahi et al. study (2020) contain only a few examples of actual applications, none of which address the use of IFC-based MVDs and IDMs to support information exchanges with BABs in relation to structural engineering, whether in terms of workflows or information requirements. This chapter aims to remedy this by presenting the prominent research findings of the Structural E-Permitting (Str.E.Pe.) project of our team at the University of Naples Federico II (Italy), ACCA Software, the Campania region, the Avellino BAB, and the Municipality of Montemarano. This work has investigated the use of openBIM standards like IFC and MVDs for improving the processes involved in applying to BABs for structural engineering permits and approvals.

3.2 The Structural E-Permit (Str.E.Pe.) project

The Str.E.Pe. project concerns the 2019 award-winning (from buildingSMART® International) research conducted by the University of Naples Federico II (Department of Structures for Engineering and Architecture) in collaboration with ACCA Software, the Campania region, the Avellino BAB, and the Municipality of Montemarano. Those involved were tasked with creating an IFC-based approach for use throughout Italy in applications for a seismic-authorisation ('autorizzazione sismica') permit (note: this approval mainly pertains to the field of structural engineering). In fact, although structural engineers are required to adhere to national building codes, they have to apply for approvals and permits to BABs, which verify them and enforce compliance. Unfortunately, the traditional practices involved in interactions with BABs consist of manual, paper-based processes that comprise the time-consuming activities of printing documentation and completing application forms and checklists. Improving these processes is, therefore, a key issue in countries like Italy that are characterised by territories with high levels of seismicity.

3.2.1 Methodology

In detail, the Str.E.Pe. project was organised into three stages, as depicted in Figure 3.2.

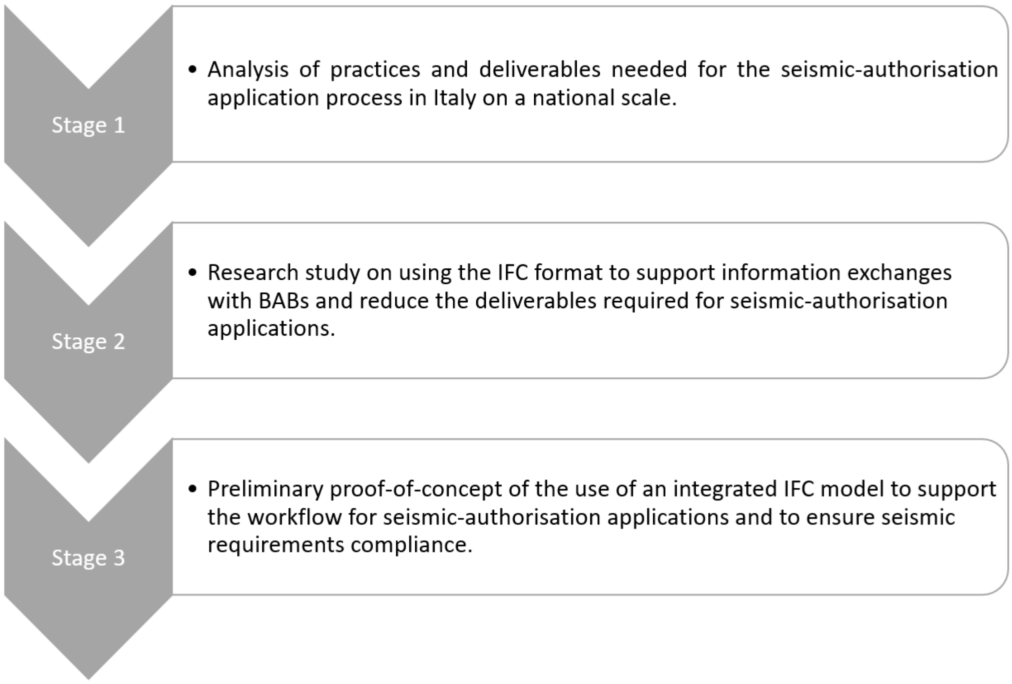


Figure 3.2: The stages of the Str.E.Pe. project.

The details of the three stages outlined above are set out in what follows.

3.2.2 Stage 1

3.2.2.1 Analysis of the practices and deliverables required for seismic-authorisation applications in Italy

The issue of seismic prevention is an extremely sensitive topic in Italy. As a result, the last few decades have seen the Italian government identify two features requiring a simultaneous focus: classifying the entire country seismically based on the intensity and occurrence of previous seismic events; and developing specific reference standards for structures built in areas where there is seismic activity. In 2004, a study conducted by the 'Istituto Nazionale di Geofisica e Vulcanologia' (INGV) concluded that the whole of Italy should be regarded as seismic. It therefore produced the seismic-hazard map shown in Figure 3.3 (source: http://esse1.mi.ingv.it/, 2020), which portrays four different seismicity levels: very low, low, high and very high. Every Italian region must identify the appropriate level for each municipality under its jurisdiction and can enforce stricter seismic-risk regulations, if required. Currently, there are two types of building permit available for seismic areas in Italy (i.e., the entire country): seismic deposit (in Italian: ‘deposito sismico’), which is required in areas of very low seismicity; and seismic authorisation, which is needed everywhere else. Each of these permit types has its own application practices. However, for reasons of brevity, our focus is on the second.

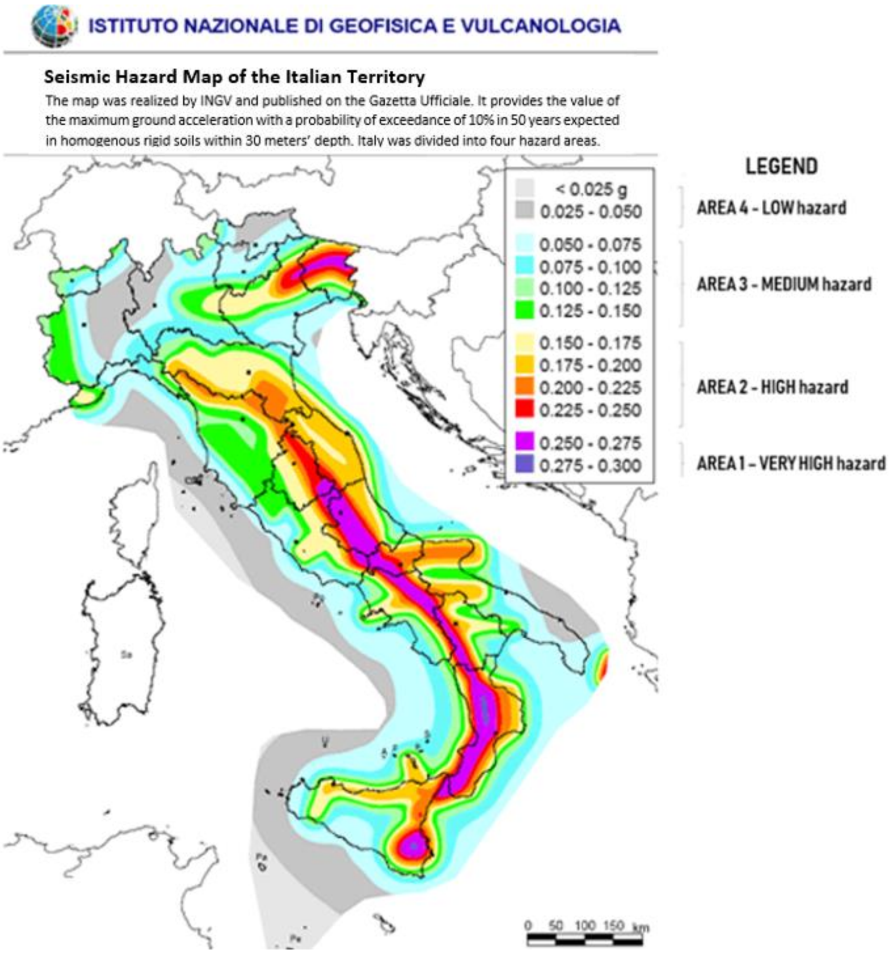


Figure 3.3: The seismic-hazard map of the territory of Italy (source: http://esse1.mi.ingv.it/ 2020).

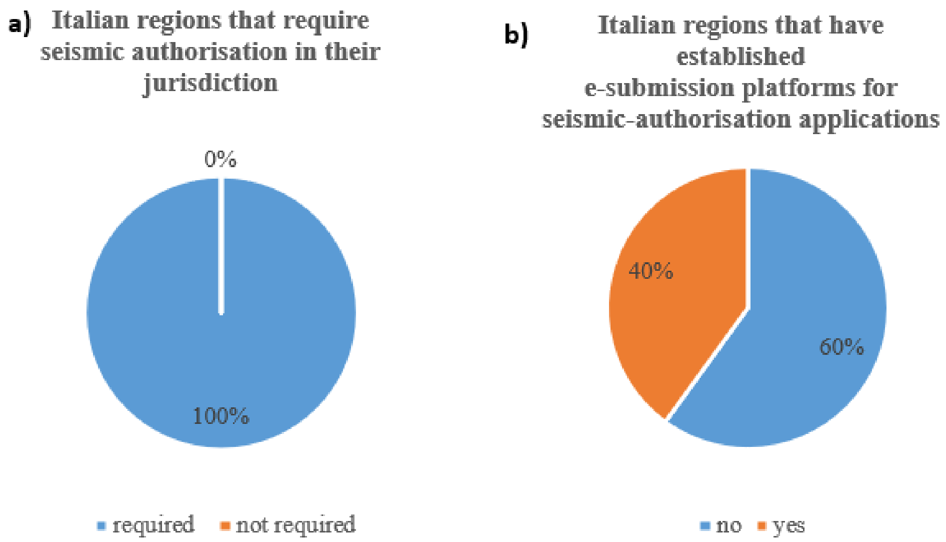
As an academic partner in the Str.E.Pe. project, we have undertaken a process of researching, organising and synthesising the seismic-authorisation application practices in all 20 Italian regions. Table 3.2 summarises our research questions, main tasks, and research findings.

Table 3.2: Summary of the process of researching, organising and synthesising the seismic-authorisation application practices in all 20 Italian regions.

Research questions	Tasks undertaken	Research findings

1. Do all Italian regions have a process for applying for a seismic-authorisation permit?	Internet searches on official websites for each region that describe the procedures for applying for a seismic-authorisation permit. Obtaining guidelines and instructions that describe the documentation required to apply for a seismic-authorisation permit in each region. Downloading the application forms available on the websites.	100% of Italian regions have a process for applying for a seismic-authorisation permit. Official websites provide both application forms to download and instructions to follow.
2. Has any Italian region got an online permitting platform for applying for a seismic-authorisation permit?	In-depth analysis of the instructions available on the official websites of all 20 Italians regions.	40% of Italian regions have an online permitting procedure vs. 60% that still rely on manual processes.
3. Which deliverables are required when applying for a seismic-authorisation permit? Are BIM models considered?	Analysis of the guidelines and instructions (obtained as explained in point 2 above) that describe the documentation needed to apply for a seismic-authorisation permit in each region.	The deliverables comprise, at most: • Application form. • 2D drawings. • Reports with technical specifications. • A building permit issued by the municipality with jurisdiction over the area where a project is to be located. • Additional checklists and forms summarising a project's structural technical specifications. There is no mention of BIM models.
4. Does any Italian region require the completion of additional checklists and/or forms that summarise the data concerning the structural project?	Analysis of guidelines and instructions (as above) that describe the documentation needed to apply for a seismic-authorisation permit in all regions.	25% of Italian regions have additional checklists or forms that must be completed manually.

In detail, we identified that all 20 regions have a process for applying for seismic-authorisation permits. In general, a structural engineer (or his/her representative) acts on behalf of a client and applies for a permit to the BAB with jurisdiction over a project. Once the BAB receives the application, including any required deliverables (see Table 3.2), they are checked to ensure the suitability of the design and compliance with relevant building codes. The BAB also oversees the application technically and administratively. If the procedure has a positive outcome, meaning no revisions are required, the BAB grants the seismic-authorisation permit, which enables the building process to advance to the construction phase. Alternatively, the BAB may ask for changes, which will require the submission of supplemental materials and revisions until it is satisfied. When the demands of the seismic-authorisation application process have been met, the BAB must issue a building permit within 60 days. Our investigation identified that only 40% of Italian regions have online permitting (i.e., e-permitting) platforms, although some allow engineers to choose between a manual paper-based process and an online version. The remaining 60% still rely on manual practices. Moreover, 25% of regions require applicants to complete additional checklists and/or forms summarising the data on a project. These forms and checklists can vary per type of structure: some differ according to the construction system (reinforced concrete, masonry, steel, or wood) and the kind of intervention (new or existing buildings), while others have just a single format that is suitable for all cases. None of the regions employs procedures that accept BIM models, even when online permitting systems are available (see Figure 3.4).



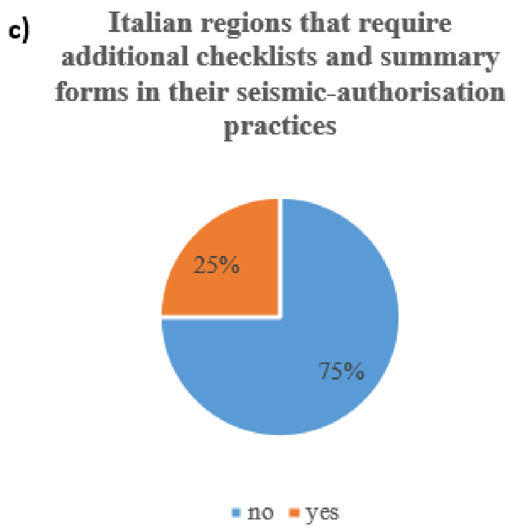


Figure 3.4: a), b), c) Fundamental outcomes of our study on the seismic-authorisation application practices in the 20 Italian regions.

3.2.2.2 The role of structural engineers

Structural engineers follow a somewhat standardised workflow to conceive and design a structural project and satisfy the information requirements that enable them to apply for a seismic-authorisation permit. We have identified roughly five steps:

1. Conceiving and designing the structural project.
2. Producing a structural finite element model (FEM) with finite element analysis (FEA) software; using the FEM to conduct structural analyses.
3. Using the FEM to perform structural assessments and ensure compliance with current building codes.
4. Satisfying the information requirements for the seismic-authorisation application.
5. Applying to a BAB for a seismic-authorisation permit.

Figure 3.5 is a detailed portrayal of the traditional workflow followed by a structural engineer to create a structural project and apply for a seismic-authorisation permit.

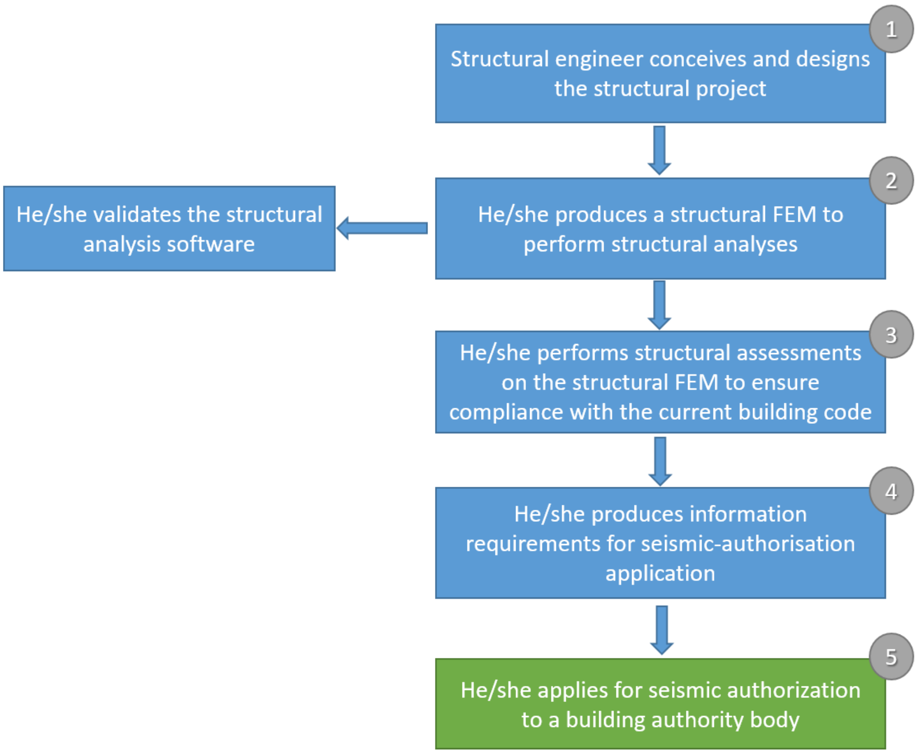


Figure 3.5: Traditional workflow for the production of documentation to acquire a seismic-authorization permit.

Structural engineers are required to validate the FEA software they use. Commonly, this process involves a simple scheme (a column or a beam bearing only gravity loads) that is resolved with both the software chosen and a calculation produced by hand. A comparison of the results will provide proof of the reliability of the software. Finally, information requirements comprise the following documentation:

- An application form.
- 2D drawings and reports containing technical specifications.
- A building permit issued by the municipality with jurisdiction over the area where a project is to be based (in Italian: 'titolo abilitativo').
- Additional checklists and forms completed with, and summarising, the project's technical specifications.

3.2.2.3 An overview of international building-approval and permitting practices relating to structural engineering

'Performance standards' form part of seismic regulations worldwide, compliance with which protects engineering practitioners in relation to their legal responsibilities, without depriving them of discretion and autonomy. In

Italy, the technical requirements are, to some extent, embedded in legal standards, thus becoming binding prescriptions. Local authorities may also have the power to introduce additional requirements to ensure code compliance. Given the huge number and wide variety of building-work approval practices in place globally, Table 3.3 provides an overview on several countries of interest, setting out what is known of their authorisation processes in relation to structural and seismic designs. In detail, I describe reference building codes and the main enforcement strategies for New Zealand, California (USA) and Greece, all of which, along with Italy, have played a prominent role in developing the field of seismic engineering [8].

Table 3.3: Summary of reference building codes and enforcement strategies in New Zealand, California and Greece.

Country	Reference building code	Considerations
New Zealand	The primary legislation governing the construction industry is set out in the Building Act 2004 n°72 (source: https://www.building.govt.nz n.d.), which was enacted by the Ministry of Business Innovation and Employment.	Territorial authorities (for instance, local councils) are empowered to control the building activity in their district and to oversee a consent process that enables building work to start. If they are registered as Building Consent Authorities (BCAs), they also ensure compliance with the building code.
	The minimum performance standards that must be met are defined in Schedule 1 of the building code (source: http://www.seismicresilience.org.nz/topics/resilient-design/codified-seismic-design/. n.d.). This is a performance-based standard that allows more than one way to meet the legislation's requirements.	Although the building code is a performance-based system, it allows territorial authorities to introduce additional requirements to ensure compliance, for example in relation to the verification method or acceptable solutions. Designers can submit an alternative if they can demonstrate to the BCA that the proposal will comply with the building code.
California - US	The California Building Standards Code (CBSC) was published in 2016. This sets out the basis for the design and construction of buildings in the state and is upheld by the California Building Standards Commission (source: https://www.dgs.ca.gov/bsc).	In relation to approval practices, the Building Division (or Building Department) ensures compliance with standards by: setting out procedures for reviewing and approving plans and specifications; issuing permits; and conducting building inspections.
		When it comes to local jurisdictions, each city or town can modify the CBSC if it requires more restrictive dispositions. An example is Los Angeles (source:http://www.ladbs.org/services/core-services/plan-check-permit), which provides check-lists (dubbed standard correction lists) that are intended to

		facilitate and guide an interested party through the permit process. There is a further process for structures in seismic areas: the buildings that contain devices like isolators are also subject to a 'structural seismic peer review protocol' which requires a descriptive document on the process.
Greece	The Greek government enacted the country's anti-seismic regulations - the Ελληνικός Αντισεισμικός Κανονισμός (E.A.K.-2000) - following the Athens earthquake in 1999; before then, Eurocodes were used for both buildings and bridges. EAK-2000 is currently on the statute books, but its provisions only refer to buildings; meanwhile, engineers may discretionally refer to EN 1998-1:2004 [12] for bridges.	A new approval system for private work has been in place since 2010 and aims to reduce bureaucracy. In addition, the delivery of project documents in a digital format has recently become mandatory. Municipal disciplinary committees take charge only when it comes to assessing the completeness and accuracy of project-delivery documentation (plans and technical specifications); ensuring that projects comply with the reference code is the responsibility of structural engineers.

3.2.2.4 Criticalities

It is notable that, as highlighted above, no Italian region has ever addressed the possibility of using BIM models in seismic-authorisation applications, and nor is there any example of their employment internationally. In Italy, alternatives to the (manual) submission of paper documentation involve e-permitting systems where deliverables corresponding precisely to these documents can be uploaded in the PDF format. Clearly, this is nothing more than the replacement of paper documentation with a digital equivalent, and does not enable the implementation of any substantial automated controls during the application process.

3.2.3 Stage 2

3.2.3.1 A study on the use of the IFC format to support information exchanges with BABs in seismic-authorisation applications

Our research addressed the following subject-matters when developing a procedure that employs the IFC format to support information exchanges with BABs during seismic-authorisation applications:

- Defining a strategy that uses the IFC format to reduce the seismic-authorisation deliverables required.
- Identifying information that could be conveyed to BABs via the IFC format.

- Analysing the IFC format with respect to structural engineering, as well as the strategies available for the integration of any required information deliverables.

3.2.3.2 Using the IFC format to reduce the deliverables required for seismic-authorisation applications

Table 3.2 sets out the deliverables required to apply for a seismic-authorisation permit. These commonly comprise: an application form; 2D drawings and reports with technical specifications; and additional checklists and forms. If successful, official approval documentation is issued by an officer from the BAB with jurisdiction over the area where a project is located. We argue that the IFC format is not able to replace administrative and legal documents like application forms and building permits (issued by other municipalities), because its structure lacks standardised 'spots' for such content. However, the buildingSMART® RR is currently analysing the possibility of extending the IFC structure to enable it to include at least one entity (or class) that specifies the state of approval in relation to the information submitted. Even so, this would represent only a small step forward, meaning that administrative and legal documents in the paper format would still be required.

We believe that the IFC format could be better employed in reducing the amount of technical documentation required; for example, 2D drawings could be replaced entirely by IFC models that include sufficient detail on reinforcements and connections. This would enable BAB officials to use IFC viewers to explore models in detail. Commonly, technical reports are produced automatically by Finite Element Analysis (FEA) software that: performs structural analyses according to a reference building code (i.e., Eurocodes); and deploys tools to design and verify structural elements. However, this software cannot produce completed checklists and forms that summarise a project's technical structural specifications, because these are rarely standardised and, therefore, depend closely on the internal practices of BABs. In fact, additional checklists and forms give BAB officers a quick and clear overview of structural projects, although these require completion by hand by structural engineers. We argue that technical reports are essential for understanding project choices and designs, but checklists and summary forms could be replaced by an IFC model that integrates all the valuable information required. This would enable BAB officers to leverage IFC models, integrating the data contained in checklists in order to: increase their understanding of structural projects, as they would be able to visualise models and read technical information concurrently; and use data in the IFC format to conduct preliminary counterchecks. Figure 3.6 depicts an information flow that could be employed to incorporate structural information in an IFC model to obtain an integrated IFC.

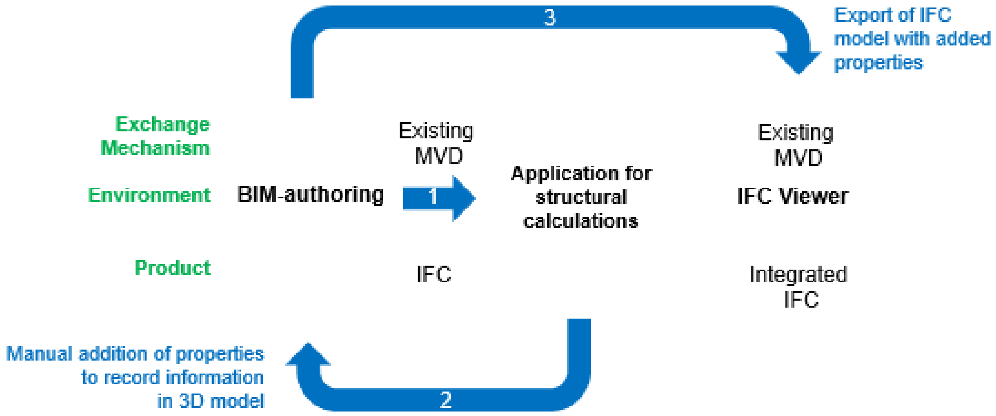


Figure 3.6: Possible information flow for integrating structural information into an IFC model.

Additionally, the availability of IFC models in an e-permitting platform could promote the use of novel workflows by BAB officers in their examinations of documentation that can be linked to a model's objects. In this way, IFC models would also function as a key for accessing project documentation. This would improve current paper-based practices fundamentally.

We believe that an integrated IFC would be a valuable deliverable when it comes to improving structural permit and approval practices. As a consequence, the following section describes a study on content that could be incorporated in the IFC format, as well as a reference integration procedure that could overcome the criticalities of the process depicted in Figure 3.6.

3.2.3.3 Identifying information for integration into the IFC format to support seismic-authorisation applications

In order to identify the information that the IFC format would need to manage, we analysed the checklists and forms we had obtained in Stage 1, producing a comprehensive dataset that would satisfy the information requirements of all the Italian BABs. Table 3.4 sets out the data identified by our study in relation to new reinforced concrete structures.

Table 3.4: All the information sought by building authorities in applications for seismic-authorisation permits for new reinforced concrete structures.

ID	Brief description of information	Data type	Value	Source

1.1	Brief description of the work	String	-	Engineer
1.2	Land register data	String	-	Engineer
1.3	Name of the owner	String	-	Engineer
1.4	Geographical coordinates (latitude; longitude)	Number	-	Engineer
1.5	Peak ground acceleration at the site of the work (a_g)	Number	-	FEM
1.6	Existence of any proscriptions and/or urban constraints	Boolean	Yes/no	Engineer
1.7	Kind of work	String	Public/private/ bonded (historical)	Engineer
1.8	Type of work	String	Ordinary building/ industrial warehouse/ geotechnical work/ other	Engineer
1.9	Construction system	String	Reinforced concrete/steel/ masonry/ wood/mixed	FEM
1.9.1	Existence of any seismic device (isolators/dampers)	Boolean	Yes/no	Engineer
1.10	Type of bearing structure	String	Frame (beams-columns/ walls/mixed/other)	FEM
1.11	Type of foundation	String	Shallow footings (combined, spread, raft)/deep footings (piles)/jet grouting/other	Engineer
1.12	Construction category of use: residential, commercial, offices, parking, etc.	String	Categories from A to K according to §2.5.2 NTC 2018	FEM
1.13	List of main geometrical information: total plan surface area [m^2]; total volume[m^3]; basement floors [n°]; storeys [n°]; max floor span [m]; max depth of the footings [m]; max height of the roof [m]; other	Chart	-	FEM
2.1	Ground investigation type	String	Geotechnical tests/geophysical tests (direct or indirect)/other	Engineer

2.2	Ground type, accounting for the influence of local ground conditions on the seismic action	String	Categories from A to S2 according to §3.2.2 NTC2018	FEM
2.3	List of ground parameters: v_{s30}[m/s]; N_{spt30}, [-]; c_u [kPa]	Chart	-	FEM
2.4	Type of ground according to topographical conditions	String	Categories from T1 to T5 according to §3.2.2 NTC2018	FEM
2.5	Existence of liquefaction phenomena	Boolean	Yes/no	FEM
2.6	List of data that define the ground profile stratigraphically: soil layers [n°]; soil layer depth [m]; soil weight ϒ[kN/m^3]; N_{SPT} [n°]; $q_{c,CPT}$ [kN/m^2].	Chart	-	FEM
2.7	Existence of aquifer	Boolean	Yes/no	FEM
3.1.1	List of all design actions: type (self-weight, imposed by category usage, wind, earthquake, snow, thermal, etc.); name; brief description	Chart	-	FEM
3.1.2	List of characteristic values of the design actions (in kN/m$^{2)}$ with respect to storeys, stairs, roofs, foundations, other	Chart	-	FEM
3.1.3	List of load combinations considered: load combination name; list of loads involved; notes	Chart	-	FEM
3.2.1	Nominal service life of the structure v_N [years]	Number	Minimum values according to §2.4.1 NTC 2018	FEM
3.2.2	Structure’s importance: class and factor	String and number	Classes from I to IV according to §2.4.3 NTC 2018	FEM
3.2.3	Designed service life of the structure v_R [years]	Number	Value obtained according to the formula [2.4.1] NTC2018	FEM
3.2.4	Existence of a local seismic-response study	Boolean	Yes/no	Engineer
3.2.5	Response spectra data according to the limit state	Chart and plot	-	FEM
4.1	List of mail geometrical data: n° of storeys; n° of spans; inter-storey height; other	Chart	-	
4.2	Existence of secondary structural elements	Boolean	Yes/no	Engineer

4.3	Existence of noteworthy second-order effects	Boolean	Yes/no (according to §7.3.1 NTC 2018)	FEM
4.4	Type of base constraints for primary structural elements	String	-	FEM
4.5.1	Type of structural analysis in cases of seismic action	String	-	FEM
4.5.2	Ductility class	String	High/low/not dissipative structural behaviour	FEM
4.5.3	Satisfied structural regularity in plan	Boolean	Yes/no	FEM
4.5.4	Satisfied structural regularity in elevation	Boolean	Yes/no	FEM
4.5.5	Capacity design	Boolean	Yes/no	FEM
4.5.6	Reinforced concrete structural element capacity assessment, taking into account confinement effects (according to §7.4.1 NTC2018)	String	-	FEM
4.5.7.1	Structural type of concrete building (§7.3.1 - Table 7.3.II NTC2018)	String	-	FEM
4.5.7.2	Structural type of pre-cast building (§7.3.1 - Table 7.3.II NTC2018)	String	-	FEM
4.5.7.3	Structural type of steel or composite steel-concrete buildings (§7.3.1 - Table 7.3.II NTC2018)	String	-	FEM
4.5.7.4	Structural type of masonry building (§7.3.1 - Table 7.3.II NTC2018)	String	-	FEM
4.5.8	Behaviour factors for horizontal seismic actions according to each limit state	Chart	-	FEM
4.5.9	Assumption of diaphragmatic behaviour at the storey level	Boolean	Yes/no	FEM
4.5.10	Existence of discontinued vertical structural elements	Boolean	Yes/no	FEM
4.5.11	Existence of noteworthy vertical seismic actions	Boolean	Yes/no	FEM

5.1	List of foundation concrete properties: concrete class; characteristic compressive strength; Young's modulus; design compressive strength	Chart	-	FEM
5.2	List of building concrete properties: concrete class; characteristic compressive strength; Young's modulus; design compressive strength	Chart	-	FEM
5.3	List of reinforcing steel properties: steel type; characteristic yield tensile strength; characteristic ultimate tensile strength; Young's modulus; design tensile strength	Chart	-	FEM
5.4	List of pre-cast concrete properties: concrete class; characteristic compressive strength; Young's modulus; design compressive strength, other	Chart	-	FEM
5.5	List of pre-stressing steel properties: steel type; characteristic ultimate tensile strength; characteristic yield tensile strength; Young's modulus; other	Chart	-	FEM
5.6	List of structural steel properties: steel class; characteristic yield tensile strength; characteristic ultimate tensile strength; Young's modulus; design tensile strength	Chart	-	FEM
5.7	List of masonry properties: masonry type; characteristic compressive strength; characteristic shear strength; Young's modulus; shear modulus; other	Chart	-	FEM
6.1.1	Fundamental vibration period of the structure	Number	-	FEM
6.1.2	Requirements for linear static analysis (lateral force method) according to §7.3.3.2 NTC 2018	Boolean	Yes/no	FEM
6.1.3	Consideration of accidental torsional effects (§7.3.3 NTC2018)	Boolean	Yes/no	FEM
6.2.1	Number of modes considered for which the sum of the effective modal mass amounts to at least 85% (§7.3.3.1 NTC2018)	Number	-	FEM
6.2.2	Consideration of accidental torsional effects (§7.3.3 NTC2018)	Boolean	Yes/no	FEM

6.2.3	Summary chart of modal information: fundamental periods in the main horizontal directions of the building; effective modal masses; and maximum roof displacements	Chart	-	FEM
6.3.1	Type of 'uniform pattern' vertical distributions of lateral loads applied according to §7.3.4.2 NTC 2018	String	-	FEM
6.3.2	Type of 'modal pattern' vertical distributions of lateral loads applied according to §7.3.4.2 NTC 2018	String	-	FEM
6.3.3	Consideration of accidental torsional effects (§7.3.3 NTC2018)	Boolean	Yes/no	FEM
6.3.4	Capacity curves and bilinear relationship data according to §7.8.1.6 NTC2018	Chart and plot	-	FEM
6.4	Non-linear dynamic analysis	String	-	Engineer
7.1	Footing assessment procedure and corresponding safety factors for actions, materials and capacities	String	According to §6.2.4.1 NTC 2018	FEM
7.2	Safety checks performed in cases of <u>shallow</u> foundations at the ultimate and serviceability limit states (ULS and SLS)	Chart: each type of check (*) is associated with a minimum value of the capacity demand ratio (C/D) and ID of the correspondi ng element	(*) Bearing resistance/sliding resistance/overall stability/structural / settlements/other	FEM
7.3	Safety checks performed in cases of <u>deep</u> foundations at the ultimate and serviceability limit states (ULS and SLS)			FEM
7.4	Checks performed on the horizontal connections at the foundation level	Boolean	Yes/no	FEM
8.1.1	List of safety checks required for each limit state according to the class of building	Chart	Available options according to §7.3.6 NTC 2018	FEM
8.1.2.1	ULS WITHOUT seismic actions: safety checks <u>performed</u> on cross-sections of primary structural elements such as beams, columns and walls	Chart: each type of check (*) is associated with a minimum	(*) Axial load/ bending moment/ shear/ torsion/ punching/ buckling/	FEM

		value of the (C/D) ratio and ID of the corresponding element	combined checks/other	
8.1.2.2	ULS (life safe) in the case of seismic actions: safety checks performed on cross-sections of primary structural elements such as beams, columns and walls		(*) axial load/ bending moment/ shear/ torsion/ punching/ buckling/ combined checks/other	FEM
8.1.2.3	ULS (near collapse) in the case of seismic actions: safety checks performed on cross-sections of primary structural elements such as beams, columns and walls		Ductility checks/other	FEM
8.1.3	Safety checks performed on secondary structural elements (§7.2.3 NTC2018)	Boolean	Yes/no	FEM
8.1.4	Safety checks performed on non-structural elements (§7.2.3 NTC2018)	Boolean	Yes/no	FEM
8.1.5	Safety checks performed on systems (§7.2.3 NTC2018)	Boolean	Yes/no	FEM
8.1.6.1	SLS WITHOUT seismic actions: safety checks performed on cross-sections of primary structural elements such as beams, columns and walls		(*) Axial load/ bending moment/ shear/ torsion/ punching/ buckling/ combined checks/other	FEM
8.1.6.2	SLS (immediate occupancy) in the case of seismic actions: safety checks performed on cross-sections of primary structural elements such as beams, columns and walls	Chart: each type of check (*) is associated with a minimum value of the C/D ratio and ID of the corresponding element	(*) Axial load/ bending moment/ shear/ torsion/ punching/ buckling/ combined checks/other	FEM
8.1.6.3	SLS (operational) in the case of seismic actions: safety checks performed on cross-sections of primary structural elements such as beams, columns and walls		(*) Axial load/ bending moment/ shear/ torsion/ punching/ buckling/ combined checks/other	FEM

8.1.7	Checks of the available distance between adjacent constructions (§7.2.1 NTC2018)	Boolean	Yes/no	FEM
9.1	Satisfied geometrical constraints for beams, columns, walls and beam-column joints according to §7.4.6.1.1-4 NTC2018	Boolean	Yes/no	FEM
9.2	Type of reinforcement constraint satisfied for each primary structural element inside and outside the critical region	Chart: each type of constraint (*) is associated with a minimum value of the required/effective ratio of the requested quantity	-	FEM
9.3	Critical region minimum length satisfied (with respect to each structural element) according to §7.4.6.1.1-4 NTC2018	Boolean	Yes/no	FEM

The first column in Table 3.4 contains a reference that assists with the organisation of the data. We have defined nine main sections: 1) description of the project; 2) properties of the foundation ground; 3) design actions (gravity loads, earthquake, snow, wind, etc.); 4) design criteria and modelling assumptions; 5) materials' properties; 6) structural-analysis methods and outcomes of the analyses; 7) structural-safety assessments for reinforced concrete structures; 8) structural-safety assessments of the foundations; and 9) construction details for reinforced concrete structures. Columns two to five, respectively, contain a brief description of the information required, the data type, a list of possible values (if any), and the information source. The data type includes strings of characters, numbers and Boolean-type data (true or false). We also provide the source of the information, ranging from FEA software to data added manually by a structural engineer.

3.2.3.4 Analysing the IFC format (ISO 16739-1:2018) from the structural engineering perspective

We conducted research to help us to achieve a detailed understanding of the capacity of the IFC format to deliver structural-engineering data, in particular the outputs of structural analyses and assessments. Our focus was on the structural aspects of the format, which integrates structural information by way of classes, attributes and properties. This occurs via concepts described within two domains and in relation to one of the four reference layers (domain layer) that make up the architecture of the standard: *IfcStructuralAnalysisDomain* and *IfcStructuralElementsDomain*. These are presented in Figure 3.7.

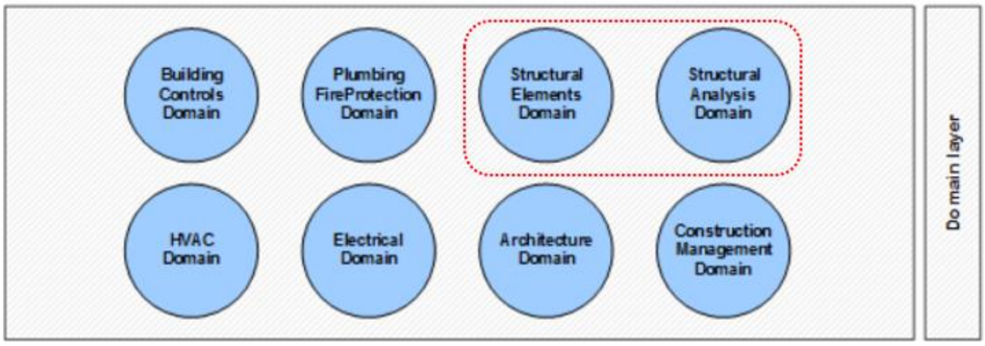


Figure 3.7: Domain layer of the IFC schema's architecture.

The *IfcStructuralAnalysisDomain* is a data schema that enables the representation of concepts that refer to the structural-analysis field and, therefore, describe '*planar and/or spatial structural analysis models which can be used by structural analysis applications*' (source: https://standards.buildingsmart.org/ifc/release/ifc4/add2_tc1/html/). In more detail, the domain introduces specific classes that allow the description of concepts that refer to (source: https://standards.buildingsmart.org/ifc/release/ifc4/add2_tc1/html/):

- '*Straight or curved structural curve elements, planar or curved structural surface elements.*
- *Point, curve, and surface connections and supports.*
- *Specifications of loadings, including point, curve, surface loads, temperature loads, their assignment to load groups, load cases and load combinations.*
- *Specifications of different structural analysis models in order to describe different aspects or parts of the building.*
- *Analysis results defined by forces and displacements.*'

The other data schema, *IfcStructuralElementsDomain*, enables the description and representation of different types of structural building elements. In fact, unlike other common building-element data schemes, this domain contains entities for representing foundations (e.g., *IfcFooting* and *IfcPile*) and structural sub-parts that are normally included in other building elements like structural reinforcements (e.g., *IfcReinforcingBar*, *IfcReinforcingElement*, *IfcReinforcingMesh*, and *IfcTendon*). Moreover, there are additional data schemas that form part of further conceptual layers constituting the IFC's schema architecture. An example is *IfcSharedBldgElements*, which enables the description of real construction objects like beams, columns and walls that correspond, respectively, to entities like *IfcBeam*, *IfcColumn* and *IfcWall*.

Unfortunately, the structure of IFC format lacks the space for descriptions of content such as the results of structural assessments. Consequently, from a structural engineering perspective, the format mainly explores the physical reality of the structural-engineering discipline (*IfcStructuralElementsDomain*, *IfcSharedBldgElements,* etc.) and the analytical context (*IfcStructuralAnalysisDomain*), enabling subsequent structural assessments to be conducted in dedicated applications. Accordingly, it is clear that the format is more appropriate for the characterisation of concepts that would have value for exporting a structural-analytical model from BIM-authoring software into FEA software. This export-import activity is supported by an existing MVD: *Structural Analysis View*, which refers to IFC version 2x3 (source: https://technical.buildingsmart.org/standards/ifc/mvd/mvd-database). This MVD provides a subset of entities with their attributes and properties, and aims to define an analytical model for use in analyses of structural-calculation applications. However, the results of structural assessments cannot be recorded in the IFC format, because this lacks suitable entities, attributes and properties. Consequently, a mechanism like a MVD cannot be employed to export this information. In any event, the task of exchanging structural-assessment results is beyond the scope of the *Structural Analysis View* MVD and does not, therefore, have a place in it.

To fill this lacuna, the IFC format requires improvement in terms of relationships, attributes and specific properties for newly-added classes. This would correspond to the creation of ‘space’ within the format for the description of structural-assessment outputs. Consequently, an IFC-based information flow could be introduced into structural-calculation applications able to integrate with a BIM-authoring environment to export content from structural analyses and assessments. Such an expanded IFC format could become a standard deliverable able to improve the processes implemented by BAB officers to visualise, verify and check the information required for structural-permit applications. Figure 3.8 sets out our proposed IFC-based workflow for exchanging information with building authorities in relation to these authorisations.

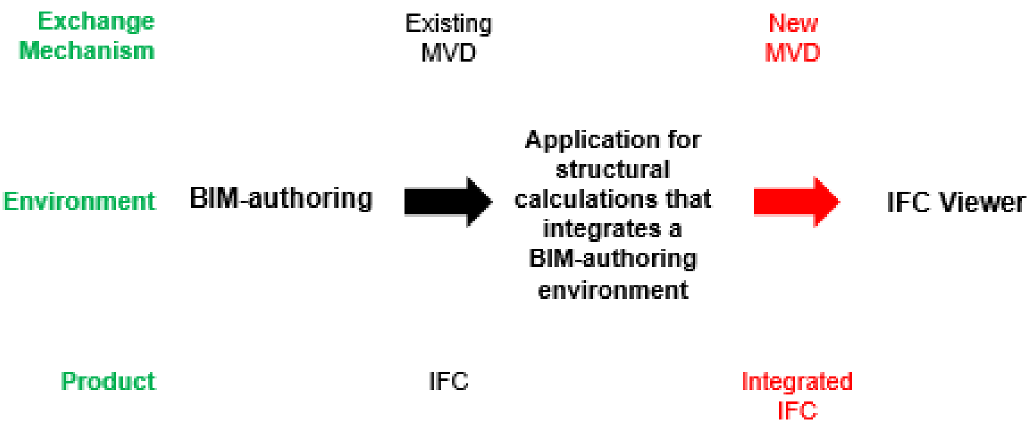


Figure 3.8: Information flow for structural e-permits.

3.2.3.5 Strategies for integrating information into the IFC format

Table 3.5 presents Borrmann *et al.*'s [13] integration strategies for use to incorporate information in the IFC format. In particular, we provide a brief description of the strategy, adoption requirements and criticalities.

Table 3.5: Summary of strategies for use to incorporate information into the IFC format.

Integration strategy	**Nature/ mechanism**	**Description**	**Adoption requirements**	**Criticalities**	**Application in the Str.E.Pe. project**
Entities & attribute definition	Static	The strategy involves developing additional classes and attributes. The latter are included within the schema (IFC) and represent the characteristics of an object.	• Broad sharing and adoption among all interested stakeholders. • Adding specific attributes for any new class that is added. These attributes represent any novel features requiring consideration.	It is not possible to add all the features considered, as this would lead to schema (IFC) management issues.	No
Properties & proxy definition	Dynamic	The strategy involves the definition of properties created dynamically. This is done by defining individual properties (*IfcProperty* and *subclasses*) and property sets (*IfcPropertySet*).	• The stakeholders involved in an information exchange (i.e., a minimum of the writer of the information and those receiving it) should agree on the meanings associated with the information in terms of properties	Different stakeholders define a huge number of arbitrary concepts (both objects and properties) for the same purpose. This leads to major redundancy.	Yes, the project focuses on the use of properties.

	This strategy also introduces the *Proxy Definition (i.e., IfcProxy)*, which allows the semantics of a generic class to be defined dynamically.	or proxies. • This strategy allows the use of standardised properties belonging to libraries like the buildingSMART data dictionary (bsDD) in order to improve the management and clarity of concepts. • This strategy allows the unlimited addition of properties to examples of IFC models. • Both *IfcPropertySet* and *IfcBuildingElement Proxy* allow the development of a meta-model characterised by different approaches related to semantic extensions. This makes it possible to describe a wide spectrum of application scenarios.	

The IFC format allows the adoption of both static and dynamic semantic-extension strategies. In relation to Table 3.5, we took the decision to adopt the second approach for the purposes of the Str.E.Pe. project. In detail, most BIM-authoring environments currently allow the creation and addition of properties that can be exported in the IFC format that is leveraging the dynamic mechanism. However, defining Psets needs both the stakeholders involved to agree on the content and unambiguous meanings to be associated with the added, and then exchanged, properties: i.e., structural engineers and BAB officers should agree on the meaning of the new properties to be exchanged in an application for a structural permit. In the following section, we will concurrently address this issue and develop a new MVD that will allow the filtering of interested entities and those affected by the addition of the new properties we propose. This would also enable the adoption of validation processes for IFC models.

3.2.3.6 Preliminary development of a new MVD for the scopes of the Str.E.Pe. project

The MVD mechanism promoted by buildingSMART is defined as '*a subset of the overall IFC schema to describe a data exchange for a specific use or workflow. MVDs can be as broad as nearly the entire schema or as specific as a couple object types and associated data*' (source: https://technical.buildingsmart.org/standards/ifc/mvd/). This presents extensive supporting technical documentation, and can be implemented in the class of software applications that could be part of IFC-based information exchanges. Within the framework of the Str.E.Pe. project, we aim to develop a new MVD that would allow the delivery of IFC models to BABs. These would integrate specific information relating to structural assessments that is currently only contained in structural reports and specifications, or has been collected manually for checklists and summary forms. In this section, the focus is on the definition of content for transmission in IFC models via the new MVD; meanwhile, in Section 4, we illustrate how the Str.E.Pe. project leverages the IFC models obtained with this new MVD to overhaul the process of applying for seismic authorisations. Our definition of content started with the information in Table 3.4, although this only refers to newly-designed reinforced concrete structures according to the Italian building code: *Norme tecniche per le costruzioni - NTC 2018* [14]. The information in Table 3.4 was obtained using software for structural calculations. To enable the addition of new properties representing the outputs of structural assessments, we examined structural applications that integrate a BIM-authoring environment. Deliberately, therefore, we do not go into detail about mapping the data from structural-calculation software in the IFC format: this is beyond the scope of both this chapter and the Str.E.Pe. project. Instead, we both present information that can be transferred via the dynamic mechanism of adding properties and identify the classes that would be affected by these integrations; in this way, a new MVD will be defined that will enable the IFC format to be used to present integrated IFC models to BABs. This approach allows the standardisation of the information flow. This means that all the software houses involved in structural-calculation applications could employ this new MVD to produce integrated IFC models whereby information extrapolated from structural reports and assessments is written in automatically in places identified by our proposed Psets.

Our work is continuing on the technical development of the new MVD and the creation of the reference documentation, with the ifcdoc tool being used for this purpose (source: https://www.buildingsmart.org/standards/groups/ifcdoc/). Nevertheless, the development of a MVD that would apply to all new reinforced concrete structures faces several problems relating to:

- Reference standards: structural designs and calculations must refer to a reference standard, which depends on the country where an engineer is working. Reference codes regulate the types of assessment required; additionally, codes differ in terms of their approaches, which can be prescriptive or performance-based. This affects the quantitative and qualitative outputs of structural assessments. For this reason, we argue that, unfortunately, the particular information required for integration into an IFC standard for structural-permit applications very much depend on the reference code being considered. In this chapter, however, reference is made to the Italian *Norme tecniche per le costruzioni - NTC 2018* [14].
- The adopted materials and structural typologies: there are different types of reinforced concrete structure, e.g., cast-in-place, prefabricated and prestressed. We chose to not consider other structural materials simultaneously, e.g., masonry, steel, wood and hybrid configurations; design codes differentiate between such materials, because different structural elements and systems require different capacity models and structural-assessment procedures. As a consequence, to avoid further complications, our focus is on reinforced concrete structures, in particular all the possible configurations of the load-bearing structure (frame, wall, mixed) and resulting structural elements (beams, columns, walls, slabs).
- The neglect of retrofit interventions in existing structures: a decision was made to focus the study on new reinforced concrete structures; in doing so, we have neglected existing structures, for which structural engineers commonly design structural retrofit interventions. The basis of the decision was the differences between the information required for new and existing buildings. The latter need two sets of outputs: one from a preliminary phase where the structural performance is assessed, and another in relation to the design and assessment of any corresponding structural retrofit interventions required. This would

render the information in Table 3.4 ineffective. Additionally, these two phases (assessment and retrofit) may require the use of different structural-analysis methods and different capacity models.

The issues described herein reflect the boundaries we have set for the development of a new MVD, although our approach has the potential to apply to all structural materials, as well as to existing structures. Our MVD is associated with a particular baseline (IFC4 version), which filters the entities affected by integration and information exchanges relating to some of the proposed Psets. This enables descriptions of, for example: the reinforced concrete structural typology (with frames, with frames and walls, etc.), as well as the safety factors identified by local and global assessments relating to all the limit states required by the reference building code. We have currently distinguished some of the classes affected by integration, such as *IfcBuilding, IfcBuildingStorey, IfcSite, IfcBeam, IfcColumn, IfcWall, IfcStructuralConnection, IfcFooting,* and *IfcPile*. We do not, however, exclude the possibility of identifying other classes as the work progresses. Once our analysis and definition of the exchange requirements is complete (i.e., all the classes affected by information exchanges are identified and the properties to be added to them are defined), the resulting MVD will be implemented in Edilus, a structural-calculation software tool that enables the incorporation of a BIM environment. This will automatically produce an integrated IFC model that includes the results of the structural assessments performed by Edilus (which extrapolates them automatically from calculation printouts).

3.2.4 Stage 3

3.2.4.1 The structural e-permit workflow

The work conducted in the previous stages was fundamental for producing a clear framework for improving the process for seismic-authorisation applications. The approach we propose implements 3D information models in the IFC format and delivers documentation in the ISO 21597-1:2020 information container data drop (ICDD) system, all via a dedicated platform. Figure 3.9 depicts the process map of the Str.E.Pe. procedure, which is written in the simplified BPMN language.

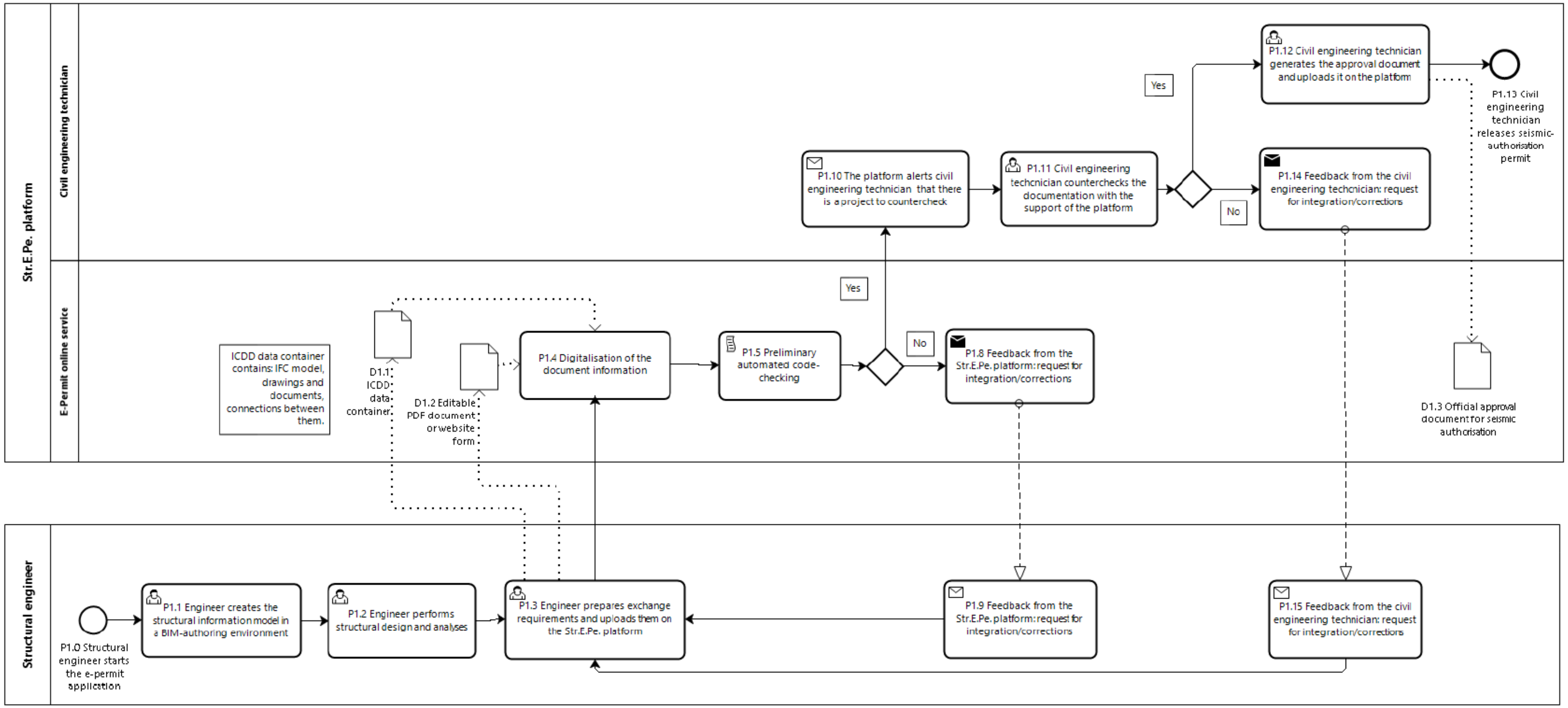


Figure 3.9: The structural e-permit workflow.

The map has 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-authorisation permit, and the technician from the BAB who is involved until the permit is issued. The second lane refers to operations carried out within the Str.E.Pe. platform. In detail, the exchange requirements foreseen by our 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 P-sets 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 end-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 standardised 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. We have deployed an ICDD exchange-container to improve information exchanges between the structural engineer and the civil engineering technician during the seismic-authorisation application process. A structural-information model and related documentation (2D drawings, reports with technical specifications) are delivered in a single data drop, and connections between the model and the documents are preserved. In addition, the platform offers the possibility of implementing preliminary automatic code-checks specifically in order to validate IFC (structural) models.

3.3 Preliminary proof-of-concept of the use of an integrated IFC model to ensure seismic requirements compliance

In this section, I present a proof-of-concept on the use of an integrated IFC model in the Str.E.Pe. application process. The officers of the Avellino building authority have tested the proof-of-concept and assessed (qualitatively) its feasibility. Based on our advice, they have used a SWOT analysis specifically on the use of an integrated IFC model that supports them in checking the compliance of the structural project with seismic requirements. However, as previously mentioned, an MVD is still under development, meaning that this preliminary proof-of-concept deploys an IFC model where information on structural safety has been added manually. In detail, we applied the Str.E.Pe process to the project renovating the school in Montemarano. This involves the deconstruction of an existing building and replacing it with a new reinforced concrete structure. Figure 3.10 depicts the new school's structural and architectural BIM models; the former was created with Edilus [15]and the latter with Edificius[16], both of which are produced by ACCA Software®.

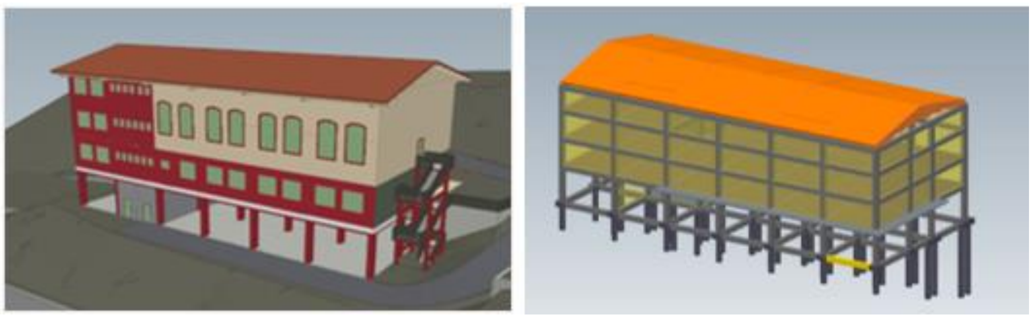


Figure 3.10: BIM architectural and structural models of the new school in Montemarano.

In the Edilus environment, we have defined Psets that relate to the project at both a global and a local level; then, we exported the integrated IFC model according to the MVD *CV2.0* (source: https://technical.buildingsmart.org/services/certification/ifc-certification-participants/). In detail, we added information at the global level to the *ifcbuilding* entity, as seen in Figure 3.11, and, as seen in Figure 3.12, information at the local level to each structural element (specifically *ifccolumn*, *ifcbeam* and *ifcslab* entities).

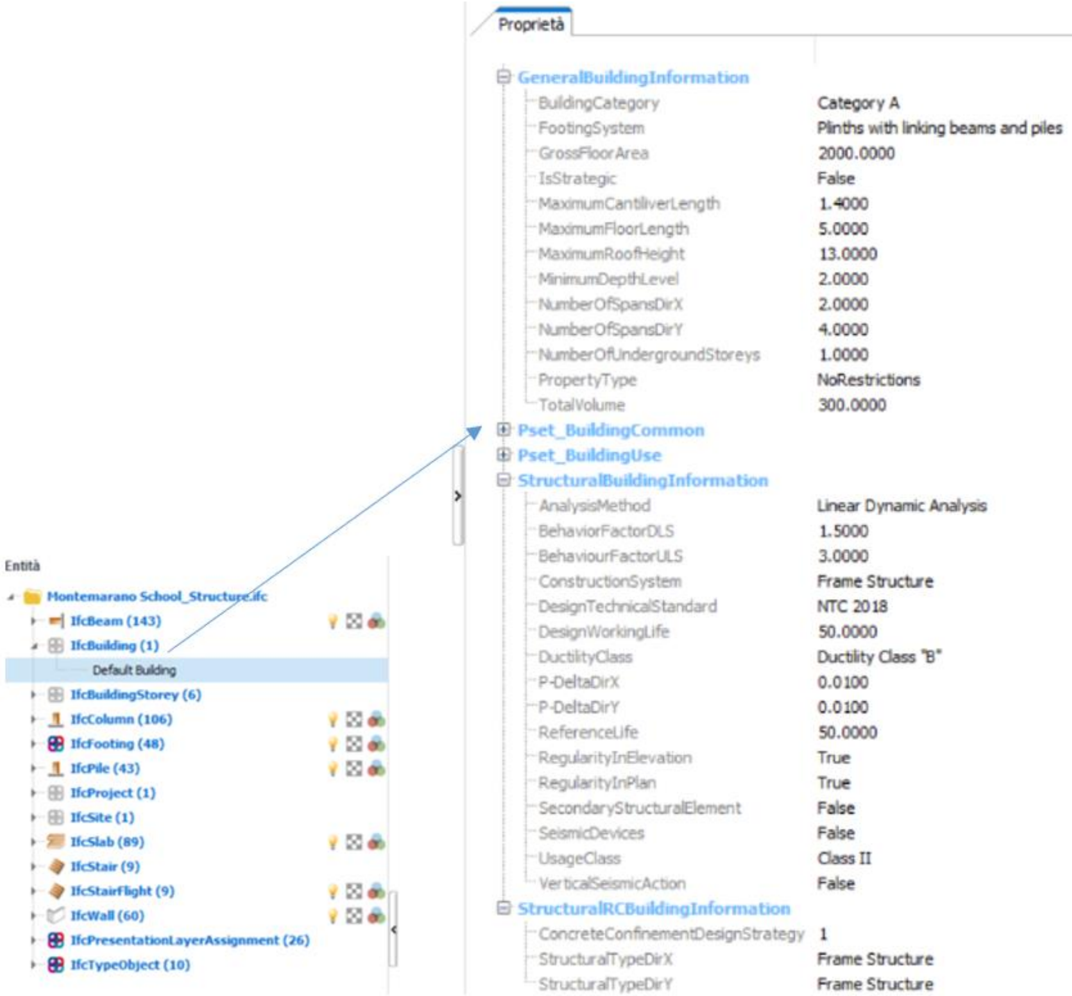


Figure 3.11: The Pset adds information on the structural project at the global level to the ifcbuilding entity.

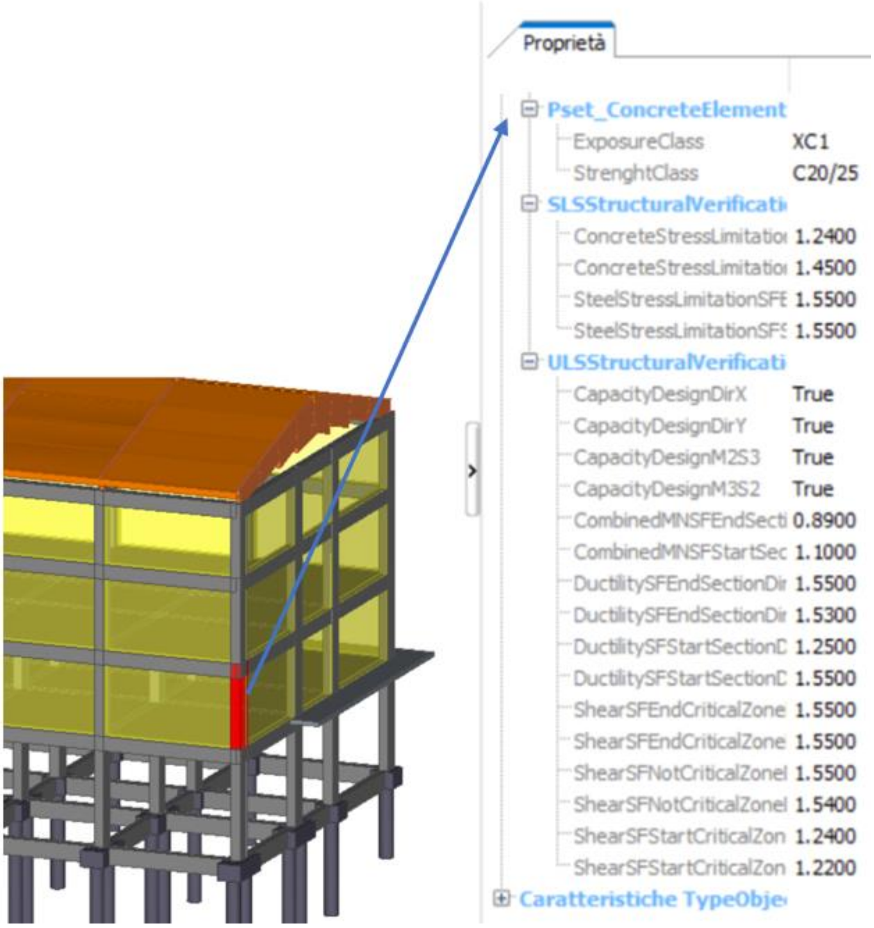


Figure 3.12: The Pset adds information on the structural project at the local level to the ifccolumn entity.

We have simulated the Str.E.Pe. submission process for the Montemarano school project using the ACCA Software® *usBIM.ePermit* platform. After the software revealed that the automatic code-check of the safety factors (SF) had been successful (which means that all the SFs are greater than one), the officers at the building authority used the *usBIM.ePermit* platform to counter-check the compliance of the school structural project with seismic requirements. First, as seen in Figure 3.13, it can see that the automated code-check process was successful; they then counter-check the uploaded documentation by leveraging its links to the IFC model (see Figure 3.14) and using the structural information added to the Psets (see Figure 3.11 and Figure 3.12) to conduct further checks in relation to the structural reports and calculations.

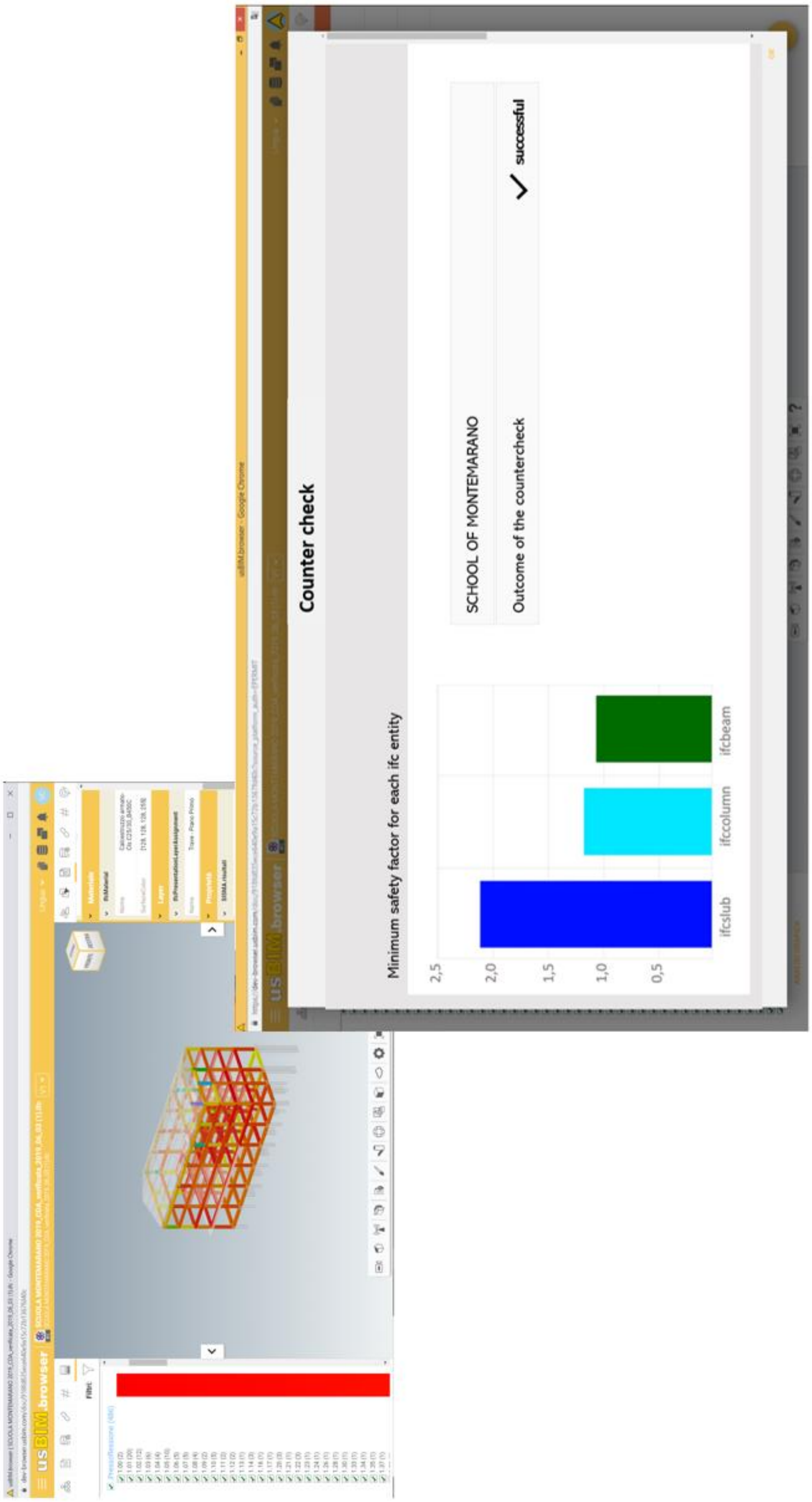


Figure 3.13: The usBIM.ePermit platform produces a positive outcome after the automated code-checking of the safety factors.

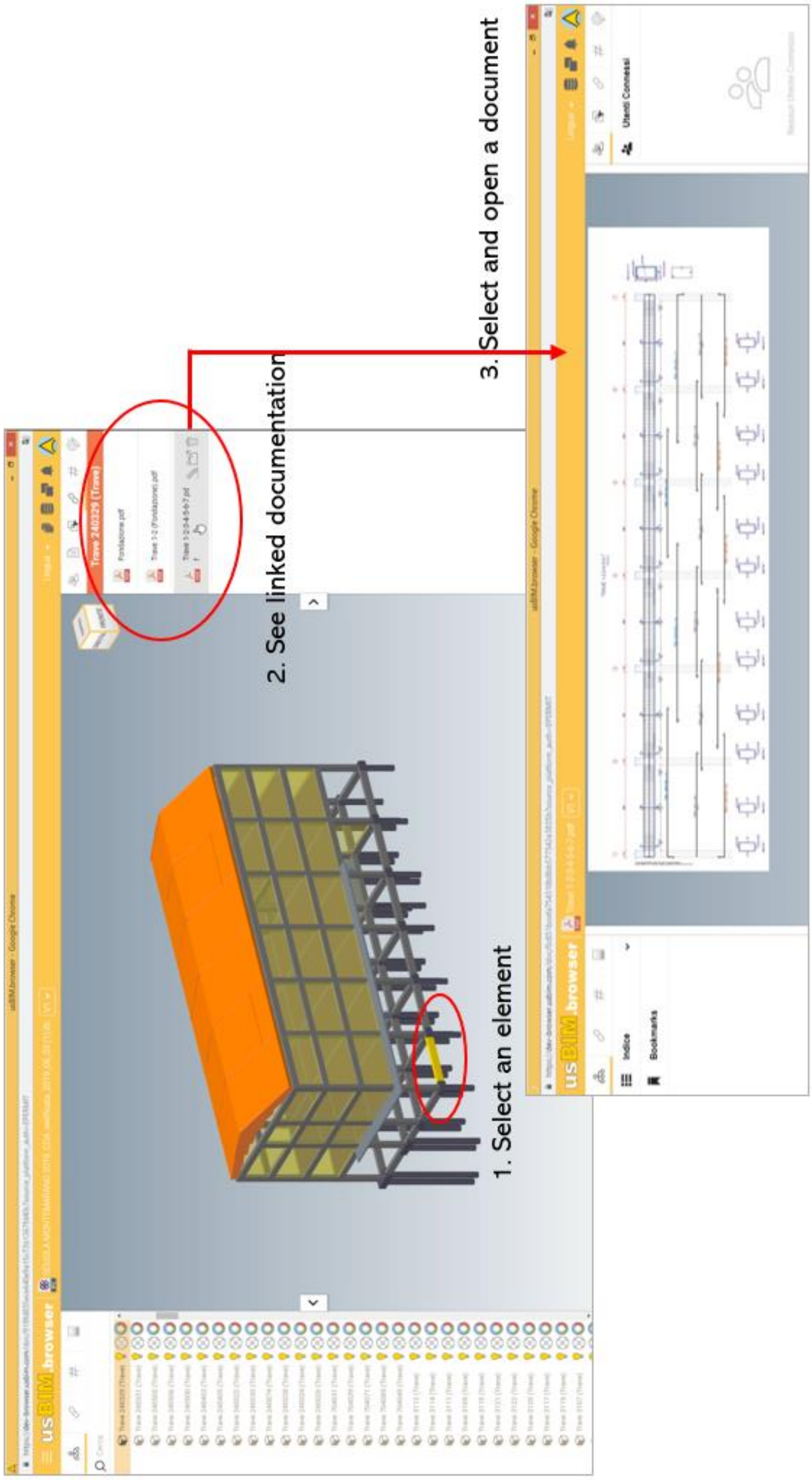


Figure 3.14: Example of the work of a civil engineering technician from a Building Regulatory Body using the Str.E.Pe. platform.

The proof-of-concept ends with the officers releasing the seismic-authorisation permit (no integration required) and uploading it to the *usBIM.ePermit* platform. Finally, the officers assessed the feasibility of the proof-of-concept with a SWOT analysis on using IFC models to support them in assessing the compliance of structural projects with seismic requirements (see Figure 3.15).

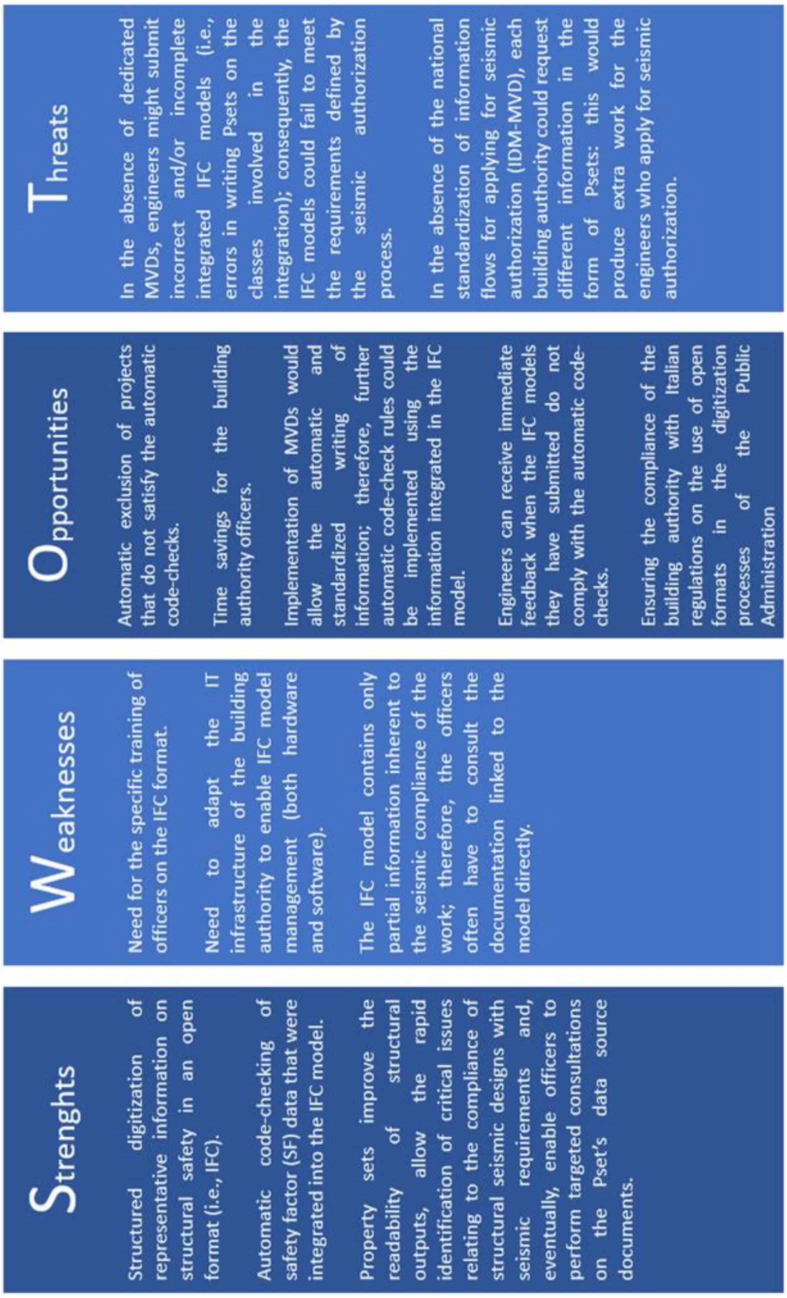


Figure 3.15: SWOT analysis conducted by the building authority of Avellino on using an integrated IFC model to check compliance with seismic requirements.

Concerning strengths, the Avellino building officers valued the fact that the application they receive has already successfully passed an automatic code-check on the requirements of SFs greater than one. After initial work studying the IFC format and leaning to use the *usBIM.ePermit* platform (which are the main weaknesses they encountered), the officers immediately found the opportunity to visualise information on the structural project, directly from the IFC model, to be an intuitive process. In particular, they are able to access linked documentation when necessary, but can also save time when it comes to understanding the overall structural project's setting, which is presented in the Pset at the global level. Moreover, the local Psets enable them to achieve a preliminary understanding of the stresses to which the structural elements are subjected. However, they would prefer to only have to access documentation occasionally, and therefore think that there are opportunities for improvement in defining other automatic code-checking rules and expanding the information they can access directly from the IFC model. These improvements could save time in processing non-compliant applications and, concurrently, speed up the feedback given to the engineers applying for seismic authorisation. Whether the use of an open format like IFCs could also enable the building authority to be compliant with Italian regulations on the digitalisation of processes in public offices was a further issue; the officers raised serious concerns about receiving incorrect or incomplete IFC models from the engineers making the application. They therefore support our investigation into developing an MVD that automatically and correctly exports IFC models for the seismic authorisation process. They also believe that the standardisation of Psets should be done at the national level in order to avoid building authorities developing customised Psets: this would complicate and significantly increase the work of engineers.

3.4 Further developments and conclusions

It is our view that the Str.E.Pe. project fits perfectly within the current research trend of reforming processes for applications to BABs for structural-engineering permits and approvals. Our focus has been on defining the information requirements for seismic-authorisation permits in Italy. This was a starting point for outlining the content that the new MVD under development would allow to convey automatically. Currently, our work on the MVD concerns content definition and the generation of technical documentation (.mvdXML, html, etc.). We also expect to employ: 1) an additional tool like xbimXplorer (source: https://docs.xbim.net/downloads/xbimxplorer.html), which will make it possible to read BIM models in the IFC format (in the different versions of IFC2x3 and IFC4); and 2) .mvdXML files to, for instance, validate the IFC schema and content in terms of entities and related properties, and query the syntax for the data extraction. Of all the available plugins, we intend to use the "buildingSMART mvdXML validation".

In conclusion, the Str.E.Pe. project is a first attempt to do so, using a dedicated MVD for this purpose. We have focused on defining and standardising content that is integrated into openBIM models for transfer to BAB officers: this approach (finally) makes a substantial change to the traditional practices that are still based on the delivery of paper reports and technical specifications. The preliminary proof-of-concept we have deployed in collaboration with the Avellino building authority have proved that the use of integrated IFC models is feasible in the seismic-authorisation process that the building officers implement, provided an initial phase of training on the IFC format and the e-permit platform is provided. Opportunities to save time are also possible if further automatic code-checking rules are implemented. Accordingly, officers support our intention to develop an MVD for the seismic-authorisation process. Unfortunately, deliverables in addition to BIM models in the IFC format are required for applications for structural-engineering permits and approvals; for this reason, we will also focus on defining the information requirements of BABs according to the (recently released) EN 17412-1:2020 standard, which provides guidelines to clarify the depth of the data needed in relation to geometry, additional information, and documentation.

References

[1] X. Wang, *BIM Handbook: A guide to Building Information Modeling for owners, managers, designers, engineers and contractors*, vol. 12, no. 3. 2014.

[2] Y.-C. Lee, C. M. Eastman, and J.-K. Lee, “Validations for ensuring the interoperability of data exchange of a building information model,” *Autom. Constr.*, vol. 58, pp. 176–195, Oct. 2015.

[3] M. Eirinaki *et al.*, “A building permit system for smart cities: A cloud-based framework,” *Comput. Environ. Urban Syst.*, vol. 70, no. March, pp. 175–188, Jul. 2018.

[4] M. Messaoudi and N. O. Nawari, “BIM-based Virtual Permitting Framework (VPF) for post-disaster recovery and rebuilding in the state of Florida,” *Int. J. Disaster Risk Reduct.*, vol. 42, no. June 2019, p. 101349, Jan. 2020.

[5] K. Shahi, B. Y. McCabe, and A. Shahi, “Framework for Automated Model-Based e-Permitting System for Municipal Jurisdictions,” *J.*

Manag. Eng., vol. 35, no. 6, p. 04019025, Nov. 2019.

[6] M. Muto, "e-submission common guidelines for introduce BIM to building process - e-submission common guidelines for introduce BIM to building process Technical Report No. RR-2020-1015-TR," 2020.

[7] "ISO 16739-1:2018 - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries -- Part 1: Data schema." .

[8] R. Reitherman, *Earthquakes and Engineers: An International History*. 2012.

[9] "Building Act 2004 | Building Performance." [Online]. Available: https://www.building.govt.nz/building-code-compliance/how-the-building-code-works/building-act-2004/#jumpto-changes-to-the-building-act. [Accessed: 27-Feb-2019].

[10] "Plan Check Standard Correction Lists | LADBS." [Online]. Available: http://www.ladbs.org/forms-publications/forms/standard-correction-list. [Accessed: 27-Feb-2019].

[11] "ISO 29481-1:2016 - Building information models — Information delivery manual — Part 1: Methodology and format." .

[12] "Eurocode 8: Design of structures for earthquake resistance-part 1: general rules, seismic actions and rules for buildings," *Brussels: European Committee for Standardization*. 2005.

[13] A. Borrmann, M. König, C. Koch, and J. Beetz, "Building information modeling: why? What? How?," in *Building information modeling*, Springer, 2018, pp. 1–24.

[14] L. G. NTC, "Norme tecniche per le costruzioni," *Italian technical norms for constructions*. 2018.

[15] "Edilus ACCA Software." [Online]. Available: http://download.acca.it/Files/Scheda/EdiLus-CA.pdf. [Accessed: 28-May-2021].

[16] "Edificius ACCA Software." [Online]. Available: http://download.acca.it/Files/Scheda/Edificius.pdf. [Accessed: 28-May-2021].

4 Proof-of-concept of the integration of blockchains and smart contracts into information flows in various Common Data Environments

Perspectives on the process of constructing structural systems

4.1 Introduction

The process of constructing structural systems produces a huge amount of documentation that traces human activities on a construction site. While the building information modelling approach introduces common data environments (CDEs) to support document management, communication between them is limited, and mainly involves the use of email and activities susceptible to human error. This chapter proposes a proof-of-concept for the integration of blockchains and smart contracts into information flows used in various CDEs. The focus of the proposal is on reducing human error and increasing the reliability and transparency of decision-making processes on construction sites pertaining to the structural system. To this end, the proof-of-concept introduces smart contracts that have different levels of complexity, with the advanced version comparing information exchanged with data gathered by IoT sensors on site. A first implementation of the proposal is also presented. This chapter proposes a proof-of-concept of the integration of blockchains and smart contracts into information flows that are deployed in various common data environments (CDEs). The goal is to improve reliability and transparency as well as the coordination of data exchanges relating to structural safety during project construction and close-out phases. Whit this in mind, the chapter refers exclusively to the construction process as it relates to structural systems.

Structural and civil engineers, acting as project managers (PMs) and inspectors, oversee construction work and ensure its structural safety by: 1) checking structural materials when they arrive on site; 2) interpreting and analysing the results of tests on these materials; 3) inspecting structural systems to ensure compliance with safety standards and project specifications; and 4) overseeing close-out tests. These tasks are mostly manual and human-dependent, producing outputs like reports (in PDF format) or scanned paper documents, which often require the signatures of multiple parties. This documentation is fundamental for demonstrating the safety and integrity of as-built structural systems and is therefore an essential component of an asset information model (AIM). These documents are mainly exchanged by email (or certified email), with an additional goal being to obtain the signatures of all the parties involved in a project. This process is sometimes still executed manually when digital approaches are unavailable. The efficiency, consistency, and coordination of structural-safety outputs suffer when these traditional approaches are used, causing delays, redundancy, the loss of documentation, and errors due to human-dependent document management.

My research aim arises from the need to overcome inefficiencies and increase reliability and transparency in the management of structural-safety documentation. Consequently, this chapter proposes a proof-of-concept of the integration of blockchains and smart contracts into information flows in various CDEs. The goal is to produce an approach that bypasses obsolete and incomplete data-exchange processes based on email, while concurrently providing a tool to create an immutable, trustworthy source that assembles the entire storyline of the structural-safety information exchanges that take place during the building process. Accordingly, my proof-of-concept introduces smart contracts that have different levels of complexity, with the advanced version comparing information exchanged to data obtained by Internet of Things (IoT) sensors deployed on site. Improving the immutability, transparency, and dependability of structural-safety information and documentation can prevent litigation arising from events on construction sites, because every significant event is traced in the blockchain, which is a verifiable and is a reliable evidence resource. Adopting the blockchain technology may have other benefits, such as encouraging the use of digital, rather than paper-based, documentation, thereby increasing the attention paid to the process of constructing structural systems. Finally, my framework could also be used both to fully integrate any information collected and to coordinate in-situ, automated construction processes relating to structural components (e.g., one that implements additive manufacturing technologies) and traditional construction procedures.

This chapter has six sections, the first of which is the Introduction, where the problem statement and research scope are described. Section 2 contains a brief description of current blockchain applications in the construction sector. Section 3 presents the proof-of-concept for integrating blockchains and smart contracts into information flows employed in various CDEs. Section 4 illustrates the first implementation of a decentralised application (DAPP) that utilises a basic level smart contract. Section 5 describes the testing of my proof-of-concept, which involved comparing the proposed and traditional approaches, while Section 6 contains my conclusions.

4.2 Blockchain technology in the construction sector: a brief overview

Leveraging blockchain technology to improve work processes in the construction industry is a somewhat recent academic research field. Figure 4.1 depicts the results of a query on the Scopus database using the following attributes: TITLE-ABS-KEY (Construction AND blockchain). The first reports identified were from 2016, but their number increased significantly between 2018 and 2020, evidencing the growing attention paid to this research field by the construction community.

Year ↓	Documents ↑
2021	15
2020	187
2019	166
2018	71
2017	26
2016	3

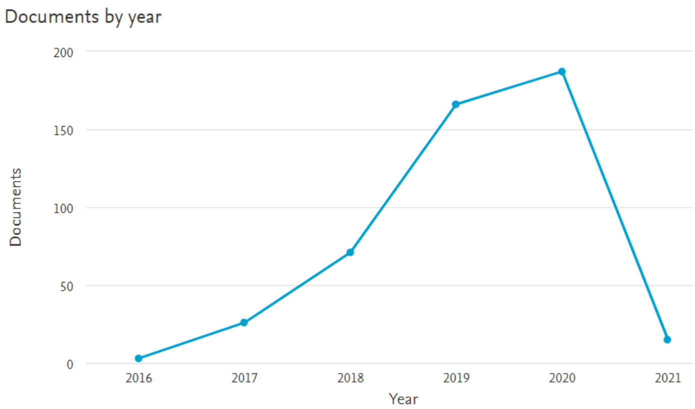


Figure 4.1: Research into the use of the blockchain technology in the construction industry: publications by year (Scopus).

Of the most recent studies, the work by Yang *et al.* [1], which examines an interesting use of blockchains in the construction industry, warrants a deeper analysis. Meanwhile, Li *et al.* [2] provide an in-depth exposition of the adoption of blockchain in other domains of the architecture, engineering and construction (AEC) sector, e.g., real estate, smart cities, and smart energy. The Yang *et al.* [1] study identified 27 relevant reports by authors from 12 countries, including journal and conference papers and book chapters. These are analysed in-depth and classified based on two criteria: (blockchain) integrated with other digital technologies; and the digitalisation of work processes. According to the authors, the integration of blockchain with building information modelling (BIM) technologies is currently the most popular field of research in the construction domain (the study highlighted 13 publications on the subject). Integration of blockchain with the IoT, radio-frequency identification (RFID), and sensors is also investigated (the study highlighted a total of 8 publications on these subjects). Moreover, the digitalisation of work processes mainly affects those processes relating to information management, supply-chain management, and smart contracts and cryptocurrencies (economic management). Yang's team described the following work processes: automatic payments; contract execution (e.g., tendering); construction procurement in the supply chain; supply-chain logistics relating to construction materials; management of data and intellectual property rights in the design phase; recording building performance; registration of land titles; information management for all building stages; and equipment leasing. Other work processes could be added to this list, since this is an open research field. However, Yang *et al.* also noted that most of the publications they reviewed contain only inceptions of such processes, with the few that present proofs-of-concept mainly doing so in relation to cryptocurrencies. This is unsurprising, as the blockchain technology was first applied to cryptocurrencies in 2008 by Nakamoto.

The issue of information management has been addressed by Turk and Klinc [3], Wang *et al.* [4] and, recently, Sheng *et al.* [5] and Elghaish *et al.* [6]. Turk and Klinc first proposed the use of blockchains in archiving operations and when making changes to information models created with BIM-authoring software. Their methodology would enhance trace-back processes for establishing intellectual property rights and responsibilities in the design phase, and commercial enterprises like Bluebeam are currently attempting to implement the approach (available at: https://www.bluebeam.com/). Meanwhile, Wang *et al.* have argued that blockchain can be used to develop notarization-related applications that significantly reduce the time presently needed to verify the authenticity of documentation. In their approach, documents can be stored in a ledger distributed to relevant parties, which is where any creations, deletions and updates are recorded, with the traceability, immutability, and transparency of the blockchain technology ensuring their authenticity. However, in this case, the contribution of Wang's team mainly involves highlighting the possible benefits of a blockchain-based approach to document management; indeed, no possible applications are discussed, and the implications or possible ways of connecting with BIM-based information management are likewise not considered. In contrast, the focus of the current chapter is on this type of application, with Section 5 proposing a blockchain-based solution for document management in the collaborative BIM processes deployed during a project's construction phase.

Sheng *et al.* [5] also focus on the construction phase, and develop a blockchain-based framework for managing the quality of information. Their goal is the provision of reliable and secure information as a way to streamline the management of non-conformances and determine the party responsible for ensuring that quality standards are met. Although this team sets out a solution based on the Hyperledger Fabric architecture [7], which could be promoted and applied in practice, it also acknowledges that the use of blockchain technology in the construction industry is still in its infancy. Consequently, their work requires further development to overcome two fundamental limitations, namely the premises that: participants will agree to use blockchain to manage the quality of information; and that the data on the chain is tamper proof, even though there is no guarantee that fraudulent data will not be uploaded. In this regard, Li *et al.* [8] highlight that improvements can be made by exploring the potential of the co-evolution of the blockchain technology with BIM, the IoT and smart contracts.

Finally, Elghaish *et al.* [6] have proposed a framework involving the use of blockchains in projects that adopt integrated project delivery (IPD) to manage economic flows. The framework would enable core members of a project team to automatically execute all financial transactions (or automatic payments) by coding the three main transactions of IPD projects reimbursed costs, profits, and cost savings as functions of an IPD smart contract. The interoperability between the proposed framework and 5D BIM is also investigated in the study. In this regard, Di Giuda *et al.* [9] argue that blockchain can provide a trustworthy infrastructure for implementing automatic contract executions to support BIM-based processes relating to tenders and payments in the construction phase.

Blockchain applications for the management of the construction supply chain are still in their infancy [10]. However, there are only a few examples of business value in relation to other supply chains that are being delivered by live solutions [11]. Wang *et al.* [12] try to address blockchain applications in the construction supply chain domain, proposing a blockchain-based framework for improving supply chain traceability and information sharing in precast construction. Specifically, they use the functions of a smart contract (named ‘chain-code in the Hyperledger Fabric architecture) to replace fundamental steps in the supply chain for precast construction elements, such as asking, ordering, producing, transporting, and delivering. However, the proposed solution does not include any integration with economic flows and implementations. The ongoing research of Kifokeris and Koch [13] also tries to integrate economic flows with blockchain applications in the construction sector, with Sweden's construction supply chain highlighted as a prolific ground for developing a digital business model right from the start. This is because general contractors and suppliers in the country often turn to independent third-party logistics consultants, who assist in coordinating and handling complex, recurring, and conflicting flows relating to deliveries of materials, arrival of incoming goods, and other sub-systems. A digital business model, according to these authors, could reduce the need for such intermediaries.

A completely new use is combining blockchain technology and additive manufacturing. According to Zhu *et al.* [14], this can enable additive manufacturing in the cloud, and their research applies the game-theory application to establish the prices of 3D-printed components. More precisely, they produce estimations that leverage on-chain data that is automatically updated by IoT sensors communicating with robotic printing devices to record fundamental information from the printing process.

4.2.1 Blockchain technology

Blockchain technology belongs to the wider digital ledger family, of which there are three fundamental types: centralized, decentralized (based on hubs), and distributed. The blockchain approach belongs to the last of these, i.e., distributed ledger technology (DLT). This is a type of data structure that exists across multiple computing devices, called nodes, which are generally spread over locations or regions throughout the internet (IP/TCP) which acts as the base technology for information sharing.The ledger contains records (i.e., transactions), collected into blocks, which are linked using cryptography [15]. A blockchain (and, more generally, a DLT) has four interdependent core layers 1) ledger (record of transactions grouped, in the case of blockchains, into blocks); 2) a peer-to-peer (P2P) network; 3) a protocol, comprising governance (consensus rules); and 4) an application (or data) layer, which contains relations (smart contracts, essentially) that allow information to flow through the system.

Permissionless blockchains use proof-based consensus algorithms, including proof of work (PoW) and proof of stake (PoS), which are the most common ones [16]. These blockchains are also public (e.g., Bitcoin and Ethereum), since anyone can join the network. In contrast, permissioned blockchains like the Hyperledger Fabric framework [7] adopt voting-based consensus algorithms [17]. A permissioned blockchain is also known as a private blockchain, because it requires pre-verification of the parties participating parties within the network, who are usually known to each other. A combination of permissionless and permissioned blockchains is also possible and is known as a consortium blockchain. According to the Blockchain and Distributed Ledger Observatory, "*the main feature of blockchain technology refers to digitizing and transforming data into the digital format*" (source: https://www.osservatori.net/ww_en/observatories/blockchain-distributed-ledger). This feature is combined with other properties:

- Distribution: information is recorded by distributing it among several nodes to ensure IT security and system resilience.
- Traceability: each element (i.e., transaction) on the register is traceable in every respect and can be mapped back to its precise origin.
- Disintermediation: blockchain platforms allow the management of transactions without intermediaries, in other words, without the presence of trusted central bodies.
- Transparency: the content of the register is transparent and visible to everyone (in the public blockchain), as well as easily accessible and verifiable.
- Immutability: once written into the register, the data cannot be changed without the network consent.
- Trust: this is built by the P2P network via the consensus mechanism, with no need for intermediaries, even though there is no trust among the parties involved.
- Opportunity to program transactions: it is possible to schedule actions that take place when certain conditions occur on the blockchain (i.e., smart contracts).

4.2.2 Smart contract

A smart contract is an agreement, written in a machine-readable language, that can execute a part of its function by itself [18]. Self-executed functions consist of predefined actions that are initiated when certain conditions (named 'trigger events') are met in the blockchain system. Commonly, smart contracts are used to automate repetitive processes that rely on the information stored in a blockchain [19]. However, they also have a role of interacting with the blockchain to broadcast transmissions and recall the data stored in blockchain blocks.

4.3 Proof-of-concept: integrating smart contracts and the blockchain technology into BIM collaborative processes used in different CDEs.

Adopting the BIM methodology requires stakeholders to define internal and collaborative processes to support information management throughout the building process. For a specific project, collaboration occurs in the Common Data Environment (CDE), which is defined in ISO 19650-1:2018 [20] as: *"an agreed source of information for any given project or asset, for collecting, managing, and disseminating each information container through a managed process",* where the information container is a "*named persistent set of data and information within a file, system or application storage hierarchy*". The same standard also highlights that there are at least two CDEs: that one of the appointing party and that of the appointed party; the latter is also known as a distributed CDE. A distributed CDE is where collaboration among the stakeholders occurs, meaning there are gateways for the exchange of information between CDEs (i.e., the diamonds in Figure 4.2). The DIN SPEC 91391-1,2:2019 *Common Data Environments (CDE) for BIM projects – Function sets and open data exchange between platforms of different vendors – Part 1 and Part 2* provides reference communication strategies for the CDEs of different vendors, and these deploy application programming interfaces (APIs) specifically to manage milestones and data drops, specifically.

Generally, the stakeholders participating in the building process already have a platform (or a database) for managing and archiving information before work starts on a specific project. The quality and efficiency of these tools depend on a stakeholder's needs and purchasing power. The split can depend on contractual arrangements, functional needs, and technological necessities. Figure 4.2 depicts a possible configuration of CDEs in the construction phase: general contractor, PM, client, design project team, and suppliers, all of which have their own CDE. Information exchanges relating to structural systems can include:

- BIM models.

- 2D shop drawings.
- Technical documentation, e.g., inspection reports, reports of material acceptance and testing certificates.
- Accounting documents, including bills of lading, construction journals and interim payment certificates (*'stato avanzamento lavori'* in Italian).

However, both the technical and accounting documentation is generally in the form of PDFs or, more often, scanned paperwork; in either case, it is exchanged by stakeholders using certified and non-certified electronic mail rather than APIs. As a consequence, the sender has to download documentation from his/her CDE and send it as an attachment to the recipient, who in turn has todownload it from the email and then upload it to his/her own CDE. In addition, metadata is difficult to transfer and the trace-back of versions can be complicated. Moreover, the work of PMs and inspectors becomes more difficult because some emails and attachments can easily be missed. It is, nevertheless, worth noting that this documentation is a fundamental part of the project information model (PIM) for structural systems.

It is my view that the criticalities I have highlighted can be overcome by introducing the Decentralized Application (DApp) tool, which is also based on blockchain technology. This leverages the APIs of CDEs and smart contracts to support exchanges of documentation related to structural systems during the production stage, with particular attention paid to the execution, testing, and close-out phases of the structural system.

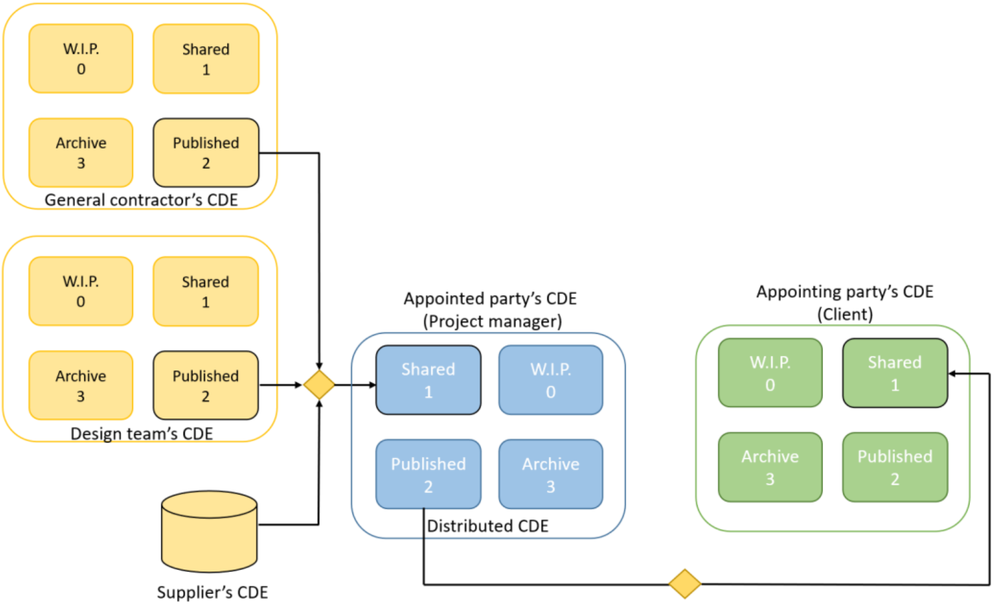


Figure 4.2: Possible configuration of CDEs in the construction stage.

I propose a blockchain-based tool to trace flows of information between CDEs and secure the information containers exchanged. Specifically, the tool will allow:

- The automatic transfer of information containers from CDE 1 to CDE 2.
- The creation and automatic transfer of transmittal documents.
- The creation of Hash fingerprints of information containers to be uploaded on the blockchain (this process is also known as the notarisation of documentation).
- The certification of information flows' principal metadata (sender, recipient, date, type of information container).
- The recall of information from the blockchain to support checking and inspection activities.

Figure 4.3 illustrates the process of transferring an information container.

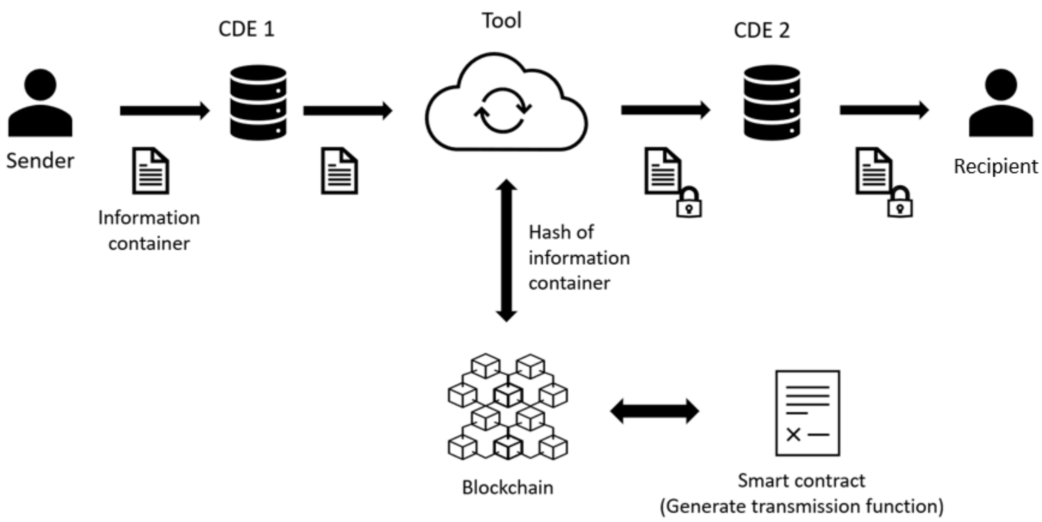


Figure 4.3: Notarization on the blockchain of information flows between CDEs.

The tool leverages the APIs of CDEs to automate information exchanges. Prior to delivering information containers to the recipient CDE, the tool interacts with a smart contract that generates a transmission on the blockchain, which contains Hash fingerprints of the containers (which can be in any format: .pdf, .xls, .doc, .ifc, etc.). I have preferred using a public blockchain in previous section because I have focused on a single project, but it is worth noting that an ad hoc private (or consortium) blockchain could also be used. However, in my opinion, this effort should go along with application to a large number of projects to be managed and a large number of practitioners of the AEC sector to converge.

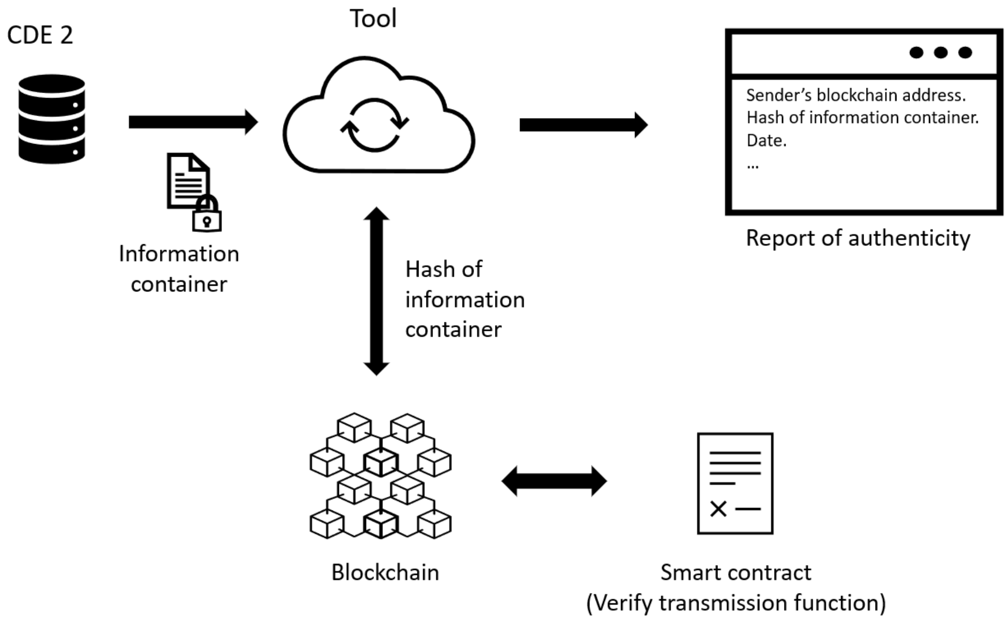


Figure 4.4: Recalling information from the blockchain.

Finally, the smart contract also enables the information containers to be verified, because it can recall information from the blockchain, as depicted in Figure 4.4. I discuss the smart contract capabilities further in section 4.4.

In conclusion, the improved immutability, transparency, and reliability of structural safety information and documentation can prevent litigation relating to construction sites, because all significant events are traced on the blockchain and can be retrieved whenever required.

4.3.1 Levels of implementation of smart contracts

In my view, smart contracts can be implemented in information flows between CDEs of increasing levels of complexity and automation, as reported below.

I. *Basic level*: A smart contract automatically generates a transmission whenever there is a transfer of information containers from one CDE to another. It also records the Hash fingerprint of the exchanged containers. Figure 4.5 depicts an example of this type of implementation for a case of third-party accreditation (universities, testing organisations, etc.), delivering a certificate of testing to the PM's CDE.

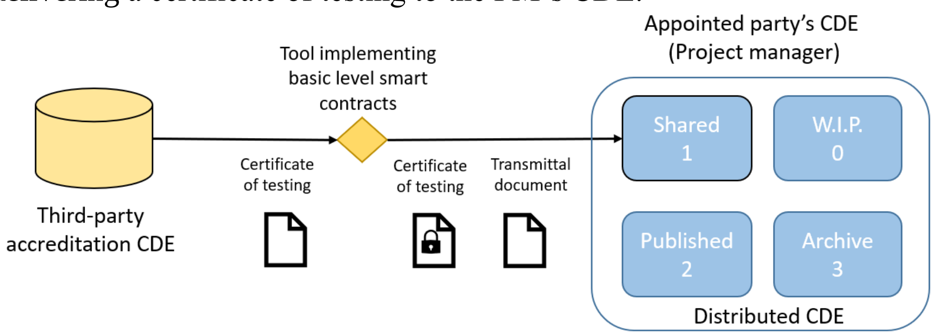


Figure 4.5: Basic level smart contract.

II. *Intermediate level:* A smart contract collects multi-party consents before exchanging information containers and can encompass the functionalities described above. Figure 4.6 depicts this type of implementation as it relates to the case of a PM delivering documentation to a client for interim-payment certificates, which can be approved by the general contractor concurrently.

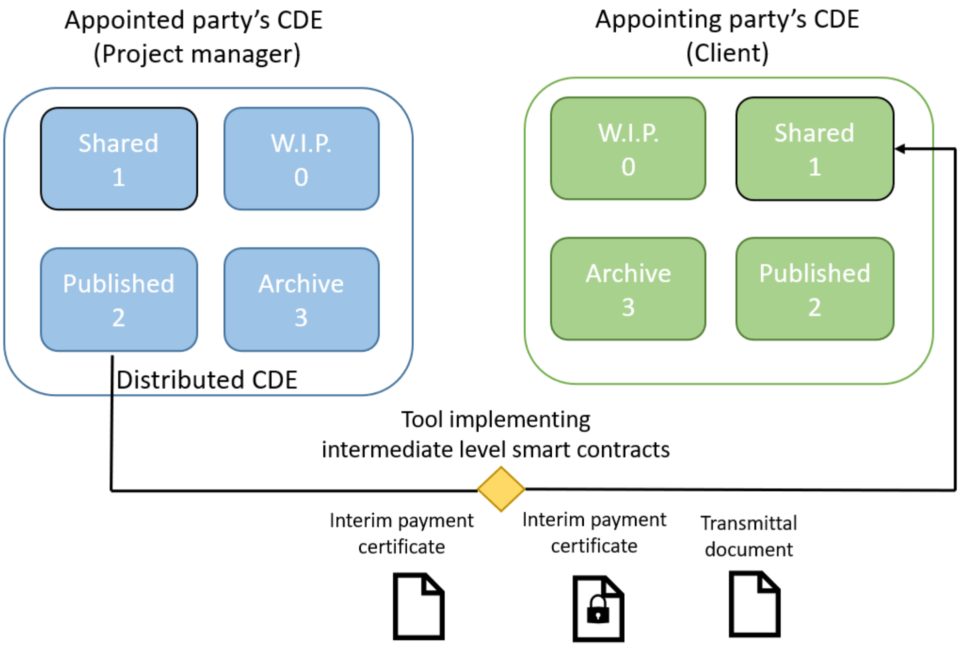


Figure 4.6: Intermediate level smart contract.

III. *Advanced level:* A smart contract performs automatic assessments of exchanged information containers in relation to their format, size, structure, and data content. Figure 4.7 depicts this type of implementation for the delivery of an as-built model for interim-payment certificates. The implementation of IoT systems on a construction site and Artificial Intelligence (AI) algorithms for monitoring construction works will enable automatic assessments of the validity of the exchanged information containers, based on the rules set out in the smart contracts. Ultimately, an AI algorithm will be able to verify the correspondence between the as-built model and the reality on the ground, thereby approving, or at least suggesting the approval of, the interim-payment certificates.

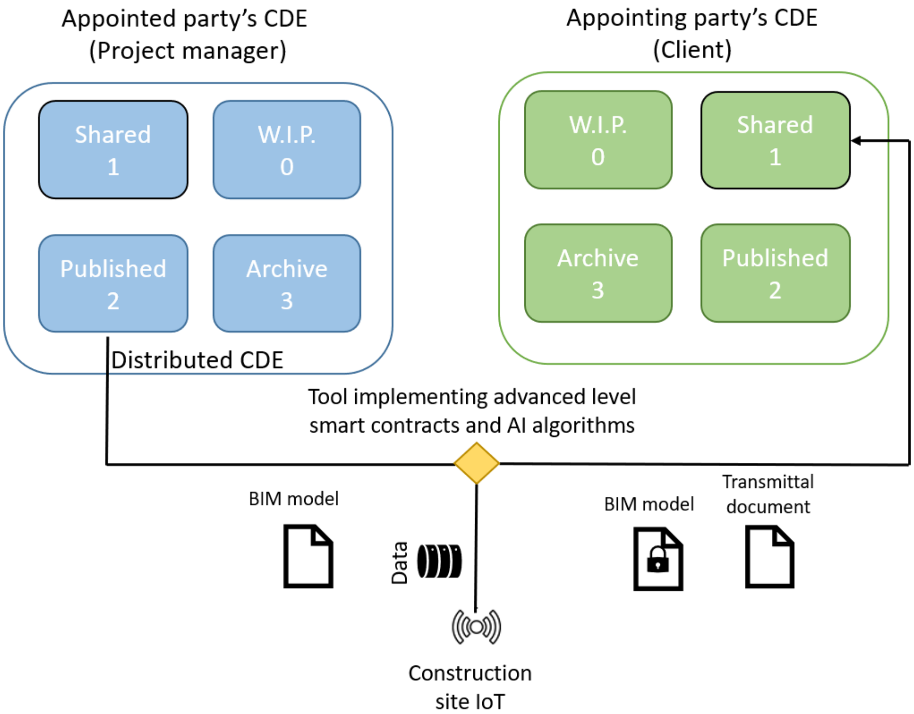


Figure 4.7: Advanced level smart contract.

Levels I and II can address the management of construction-site documents pertaining to structural systems. The purpose of this documentation is to gather information on a construction site that could not be otherwise obtained. This data mostly relates to temporary tasks, and documents that therefore contain it are generally signed by multiple stakeholders at a time to ensure the sharing of liabilities. Level III addresses making improvements to the traditional paper-based approach, which would otherwise be inefficient if in-situ automated construction processes concerning structural components like additive manufacturing were adopted. This level constitutes a significant improvement with respect to the current approach and can solve several additional issues (errors, long time required, etc.) related to the typical and complex tasks performed by humans in this scenario.

4.4 The first implementation of a basic level smart contract

To evaluate the benefits and limitations of the proposed approach, a DAPP was employed to exchange documents between CDEs. DAPPs are able to interact using smart contracts with blockchains and allow users to perform operations via user interfaces developed ad-hoc. I chose to use DAPPs based on the Ethereum blockchain (source: https://ethereum.org), since this was the first one to have a smart contract functionality, and since its native language, Solidity, is the language most frequently employed by developers. Moreover, the use of Solidity guarantees that the code can be reused, even on different blockchains. This is achieved with the Ethereum Virtual Machine (EVM), which is an emulator of the Ethereum blockchain and guarantees the portability of the code. In this first application, files were transmitted between two personal cloud environments that allow simulating data to pass between generic CDEs. Specifically, the Dropbox API was used for data management by the DAPP. Figure 4.8 is depicts the basic level smart contract I have created to communicate with the Ethereum blockchain, using the Solidity language.

```
pragma solidity ^0.5.5;
contract Bcl {
// Defining the structure Transmission
struct Transmission{
address Sender;
address Recipient;
bytes32 FileName;
bytes32 DocType;
uint mineTime;
uint blockNumber;
bytes32 FileHash;
bool Current_version;
bytes32 FileHash_New;
}
bytes32 constant NULL = "";
//Defining a array with the list of transmitted hashes
bytes32[] public ListdocHash;


// Defining the structure map to store the docHashes in order to have
//an accesskey to the Transmission
mapping (bytes32 => Transmission) private docHashes;
constructor() public {
// constructor
}

//Add transmission function
function Add_transmission (bytes32 _FileName,bytes32 _FileType,
bool _NewVersion, address _Recipient, bytes32 _FileHash,
bytes32 _OldFileHash) public {
// If the submitted file is new
if(_NewVersion == true) { // if else statement
//Add new transmission
Transmission memory newTransmission =Transmission (msg.sender,_Recipient,
_FileName, _FileType,now, block.number, _FileHash, true, NULL);
docHashes[_FileHash] = newTransmission;
ListdocHash.push(_FileHash);
```

```
} else {
//If it is a revision: Update the old version
if (docHashes[_OldFileHash].Sender == msg.sender){
docHashes[_OldFileHash].Current_version = false;
docHashes[_OldFileHash].FileHash_New = _FileHash;
Transmission memory newTransmission =Transmission (msg.sender,_Recipient,
_FileName, _FileType, now, block.number,_FileHash, false, _OldFileHash);
docHashes[_FileHash] = newTransmission;
ListdocHash.push(_FileHash);

}}


}

//Return transmission register function
function Return_reg()
public view
returns (address[] memory, bytes32[] memory, bytes32[] memory, uint[] memory,
uint[] memory, bytes32[] memory, bool[] memory) {
//Initialisation of vectors
address[] memory Senders = new address[](ListdocHash.length);
bytes32[] memory FileNames = new bytes32[](ListdocHash.length);
bytes32[] memory DocTypes = new bytes32[](ListdocHash.length);
uint[] memory mineTimes = new uint[](ListdocHash.length);
uint[] memory blockNumbers = new uint[](ListdocHash.length);
bytes32[] memory FileHashs = new bytes32[](ListdocHash.length);
bool[] memory LstVers = new bool[](ListdocHash.length);

//Cycling through all the values I have on the hash list
for (uint i = 0; i < ListdocHash.length; i++) {
Senders[i]=docHashes[ListdocHash[i]].Sender;
FileNames[i] = docHashes[ListdocHash[i]].FileName;
DocTypes[i] = docHashes[ListdocHash[i]].DocType;
mineTimes[i] = docHashes[ListdocHash[i]].mineTime;
blockNumbers[i] = docHashes[ListdocHash[i]].blockNumber;
FileHashs[i] = docHashes[ListdocHash[i]].FileHash;
LstVers[i] = docHashes[ListdocHash[i]].Current_version;

}
//Returning the Register of transmissions
return (Senders, FileNames, DocTypes, mineTimes, blockNumbers, FileHashs,LstVers);

}

function Verfy_trans (bytes32 TdocHashes) public view returns(address,bytes32,
bytes32,uint, uint,bytes32){
if((docHashes[TdocHashes].Recipient == msg.sender ||
docHashes[TdocHashes].Sender == msg.sender) &&
docHashes[TdocHashes].Current_version == true ){
return
(docHashes[TdocHashes].Sender,docHashes[TdocHashes].FileName,docHashes[TdocH
ashes].DocType, docHashes[TdocHashes].mineTime,
docHashes[TdocHashes].blockNumber, docHashes[TdocHashes].FileHash);
}

}

}
```

Figure 4.8: An example of a basic level smart contract in the Solidity language.

The trust of the actors in the identity of those who can actually interact with the smart contract is ensured by the definition, from the beginning, of a list of users identified in the smart contract with their addresses. Moreover, the DAPP associates to each user an intelligible name defined on the basis of the agreements stipulated between the participants. After the distribution of the smart contract on the blockchain, new users can be enabled through a specific function that only the already enabled users can use.

Next, the smart contract handles the transfer of a generic file as a transmission. More specifically, at the beginning of the smart contract, I define the structure of the registry of transmissions where the first seven fields (the address of the sender, the address of the recipient, the name of the exchanged information container, the type of exchanged information container, the Hash function of each exchanged information container; the number of the block, the date), which are immutable, are initialized every time that a file is sent (i.e., a transmission). The last two fields (current_version and fileHash_New) can vary because these allow me to manage the versioning of files. I then implemented the following methods to handle the register of transmissions in the next stage:

- Constructor - this phase is used to initialize the register of transmissions.
- Adding the transmission - this phase is used to add new raw to the register of transmissions, to produce a unique code of the exchanged information container and record on blockchain all the data that describe the structure of the transmission. This also allows a new version of a previously exchanged file to be managed.
- Returning the register of transmissions.
- Verifying the transmission - this step is undertaken to recall the register of transmissions from the blockchain to check the authenticity of a transmission and the corresponding exchanged information containers.

This proposed smart contract enables file authenticity to be managed, the ‘verifying the transmission’ function makes it possible to confirm that a generic file, sent in transmission ‘*i*’, is authentic. This is achieved by comparing a Hash of the file generated when the Hash was uploaded on to the blockchain at the point of the transmission. The proposed smart contract also enables the versioning of a generic file to be managed: the ‘adding the transmission’ function makes it possible to update the version of a previously transmitted file that the system identifies from its Hash. The distinction between a new transmission and a transmission to update a file is managed automatically at DAPP level. Figure 4.9Figure 4.8 depicts the algorithms of the function of the basic level smart contract we have created.

Algorithm 1: Add Actor

```
Input: ActorList,NewActorAddress,NewActorAgreementsRef
ActorList is the set of all static Ethereum addresses which can interact
  with the smart contract. Each address refers to an agreement's
  number.
if Msg.Sender belongs to ActorList then
    Add NewActorAddress and New ActorContract to ActorList
else
    show "ERROR O1: You are not authorized to add actors."
```

Algorithm 2: Add Transmission

```
Input: ActorList,FileName, FileType,FileHash, NewVersion,
       OldFileHash
ActorList is the set of all static Ethereum addresses which can interact
  with the smart contract. Each address refers to an agreement's
  number.
if Msg.Sender belongs to ActorList then
    if Newversion==True then
        Add New transmission to Transmission map
    else
        if Msg.sender == Transmission author then
            Update exsisting transmission from Transmission map with
              new hash
        else
            show "ERROR 03: You are not authorized to update a file
              you did not create."
else
    show "ERROR O2: You are not authorized to Transmit File."
```

Algorithm 3: Check Transmission

```
Input: Transmission
ActorList is the set of all static Ethereum addresses which can interact
  with the smart contract. Each address refers to an agreement's
  number.
if Msg.Sender belongs to ActorList then
    if TransmissionToCheck belongs to Transmission map then
        Return Transmission details
    else
        show "ERROR O6: Transmission not found."
else
    show "ERROR O5: You are not authorized to Check Transmission."
```

Algorithm 4: Return Register

```
Input: Transmission
ActorList is the set of all static Ethereum addresses which can interact
  with the smart contract. Each address refers to an agreement's
  number.
if Msg.Sender belongs to ActorList then
  └ Return Transmission Maps elements
else
  └ show "ERROR O4: You are not authorized to Check Transmission."
```

Figure 4.9: Algorithms of the functions of the basic level smart contract.

4.4.1 Ensuring structural safety and integrity of the structural system during the building process: the Italian perspective

The construction process of a structural system involves several actors, some materially build the structural system while others oversee the construction process with the specific intent to ensure structural safety and integrity of the structural system. In detail, there is:

- Client - who needs and finances the construction process of an asset:
- Project manager (PM) ('direttore dei lavori' in Italian) - who represents the client's interests on the construction site and oversees the entire building process. Generally, he/she has collaborators simply knows as the PM's team.
- General contractor (GC) - who materially builds an asset.
- Sub-contractors - who materially build an asset in a subordinate condition to the general contractor.
- Structure inspector ('collaudatore' in Italian) - who inspects and tests structural systems to assess structural safety and integrity during the construction phase and closeout phase. The structure inspector provides a third-party opinion on structural systems.
- Suppliers - who provide and deliver construction material, such as structural materials and structural components, on job sites.
- Statutory and regulatory authorities - local authorities that oversee all construction process and release permits and authorizations essential to the legitimate construction process and subsequently authorise usability of structures.

- Third-party accreditation (universities, testing organizations, etc.) - who tests structural materials and components.

According to Italian law (Codice dei contratti pubblici, Decreto Legislativo n. 50 del 18/04/2016), the PM is required to:

- Checking that construction works are carried out according to the best practices of civil and structural engineering.
- Checking that construction works are carried out in full compliance with the project's specifications and the contract's conditions.
- Carrying on acceptance of structural materials on the construction site.

In detail, a structural system can consist of pre-cast elements (reinforced concrete and pre-stressed reinforced concrete columns and beams), cast in situ elements in reinforced concrete, manufactured steel elements, and pre-assembled structural systems made with different innovative technologies. The structural system is designed by a structural engineer; he/she defines materials and their mechanical properties, chooses the type of structural system, and assesses its performance according to the reference standards. Finally, the structural engineer provides detailed documentation of the project including plans and technical specifications. A general contractor builds the structural system (in collaboration with sub-contractors) and chooses suppliers that will provide structural materials and components. PM oversees the building process of structures and verifies structural materials and components, and ensures compliance with project documentation. Finally, the structure inspector approves the structural system through in-situ inspections and tests both during the assembling process and at the end. Figure 4.10 goes more into details of the assembling process of structural systems and illustrates the fundamental steps of this process. There is:

1. Approval of suppliers of structural materials and components on the construction site.
2. Delivery of structural materials and components on the construction site.
3. Acceptance of structural materials and components on construction site.
4. Taking samples of structural materials and components on the construction site.
5. Delivery of samples to a third-party organization.

6. Final inspection and test of the entire assembled structural system.

PMs, GCs, and structural inspectors are all liable for the performance of the structural system they oversaw and contributed to build. Currently, these responsibilities are tracked and recorded by means of the complex and extensive paper documentation, enforced by law, summarised in Table 4.1. Documentation is produced and collected during the assembling process of structural systems. Commonly, paper documentation is physically stored in PMs' offices to be delivered to the client in the closeout and handover phase. The adoption of such complex and extended documentation is a tool for dealing with traditional lack of trust among stakeholders on construction site: employer and construction manager-structures do not trust main contractor and sub-contractors, neither suppliers; structure inspector does not trust anyone. Additionally, this laborious practice shows unavoidably its limits when it comes to fast retrieval and exchange of information and to prevent forgery of information.

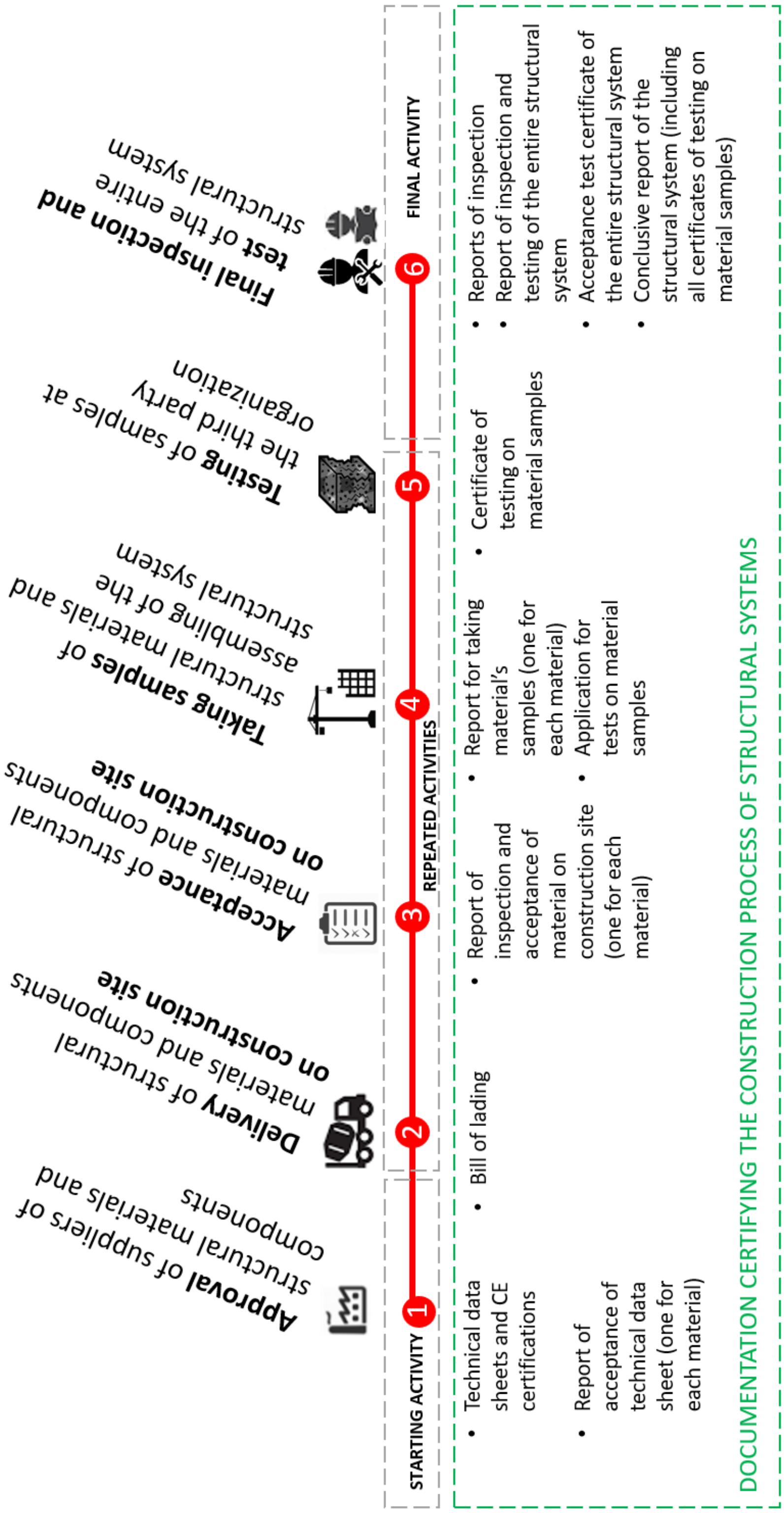


Figure 4.10: The assembling process of structural systems.

Table 4.1: List of documents involved in the assembling process of structural systems.

		Material			Stakeholder		
Document (Italian)	**Document (English)**	**Concrete**	**Steel**	**Pre-stressed concrete**	**Creator**	**Signers**	**Recipient**
Scheda tecnica/Certificati di prodotto	Technical datasheet	X	X	X	Supplier	Supplier	PM, GC
Verbale di approvazione scheda tecnica materiale	Report of acceptance of the technical data sheet (one for each material)	X	X	X	PM	PM, Supplier	Supplier, GC
Bolla di accompagnamento (dal produttore al fornitore e dal fornitore al cantiere)	Bill of lading	X	X	X	Supplier	GC	PM
Documento di sopralluogo/accettazione	Report of inspection and acceptance of material on construction site (one for each material)	X	X	X	PM	PM, GC, Third-party accreditation	GC, Third-party accreditation
Verbale di prelievo	Report for taking samples (one for each material)	X	X	-	PM	PM, GC Third-party accreditation	GC, Third-party accreditation
Richiesta prove	Application for tests on material samples	X	X	-	PM	PM	Third-party accreditation, Client, GC
Certificati di prova	Certificate of testing on material samples	X	X	-	Third-party accreditation	Third-party accreditation	PM, GC

<table>
<tr><td>Verbale di visita di collaudo (visite di sopralluogo)</td><td>Report of inspection</td><td rowspan="4">They concern the entire structural system at the end of construction works</td><td>Structure inspector</td><td>Structure inspector</td><td>PM, Client, GC</td></tr>
<tr><td>Relazione di collaudo</td><td>Report of inspection and test of the entire structural system</td><td>Structure inspector</td><td>Structure inspector</td><td>PM, Client, GC</td></tr>
<tr><td>Certificato di collaudo</td><td>Acceptance test certificate of the entire structural system</td><td>Structure inspector</td><td>Structure inspector</td><td>PM, Client, GC</td></tr>
<tr><td>Relazione a struttura ultimata (contiene tutti i certificati di prova)</td><td>Conclusive report of the structural system (including all certificates of testing on material samples)</td><td>PM</td><td>PM</td><td>Statutory & Regulatory Authorities</td></tr>
</table>

4.4.2 An application in the construction process of structural systems

The process of assembling a structural system requires both practical and supervisory activities to be undertaken at the construction site. General contractors essentially produce the structure, while structural and civil engineers, as PMs and inspection engineers, respectively, oversee the construction work and ensure structural safety by: 1) checking the structural materials when they arrive on site; 2) interpreting and analysing the results of tests on the materials; 3) inspecting the structural systems to ensure compliance with safety standards and project specifications; and 4) overseeing the close-out tests. I demonstrate below the potential of my blockchain-based tool in relation to some of these activities.

Figure 4.11 presents my tool’s user interface. The interface has three areas: the CDE (or database) view (1); the transmission view (2); and the sending area and information container verification (3). It is possible in area 1 to access the information containers via both the CDE and a simple database. In area 2, all the transmissions carried out are viewable, with relevant information referring to the validation on the blockchain (date and block) and the version validity. SQL commands enable the table of transmissions to be filtered to display only the items of interest. In area 3, tools are available to calculate the Hashes of the information containers; this function is used when there are information containers to send and when there are containers to verify once they have been received.

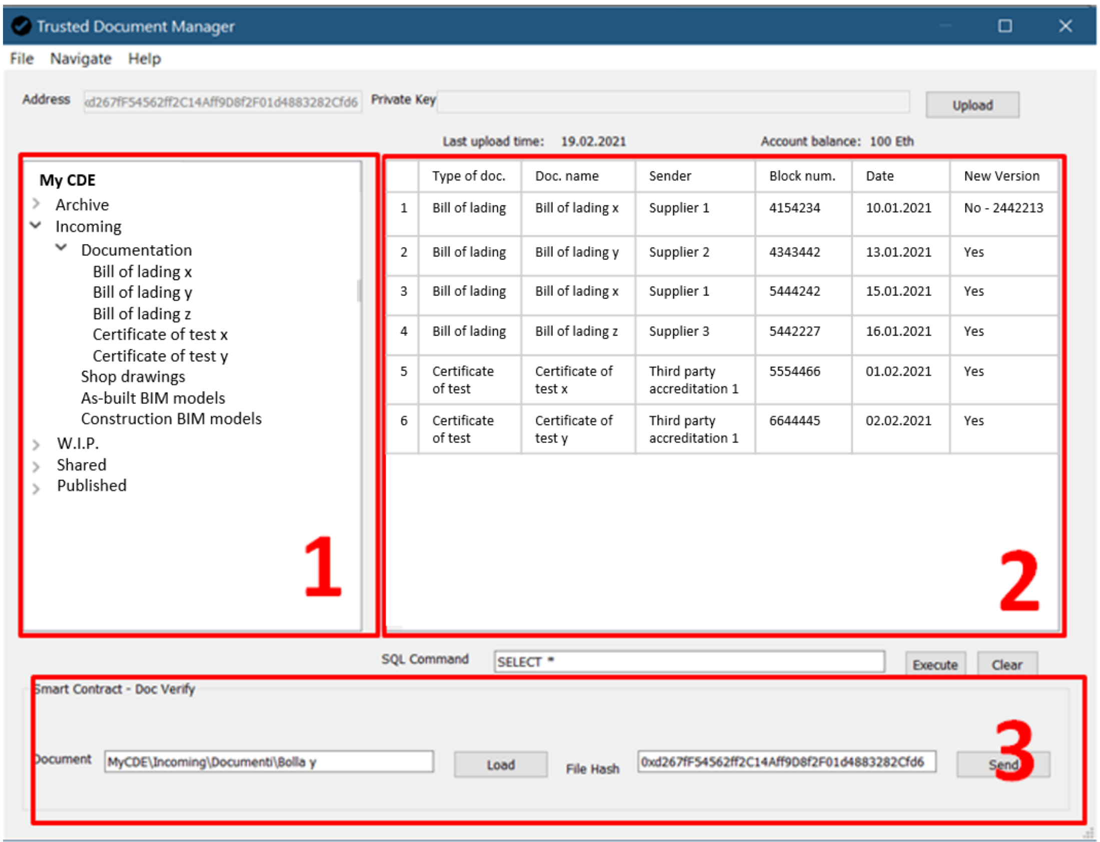


Figure 4.11: Overview of the tool's user interface.

Using the example set out in Figure 4.5, the tool allows an actor with third-party accreditation to explore his/her own CDE in the tree menu on the left of Figure 4.12; concurrently, in the table on the right, he/she is able to see all the transmissions already carried out, which can be filtered using SQL commands. An employee with third-party accreditation then accesses an information container (1), the tool calculates its Hash (2), and the employee transfers it to the distributed CDE of the PM (3).

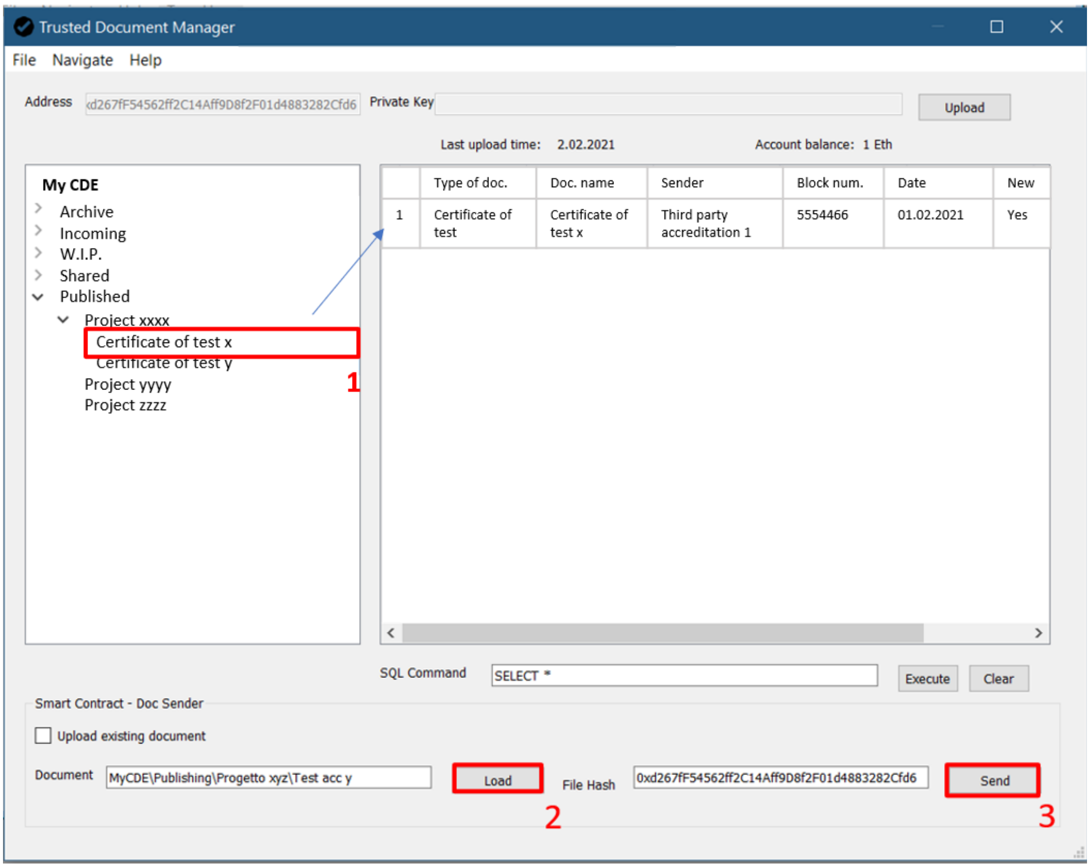


Figure 4.12: Sending information containers.

As seen in Figure 4.13, the inspector engineer (or PM) can use the tool to see all the information containers he/she has received in his/her CDE (the distributed CDE), with the specifications of each transaction displayed on the right. These specifications include information about the sender, the block where the transmission resides, the date and the valid version verification. He/she can also export a report of transactions. Additionally, the engineer and the PM can verify whether the information containers received in their CDE have been certified on the blockchain. Once the structure's inspection engineer has received the final report on the work (‘*relazione a struttura ultimata’* in Italian), he/she must certify the existence of all the attachments contained within it and their formal and substantial accuracy. From a formal perspective, and with my methodology used to implement a basic level smart contract, the tool can be employed to interrogate the smart contract that is adopted to recall information from the blockchain in order to verify the authenticity and validity of all the attached information containers.

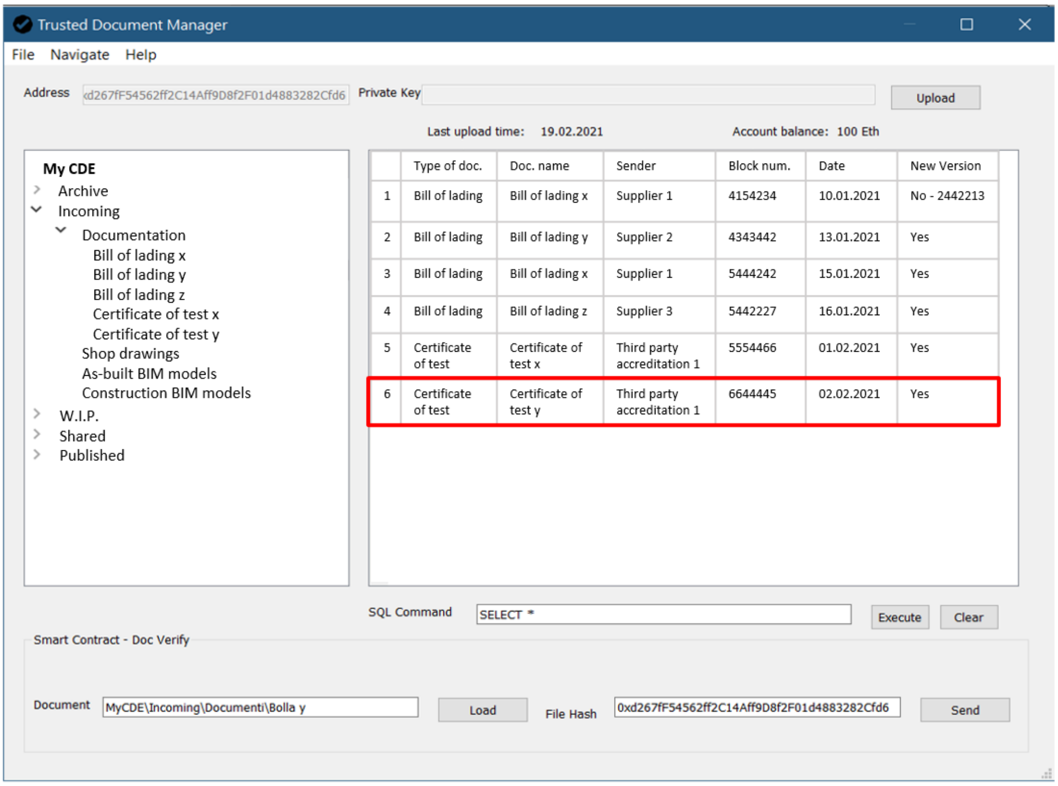


Figure 4.13: Receiving and verifying information containers.

4.5 Discussion and conclusions

My proposal I describe in this chapter uses the blockchain technology to bypass the need for emails and other, even more traditional, transmission channels during a construction project. This is achieved by certifying all the information containers exchanged and their corresponding information flows on the blockchain. This produces a universal and reliable source of information for the inspectors of structural systems both during and following the construction process. Preliminary testing of the proof-of-concept is presented in Table 4.2. Specifically, the proposed methodology has been compared to the traditional approach in terms of the common criticalities that arise in relation to the exchange of information, the reliability of the information, and the transparency of the decision-making process.

Table 4.2: Recap of the solved criticalities and the advantages of the proposal.

	Blockchain-based approach		
Solved criticalities in information exchanges	**Basic**	**Intermediate**	**Advanced**
Sending wrong files.		✓	✓
Sending the wrong version of files.	✓	✓	✓
Sending to the wrong recipient.		✓	✓
Errors in archiving incoming files.	✓	✓	✓
Reliability of exchanged information	**Basic**	**Intermediate**	**Advanced**
Information retrievals from the blockchain ledger.	✓	✓	✓
Automatic collection of the signatures of actors involved in the process.		✓	✓
Checking the correspondence between the exchanged information and recorded data obtained at the construction site by IoT sensors.			✓
Transparency of decision-making processes	**Basic**	**Intermediate**	**Advanced**
Use of certified and reliable data.	✓	✓	✓
Shared and pre-agreed decision-making procedures, which are supported by certified data.			✓

The blockchain-based approach I propose can solve common criticalities relating to the use of the traditional approach which comes with a greater risk of error when transmitting information because it requires human intervention at various stages. In addition, a traditional approach is unable to ensure the reliability of the data transmitted and the transparency of any decisions made, because the activities are largely manual and at the discretion of the people performing them (e.g., PM, inspector of structures, general contractor). Alternatively, the use of an approach based on blockchain technology enables the introduction of smart contracts that employ shared and pre-established procedures to verify the information that is transmitted. This increases the reliability and quality of the data exchanged and the transparency of the decision-making processes because of the level of complexity that is possible with the smart contracts being used; indeed, reliability and transparency are maximized when advanced smart contracts are adopted.

Finally, from my implementation of the blockchain technology and basic smart contracts, I found that the availability of open APIs for CDEs is somewhat limited, despite the indications of DIN-SPEC 91391-1, 2:2019, and that there are clear advantages to drafting the final structural report in the close-out phase, since the information stored on the blockchain can support both the recovery and verification of the reliability of the documentation exchanged.

4.1 References

[1] R. Yang *et al.*, "Public and private blockchain in construction business process and information integration," *Autom. Constr.*, vol. 118, no. February, p. 103276, Oct. 2020.

[2] J. Li, D. Greenwood, and M. Kassem, "Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases," *Autom. Constr.*, vol. 102, no. January, pp. 288–307, Jun. 2019.

[3] Ž. Turk and R. Klinc, "Potentials of Blockchain Technology for Construction Management," *Procedia Eng.*, vol. 196, no. June, pp. 638–645, 2017.

[4] J. WANG, P. WU, X. WANG, and W. SHOU, "The outlook of blockchain technology for construction engineering management," *Front. Eng. Manag.*, vol. 4, no. 1, p. 67, 2017.

[5] D. Sheng, L. Ding, B. Zhong, P. E. D. Love, H. Luo, and J. Chen, "Construction quality information management with blockchains," *Autom. Constr.*, vol. 120, no. February, p. 103373, Dec. 2020.

[6] F. Elghaish, S. Abrishami, and M. R. Hosseini, "Integrated project delivery with blockchain: An automated financial system," *Autom. Constr.*, vol. 114, no. November 2019, p. 103182, 2020.

[7] E. Androulaki *et al.*, "Hyperledger fabric," in *Proceedings of the Thirteenth EuroSys Conference*, 2018, pp. 1–15.

[8] J. Li, M. Kassem, A. L. C. Ciribini, and M. Bolpagni, "A Proposed Approach Integrating DLT, BIM, IoT and Smart Contracts: Demonstration Using a Simulated Installation Task," in *International Conference on Smart Infrastructure and Construction 2019 (ICSIC)*, 2019, vol. 2019, pp. 275–282.

[9] G. M. Di Giuda, G. Pattini, E. Seghezzi, M. Schievano, and F. Paleari, "The Construction Contract Execution Through the Integration of Blockchain Technology," in *Research for Development*, 2020, pp. 27–36.

[10] A. Tezel, E. Papadonikolaki, I. Yitmen, and P. Hilletofth, "Preparing construction supply chains for blockchain technology: An investigation of its potential and future directions," *Front. Eng. Manag.*, vol. 7, no. 4, pp. 547–563, Dec. 2020.

[11] T. Jensen, J. Hedman, and S. Henningsson, "How TradeLens delivers business value with blockchain technology," *MIS Q. Exec.*, vol. 18, no. 4, pp. 221–243, 2019.

[12] Z. Wang, T. Wang, H. Hu, J. Gong, X. Ren, and Q. Xiao, "Blockchain-based framework for improving supply chain traceability and information sharing in precast construction," *Autom. Constr.*, vol. 111, no. April 2019, p. 103063, Mar. 2020.

[13] D. Kifokeris and C. Koch, “Blockchain in construction logistics: state-of-art, constructability, and the advent of a new digital business model in Sweden,” in *Proceedings of the 2019 European Conference on Computing in Construction, July 10-12*, 2019, vol. I, pp. 332–340.

[14] X. Zhu, J. Shi, F. Xie, and R. Song, “Pricing strategy and system performance in a cloud-based manufacturing system built on blockchain technology,” *J. Intell. Manuf.*, vol. 31, no. 8, pp. 1985–2002, Dec. 2020.

[15] M. Pilkington, “Blockchain technology: principles and applications,” in *Research Handbook on Digital Transformations*, Edward Elgar Publishing, 2016, pp. 225–253.

[16] A. Baliga, “Understanding Blockchain Consensus Models,” *Whitepaper*, no. April, pp. 1–14, 2017.

[17] G. T. Nguyen and K. Kim, “A survey about consensus algorithms used in Blockchain,” *J. Inf. Process. Syst.*, vol. 14, no. 1, pp. 101–128, 2018.

[18] M. Swan, *Blockchain: Blueprint for a new economy*. O’Reilly Media, 2015.

[19] J. J. Hunhevicz and D. M. Hall, “Do you need a blockchain in construction? Use case categories and decision framework for DLT design options,” *Adv. Eng. Informatics*, vol. 45, no. November 2019, p. 101094, Aug. 2020.

[20] “19650-1: 2018 - Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 1: Concepts and principles.” 2018.

5 BIM-based workflow for structural maintenance of buildings

5.1 Introduction

Chapter five presents a novel process to manage information in the operation and maintenance phase of structures. The process belongs to a wider framework that has been developed within the BIM-to-CIM research project. The BIM-to-CIM project, literally 'from the building information modelling to the city information modelling', is a research project that aims to innovate the management of the real estate to increase the efficiency of structures and the effectiveness of management processes that affect built structures during their life cycle, through the help of BIM. The BIM-to-CIM project, which is currently in its closing phase, includes structural engineering, architecture, acoustic, systems engineering and urban planning disciplines; the last refers to the geographic information systems (GIS), specifically. The Department of Structures of Engineering and Architecture (DIST) of the Università degli studi di Napoli Federico II (UniNa) has led the BIM-to-CIM project and was responsible for the structural engineering discipline. The project has involved other five partners: the software house ACCA Software is responsible for the development of the interoperable platforms; the Politecnico di Milano (PoliMi) is responsible for the architectural discipline; the Politecnico di Torino (PoliTo) is responsible for the acoustic discipline; the Università IUAV di Venice is responsible for the systems engineering discipline; the Consiglio Nazionale delle Ricerche (CNR) - Instituto di Metodologie per l'Analisi Ambientale that is responsible for the integration with GIS.

The project has involved the development of three interoperable digital platforms using non-proprietary open formats (Open BIM), like Figure 5.1 depicts:

1) An 'Electronic Building Logbook' platform for the management of building information to trace the history of all events that occur in the operation and maintenance phase.

2) ‘Digital Management of the Building Maintenance Plan’ platform to simplify the visualization, implementation and updating of information concerning the maintenance plan of the building.
3) ‘City Information Model’ platform that is a geo-portal for multi-service information sharing and multi-field collaborations, to improve the overall efficiency of urban management on a territorial scale.

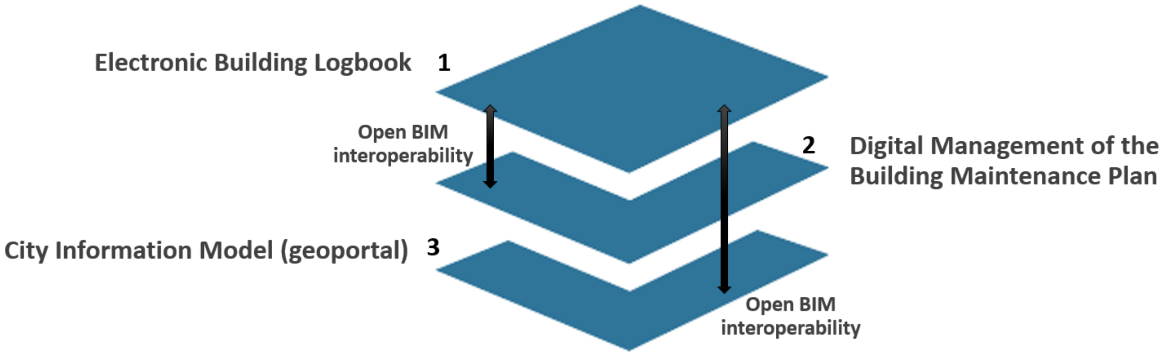


Figure 5.1: The interoperable platforms of the BIM-to-CIM project.

From the point of view of the information management process, platforms are placed in the management phase of the artefact. We therefore speak of an 'Asset CDE', i.e. a collaborative platform for the management of the artefact. The structure of a management platform is certainly linked to the purpose set by the owner of the asset, however Figure 5.2 shows the schematic relationship between a project CDE and a management CDE, highlighting the areas of application for the latter.

The second platform, the ‘Digital Management of the Building Maintenance Plan’ platform, would leverage the same IFC models from the first platform thanks to Open BIM-based interoperability. The other way around, the updated IFC model from the maintenance platform could be seen in its updated form in the building logbook platform either. In detail, the second platform manages federated IFC models of the buildings and implements functionalities that allow the implementation of the maintenance plan for both real estate managers and maintenance workers. The manager could create a maintenance ticket anytime the maintenance plan requires an activity to be done; the ticket, that specifies the appointed maintenance company, closes only when the maintenance worker finishes the maintenance activity updates information on the platform.

In the case a monitoring plan is also planned, the maintenance platform could interact with an IoT module that connects to the sensors installed on the building. This module allows real-time consultation of the monitoring data and eventually preliminary analysis of these. Finally, the last platform concerns territorial management (GIS) of the built environment. This leverages interoperability between BIM and GIS to access building data at the territorial level. These are filtered data that each partner of the project has identified to present synthetic data representative of the building's main features.

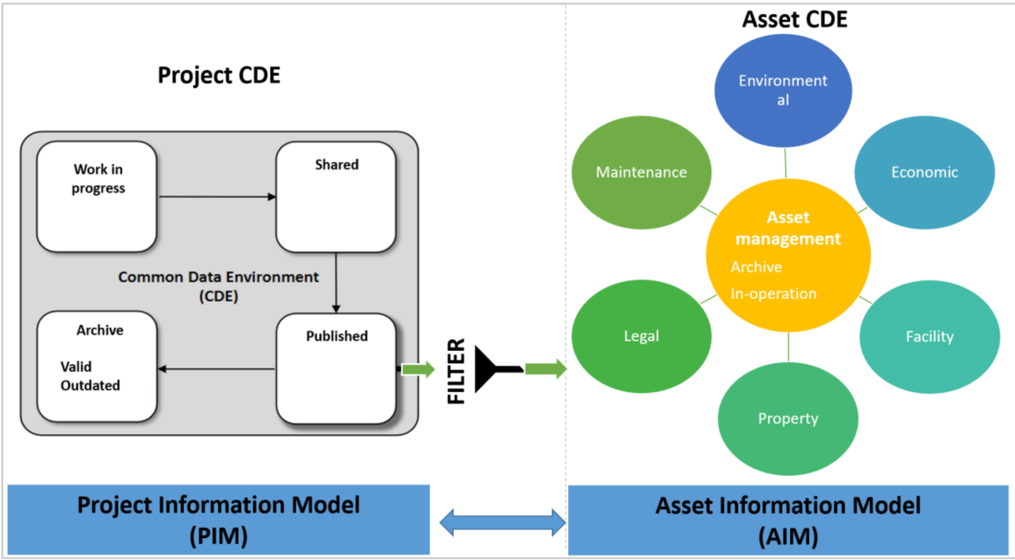


Figure 5.2: Project CDE and Asset CDE.

5.2 The Electronic Building Logbook platform

The ‘Electronic Building Logbook’ platform allows:

- Manging single and federated (i.e. including structural engineering, architectural, acoustic and systems engineering disciplines) IFC models of buildings.
- Storing information containers (i.e. documentation, IFC models, BIM models in proprietary formats). In other words, this corresponds to create the CDE for the asset management of the building (see Figure 5.2).
- Defining and assigning #TAG BIM to information containers to improve and ease their retrieval.
- Linking information containers to BIM objects that constitute the IFC model (or groups of BIM objects).
- Creating new sets of information (datasheets), in .xml or .JSON formats, which can be linked either to BIM objects.

Al posto di un faldone di documenti che ogni volta è necessario aprire in loco, il fascicolo del fabbricato diventa interamente digitale e conta ben tre sorgenti di informazioni tra loro collegate come mostrato in Figure 5.3. La prima è l'archivio, ovvero la piattaforma collaborativa su cui è stato strutturato il CDE dell'asset; i file che costituiscono l'archivio sono dotati di #TAG BIM che ne semplificano l'identificazione e la scrematura. Tra i file, è presente ovviamente anche il modello IFC dell'opera, anche uno per ogni disciplina, da federare poi per ottenere il modello completo. La piattaforma consente di visualizzare il modello e di collegare agli oggetti (o a gruppi di oggetti) di questo specifiche schede. La funzione di link vale anche tra documento e documento per cui la gerarchia per accedere all'archivio e quindi alle schede che costituiscono il building logbook si procede come di seguito: si apre il modello IFC nel browser di progetto, si clicca sull'elemento e si vede la scheda collegata; la scheda ha dati veri e propri aggiornabili all'occorrenza (magari dopo una manutenzione) ed esportabili per analisi e valutazioni se necessario. I datasheet sono collegati a loro volta ai documenti sorgente. La struttura una volta creata resta e le modifiche sono tracciate dalla piattaforma che ha un proprio registro di log.

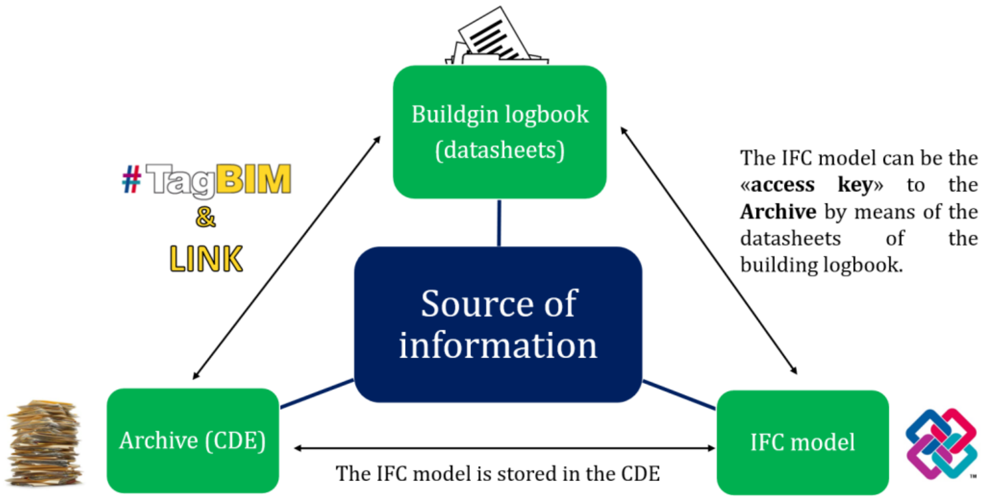


Figure 5.3: The structure of the electronic building logbook.

5.2.1 The datasheets of the structural engineering discipline

Each partner of the project has defined the datasheet templates for the discipline which is responsible for. As jointly agreed, all partners have referred to the UNI 10998:2002 - *Archivi di gestione immobiliare - Criteri generali di costituzione e cura* which defines the structure of the archives for the real estate management (see Figure 5.4).

APPENDICE A (normativa)	ANAGRAFICA IMMOBILIARE	15
A.1	Gestione dell'archivio	15
A.2	Identificazione di un sistema edilizio	15
A.3	Individuazione dei soggetti afferenti ad un sistema edilizio	15
A.4	Descrizione generale e sintetica di un sistema edilizio	16
A.5	Elaborati grafici raffiguranti i sistemi edilizi	17
APPENDICE B (normativa)	REQUISITI COGENTI	19
B.1	Tutela ambientale	19
B.2	Contenimento dei consumi energetici	19
B.3	Igiene e sicurezza edilizia	19
B.4	Agibilità edilizia	20
B.5	Prevenzione incendi	20
B.6	Conservatoria e catasto	20
B.7	Vincoli immobiliari	20
B.8	Produzione e/o trasformazione immobiliare	20
B.9	Strutture portanti	21
B.10	Impianti tecnologici	21
APPENDICE C (normativa)	ESERCIZIO IMMOBILIARE	22
C.1	Economia e finanza	22
C.2	Valori immobiliari	22
C.3	Contesto, prestazioni ed esigenze	22
C.4	Riqualificazione immobiliare	22
C.5	Manutenzione immobiliare	22

Figure 5.4: Contents of the archives for the real estate management according to the UNI 10998:2002.

UniNa-DIST was responsible for the structural engineering discipline and identified, from the study of the contents of the UNI 10998:2002, three datasheet templates. These are shown in Figure 5.5.

REQUISITI COGENTI UNI 10998 – Appendice B		
B.3 IGIENE E SICUREZZA EDILIZIA		**DOCUMENTI DI PROVENIENZA**
Rischi derivanti da calamità naturali	– Rischio sismico: indicazione della risposta sismica locale o di sito (PGA e Spettro di Risposta Elastico) – Stabilità dei pendii – Liquefazione – Dissesti idrogeologici	Relazione Geologica consegnata al genio civile
B.5 PREVENZIONE INCENDI		**DOCUMENTI DI PROVENIENZA**
Classificazione (Generale)	– Tipo di edificio – Altezza antincendi – Massima superficie compartimento – Massima superficie scala per piano – Tipo vani scala e ascensore – Caratteristiche REI di vani scala, ascensore, filtri, porte, elementi di suddivisione tra i compartimenti	Asseverazione ai fini della sicurezza antincendio
Comportamento al fuoco	– Resistenza al fuoco – Reazione al fuoco dei materiali	Cert Rei (per elementi strutturali) Dichiarazione inerente i prodotti impiegati ai fini della reazione e della resistenza al fuoco Allegati • certificati di prova • rapporti di prova • rapporti di classificazioni • alternativa • riferimenti documentali previsti dalla marcatura CE • allegati grafici
Aree a rischio specifico	– autorimesse – locali di esposizione o vendita – depositi di materiali combustibili	Relazione tecnica specifica
Impianti	– Impianti produzione di calore – Impianti elettrici – Impiego gas – Impianti antincendi – etc.	Dichiarazione di corretta installazione e funzionamento dell'impianto. Certificazione di rispondenza e di corretto funzionamento dell'impianto.
Deroghe	Informazioni specifiche per i vari casi con descrizione della situazione da derogare	Documentazione specifica emessa dai VVF

B.9 STRUTTURE PORTANTI		DOCUMENTI DI PROVENIENZA
Indagini geotecniche	Coesione, angolo di attrito, $V_{S,30}$, quota piano di falda	Relazione Geotecnica consegnata al genio civile
Sovrastruttura	Breve descrizione di: – tipologia strutturale – numero di unità strutturali – materiali (c.a., acciaio, etc.) – principali dimensioni in pianta e in altezza – n° piani e n° campate	Relazione Tecnica Generale e Elaborati grafici che afferiscono alla disciplina strutturale consegnati al genio civile
Fondazione e Sistemi di Sottofondazione	Breve descrizione di: – tipologia (superficiali, profonde) – materiali – principali dimensioni	Relazione sulle Fondazioni consegnata al genio civile
Eventuali interventi	– Breve descrizione, per ciascun intervento, di: – data – tipologia – parametri sintetici di vulnerabilità (se calcolati)	Relazione Tecnica Generale e Relazione di Calcolo consegnata al genio civile

ESERCIZIO IMMOBILIARE UNI 10998 – Appendice C		
C.5 MANUTENZIONE IMMOBILIARE - STRUTTURE		DOCUMENTI DI PROVENIENZA
Manutenzione ordinaria e straordinaria	Individuazione delle unità tecnologiche oggetto di manutenzione afferenti la disciplina strutturale	Manuale di manutenzione
	Breve descrizione, per ciascuna unità tecnologica, di: – Requisito di prestazione – livello minimo di prestazione	Programma di manutenzione – Sottoprogramma delle prestazioni
	Breve descrizione, per ciascuna unità tecnologica, di: – Tipo di controllo (degrado e danneggiamento) – Data	Programma di manutenzione – Sottoprogramma dei controlli
	Breve descrizione, per ciascuna unità tecnologica, di: – Tipo di intervento – Frequenza e durata – Risorse	Programma di manutenzione – Sottoprogramma degli interventi
Eventuali monitoraggi	Breve descrizione di: – Tipologia – Frequenza e durata (date inizio – fine; inizio – in corso) – Localizzazione delle aree di indagine e dei punti di monitoraggio – Parametri misurati (cedimenti, accelerazioni, etc.)	Relazione Tecnica di Monitoraggio Strutturale e Piano di Monitoraggio

Figure 5.5: Datasheet templates for the structural engineering discipline.

The datasheets provide sets of information to link to the IFC model of the building and identify the source of this information. This first platform, therefore, uses IFC models as the basis to achieve the digitization of the building logbook: the information is stored in both IFC models and information containers that the ‘Electronic Building Logbook’ platform stores. This acts like the CDE for the asset management phase. Additionally, information containers can be linked to IFC models, therefore, the accessibility to information starts from the model in place of the archive of documentation (see Figure 5.9).

5.3 Implementing a BIM-based workflow for the structural building logbook

In this section, the building logbook regarding the structural discipline is presented.

Figure 5.6 presents a view of the IFC model of the pilot case study from the Electronic Building Logbook platform. More precisely, this is a federated IFC model that integrates architecute and structural disciplines.

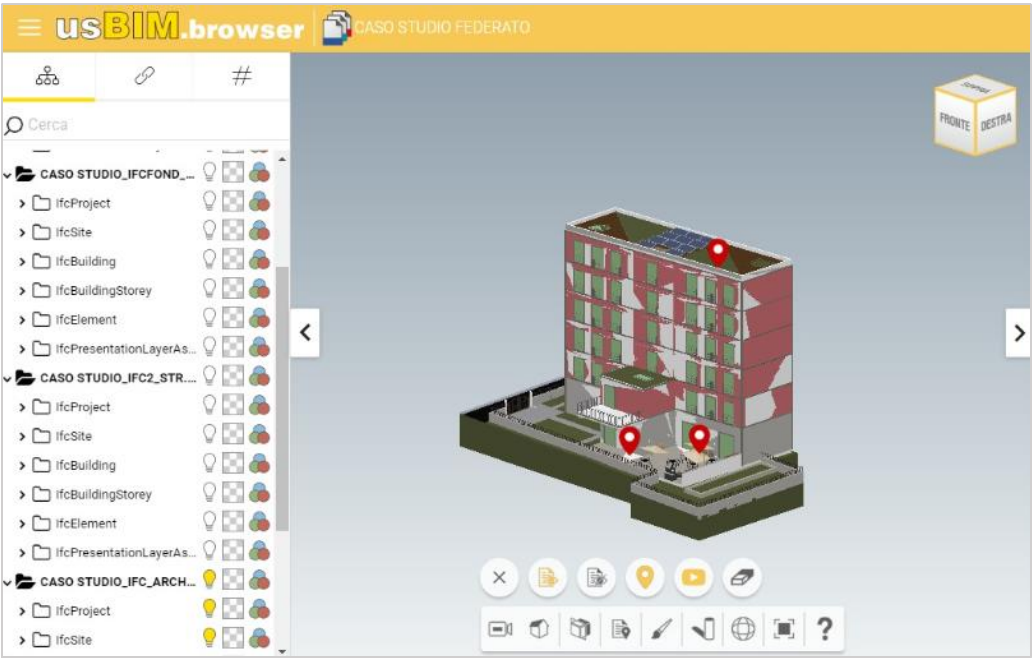


Figure 5.6: Implementation of the building logbook for the structural engineering discipline.

Figure 5.7 depicts the IFC model of the structure. The technical report of the entire structure has been linked to a ‘*multiple selection of IFC objects*’, i.e. the entire structure.

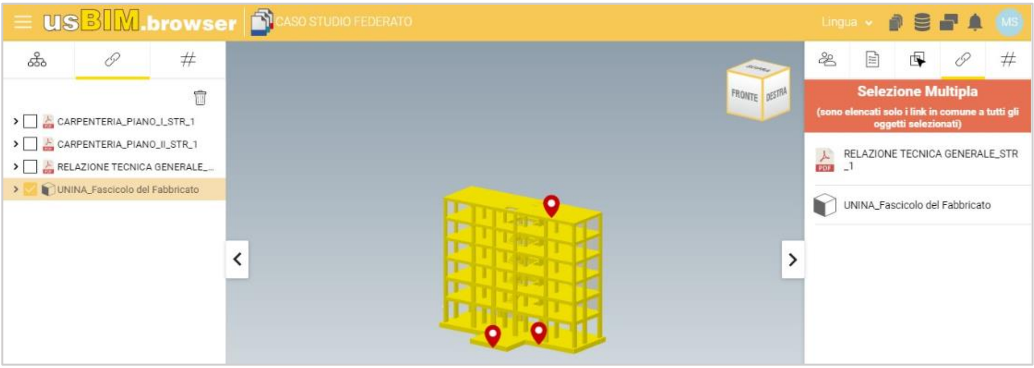


Figure 5.7: The IFC model of the structural engineering discipline.

Figure 5.8 depicts the implemented #TAGBIM and the marks that indicate the datasheets of the structural discipline.

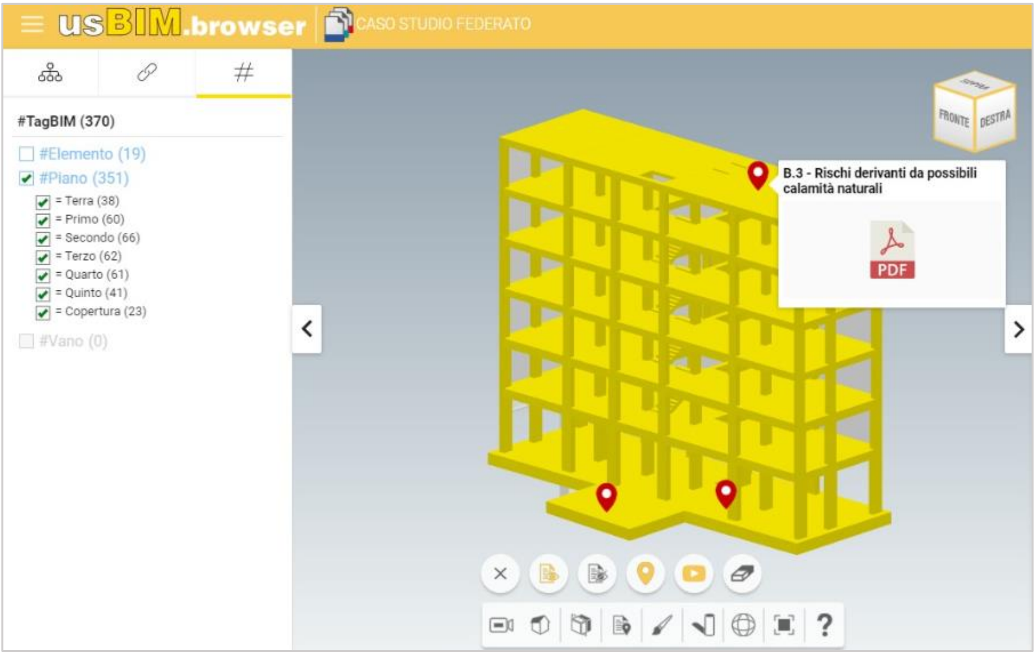


Figure 5.8: Marks and #TAGBIM .

Figure 5.9 depicts the steps to follow to access a structural datasheet.

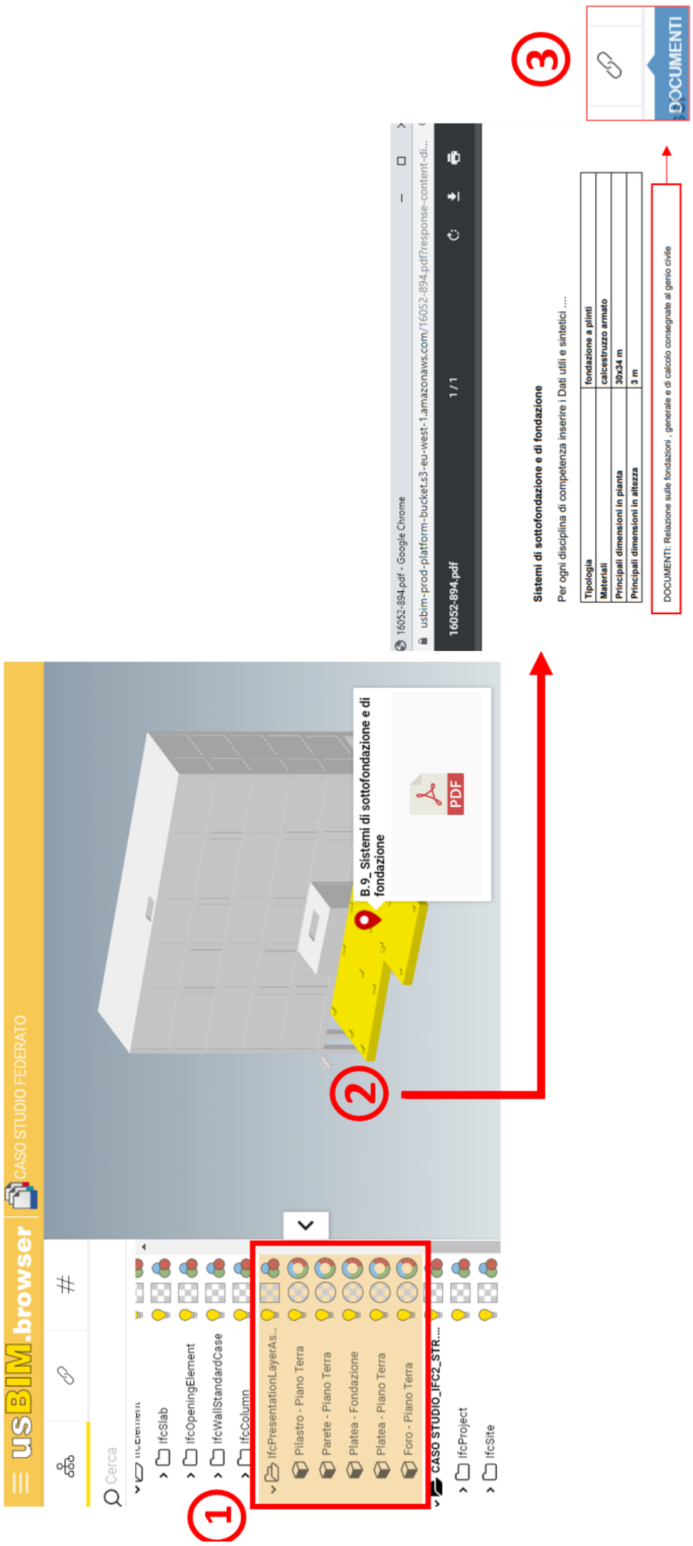


Figure 5.9: Accessing the structural datasheet from the IFC model.

5.4 Conclusions

In conclusion, this platform was specifically intended for public administrations (but also for private individuals who own large building heritages) for the evaluation of strategic actions for the management of the built heritage. From the structural engineering perspective, this platform could allow better and planned evaluation of intervention scenarios on the built environment in terms of retrofit interventions [1].

References

[1] U. Vitiello, V. Ciotta, A. Salzano, D. Asprone, G. Manfredi, and E. Cosenza, "BIM-based approach for the cost-optimization of seismic retrofit strategies on existing buildings," *Autom. Constr.*, vol. 98, pp. 90–101, Feb. 2019.

6 Discussion

In this Chapter, the main research findings that relate to Chapters 2, 3 and 4 are discussed.

6.1 Discussion on Chapter 2

In Chapter 2, I have presented the state of the art of BIM in structural engineering since I found out that no real state-of-the-art or account of contemporary experience is available on the subject. The 2019 bibliometric literature review by Vilutiene *et al.* [1] does examine (automatically) a very large number of publications (over 300), identifying variations in the main topics and keywords over the last decade and adopting clusters to present in-depth analyses of the data obtained. However, in my opinion, these interesting results do not provide a state-of-the-art or an account of contemporary experience on BIM applications in structural engineering, because there is no presentation of detected methodologies and applications, which I regard as essential. My traditional and manual approach was fundamental to enable me to analyse possibly relevant publications in order to highlight content that refers to structural engineering specifically. In fact, a preliminary analysis of the examined papers in Vilutiene *et al.* [1] reveals substantial contamination from fields such as construction engineering and architecture, explaining the significant difference between their methodology and the Authors' traditional literature review, which considered just 45 papers in great detail. Moreover, my focus is not on the technical features of software tools for use in information modelling and structural analyses for specific reasons: 1) how quickly these tools now change and the high number of applications available, which makes it difficult to produce an exhaustive list; and 2) in an attempt to prevent readers being conditioned with specified opportunities and limitations; instead, the Authors preferred to illustrate workflows and discuss information exchanges to highlight innovations for structural engineering arising from the BIM approach.

In detail, the methodology that I have followed comprised a traditional literature review and a qualitative in-depth analysis of the publications identified. This has enabled me to distinguish six main areas of research and the corresponding BIM uses in terms of their: workflows; information exchanges; employment of information models; and limitations. Consequently, Chapter 2 contains an extensive account of the contemporary experience.

BIM-uses 1 and 2, which are typical of the design phase, are currently employed by practitioners and represent my initial research on the involvement of BIM in structural engineering processes (see the results of the literature review in Table 2.1). In relation to BIM-use 1, interoperability issues between BIM-authoring software and BIM tools for structural calculations have attracted the attention of researchers in the past but are no longer a major research issue. Indeed, the focus of studies today is on the development of new work procedures to improve the effectiveness and efficiency of current design processes.

This is also the case for *BIM-use 3*, which focuses on leveraging BIM tools and methodologies to optimize early-stage structural design processes consistent with specific economic and construction criteria. Generally, this optimization involves elaborate procedures that require a capacity to develop more than one solution at the same time to identify which is the best. In reality, there is no single optimum solution in structural design, but there may be one that is the best in certain circumstances, consistent with established criteria. The issue of optimization struggles for inclusion in projects using traditional tools, because it is a time-consuming procedure and depends on the availability of information that is required in advance. The focus of most researchers is still on defining and standardizing BIM-based processes to improve structural designs. Nevertheless, the Authors have not included a specific workflow for BIM-use 3 in this paper, because of the high number of optimization approaches available and the subjectivity of the criteria adopted. Over the next few years, further developments could, however, be fostered by the new and emerging technology of artificial intelligence (AI) [2], [3]: indeed, a recent trend involves using integrated BIM and AI technologies to enable generative designs that aim to resolve complex optimization problems that may arise in the structural design stage [4].

In *BIM-use 4*, the Authors highlight the potential of the BIM approach to increase the use of more sophisticated design methodologies on the ground, especially for seismic risk assessments (e.g., PBEE, damage analyses). These consider non-structural (and, therefore, multidisciplinary) elements in the structural design phase, and thus struggle to be adopted in (traditional) current practice, because these analyses can be complex, expensive, and time-consuming. Research is focusing on developing simplified procedures for seismic risk assessments that can exploit information models to extract inputs for analyses and present results effectively. Such methodologies would be particularly valuable in countries like Italy, where there are territories with high seismic activity, and where both public and private clients may start to demand better structural performances than those guaranteed by the current building code. Further research is, however, required to define a (or an expanded) reference BIM-based workflow.

In *BIM-use 5*, the Authors demonstrate that the BIM approach can be used in existing structures in relation to the assessment of structural performance, the (optimized) design of structural retrofits, and knowledge management. Intentionally, the Authors have first underlined a substantial difference between this case and the use of BIM in new structures: the absence of the information models produced in the preliminary design phase for new buildings and, therefore, the requirement to create models starting with surveys of real assets and studies of corresponding 2D documentation, which may be unreliable or unavailable for both the design and construction phases (e.g., a requirement to deposit documentation with building regulatory authorities was only enforced in Italy in 1971). Nevertheless, the Authors provide a workflow that applies to undamaged existing structures, which is a common scenario, but existing structures that have sustained damage must also be considered in the future. In 2019, Musella *et al.* have conducted preliminary research on using a combination of BIM and AI to assess seismic damage in post-earthquake scenarios through image processing. However, further work is necessary in this regard, as well as with respect to the development of frameworks that combine collaboration platforms and information models to create central databases for organizing, retrieving, and managing data relating to in-situ tests and inspections.

Finally, *BIM-use 6*, which refers to the operation and maintenance phase of structures, is extremely sectoral, but can, at the same time, also represent a stand-alone design objective. As seen in the analysis in Table 2, the applications of the BIM approach to SHM mainly concern bridges, which are infrastructures where the structural engineering discipline is dominant. The interest of the scientific community in the combined use of BIM and SHM is very recent, which is particularly demonstrated by the high number of conference proceedings among the publications identified. However, the topic is more complex than the other BIM uses, requiring the evaluation of strategies for integrating tools to: conduct monitoring (briefly referred to as the internet of things (IoT)); update information models, and provide input data for SHM.

6.1.1 Relationship between model and process in the BIM approach

Unfortunately, the BIM acronym is often, and improperly, thought to be synonymous with BIM-authoring software, leading to a misleading notion that it is more performance software than CAD. In reality, there is a relationship between model and process in the BIM approach, with each being essential to the other. According to the Authors, having good knowledge of the technology and tools used to create information models is unproductive if the information stored is not the result of informative processes that ensure its consistency and integrity. Information is crucial in the BIM approach, and so its quality is the key factor in whether a project will, or will not, be successful. In other words, BIM tools and methodologies are a way to safeguard the quality of the information provided by the AEC industry throughout the lifecycle of a facility and in relation to all of the disciplines involved in a project. The resulting information models and related information containers contribute to the definition of both a project information model, from the concept stage to the handover and close-out phases, and to an AIM in the operation and management stage. The Authors' conclusions are set out in section 6 below.

6.2 Discussion on Chapter 3

In Chapter 3, I present the outcomes of the Str.E.Pe. project that perfectly fit within the current research trend of reforming processes for applications to BABs for structural-engineering permits and approvals. The project's focus has been on defining the information requirements for seismic-authorisation permits in Italy. This was a starting point for outlining the content that the new MVD under development would allow conveying automatically. Currently, the University of Naples Federico II is working on the MVD in terms of content definition and the generation of technical documentation (.mvdXML, html, etc.). We expect to employ: 1) an additional tool like xbimXplorer (source: https://docs.xbim.net/downloads/xbimxplorer.html), which will make it possible to read BIM models in the IFC format (in the different versions of IFC2x3 and IFC4); and 2) .mvdXML files to, for instance, validate the IFC schema and content in terms of entities and related properties, and query the syntax for the data extraction. Of all the available plugins, we intend to use the "buildingSMART mvdXML validation". This allows the validation of a MVD as a subset of data and the concurrent validation of property value. Once the MVD has been produced for the Str.E.Pe. project, another proof of concept will be proposed to the Avellino building authority for submitting IFC models automatically integrated with Psets. Additionally, further automatic code-checks will be implemented on the *usBIM.ePermit* platform. Unfortunately, as long as reference codes cannot be entirely translated into rules (algorithms), and until all documentation is available in a queryable format, it is not possible to implement a completely automatic process (i.e., without BAB officers).

However, the work described in this paper does not aim to resolve interoperability issues between BIM-authoring software and structural-calculation applications; in fact, we chose to utilise applications that can be integrated with a BIM environment (Edilus by Acca Software will be used as the demonstrator). This has allowed us to avoid frustrating interoperability issues in order to investigate another, often unnoticed, major defect: the absence of a BIM-based process that simplifies the application procedure for permits pertaining to structural engineering. Resolving this would lead to more efficient and standardised processes that structural engineers could employ to interact with BABs. Our new MVD is still under development, due to the large number of issues encountered, especially the shortcomings of the IFC format for conveying the outputs of structural assessments and analyses.

6.3 Discussion on Chapter 4

In Chapter 4, I propose a proof-of-concept of the use of blockchain technology to bypass the need for emails and other, even more traditional, transmission channels during a construction project. This is achieved by certifying all the information containers exchanged and their corresponding information flows on the blockchain. This produces a universal and reliable source of information for the inspectors of structural systems both during and following the construction process. Preliminary testing of the proof-of-concept is presented in Table 4.2. In detail, the proposed methodology has been compared to the traditional approach in terms of the common criticalities that arise in relation to the exchange of information, the reliability of the information, and the transparency of the decision-making process.

Table 4.2: Recap of the solved criticalities and the advantages of the proposal.

	Blockchain-based approach		
Solved criticalities in information exchanges	**Basic**	**Intermediate**	**Advanced**
Sending wrong files.		✓	✓
Sending the wrong version of files.	✓	✓	✓
Sending to the wrong recipient.		✓	✓
Errors in archiving incoming files.	✓	✓	✓
Reliability of exchanged information	**Basic**	**Intermediate**	**Advanced**
Information retrievals from the blockchain ledger.	✓	✓	✓

Automatic collection of the signatures of actors involved in the process.		✓	✓
Checking the correspondence between the exchanged information and recorded data obtained at the construction site by IoT sensors.			✓
Transparency of decision-making processes	**Basic**	**Intermediate**	**Advanced**
Use of certified and reliable data.	✓	✓	✓
Shared and pre-agreed decision-making procedures, which are supported by certified data.			✓

The blockchain-based approach I propose can solve common criticalities relating to the use of the traditional approach which comes with a greater risk of error when transmitting information because requires human intervention at various stages. In addition, a traditional approach is unable to ensure the reliability of the data transmitted and the transparency of any decisions made because the activities are mainly manual and at the discretion of those performing them (e.g., PM, inspector of structures, general contractor). Alternatively, the use of an approach based on blockchain technology enables the introduction of smart contracts that employ shared and pre-established procedures to verify the information transmitted. This increases the reliability and quality of the data exchanged and the transparency of the decision-making processes because of the level of complexity that is possible with the smart contracts used; indeed, reliability and transparency are maximized when advanced smart contracts are adopted. Finally, from my implementation of the blockchain technology and basic smart contracts, I found: that the availability of open APIs for CDEs is somewhat limited, despite the indications of DIN-SPEC 91391-1, 2:2019; and there are clear advantages to drafting the final structural report in the close-out phase since the information stored on the blockchain can support both the recovery and the verification of the reliability of the documentation exchanged.

6.3.1 Cost analysis

A preliminary analysis for the evaluation of costs was carried out on Rinkeby TestNet, setting the gas price at 1 Gwei. The results are presented in Table 6., which contains the costs of all functions that the smart contract deploys. Publishing the smart contract costs $3.49, each transmission costs $0.44, and the addition of a new actor costs $0.069. The recall and check functions are free.

Table 6.1: Cost analysis of the basic smart contract (1 Ether = $2132.53 on 1 July 2021).

Function	**Ether**	**$**
Deploy smart contract	0.001631936	3.490
Add actor	0.000032303	0.069
Add new transmission	0.000205268	0.440
Recall register	0	0
Check transmission	0	0

The cost of functions is influenced by both the value of Ether and the gas price, while the total cost of using the basic smart contract depends primarily on the number of actors and the number of transmissions. Although the costs are not negligible considering the current Ether price, the authors argue that: 1. Costs could be reduced in the prototyping phase through appropriate cost optimization techniques. A market analysis could also be performed at this stage to identify more sustainable blockchains. 2. The overall costs are sustainable compared to the costs of large construction projects (i.e., millions of dollars) and compared to the cost of possible litigations.

6.4 Implications and limitations

The academic implication of this work is prominent in almost every chapter. Chapter 2 proposes a reference for all academics involved in structural engineering who want to approach the BIM world for the first time. Chapters 3 and 4 open specialized research paths that need further developments: in the first case, the University of Naples is already working on the development of a special MVD for the structural discipline; in the second case, the University of Naples is working on the implementation of an advanced smart contract combining BIM and IoT. This would allow to develop a novel process that could replace the construction manager for structural elements made by 3D printing on site. Finally, chapter 5 proposes an open BIM-based approach for maintenance whose implications for the management of the operation and maintenance phase of infrastructures could also be explored.

However, since BIM falls under the domain of applied research, the processes that both the academic and industrial communities propose must be validated by an audience of industry experts in order to be widely implemented in current practice. In addition, the audience must be composed of industry experts with very heterogeneous backgrounds to account for the multidisciplinary nature of the BIM approach. This may represent a limitation for the transfer of the processes proposed in this thesis into professional practice. However, the author is striving to give more prominence to the work done and has made contact with the Italian IBIMI chapter of buildingSMART International (the University of Naples is a corporate member of this association). Since 2021 the author is part of the *working group Ri.Di.PE (Rilascio Digitale Permessi Edilizi)* for which the author is working to develop a case study that schematizes the work presented in chapter 3 so that it can become (after approval) a reference for the whole building smart international community, in particular for the regulatory room. The author also recently presented the results of Chapter 3 at the IBIMI Italian international conference to raise awareness of the topic among the Italian public administration.

The author is also a member of the Italian commission UNI/CT 033/SC 05 for the working groups GL 2, GL 4 and GL 7, which respectively focus on parts 3, 5, and 9 of the UNI 11337 series. The author hopes to be able to bring his contribution by proposing some insights from Chapter 5 in GL 07, which deals with Part 9, focused on the use of bim for the building logbook (this work has not yet started). However, the work conducted in Chapter 4 may also be of value to the UNI 11337 series, recently expanded to also contain a Part 11 on the topic of blockchain and smart.

References

[1] T. Vilutiene, D. Kalibatiene, M. R. Hosseini, E. Pellicer, and E. K. Zavadskas, "Building Information Modeling (BIM) for Structural Engineering: A Bibliometric Analysis of the Literature," *Adv. Civ. Eng.*, vol. 2019, pp. 1–19, Aug. 2019.

[2] S. Tang, D. R. Shelden, C. M. Eastman, P. Pishdad-Bozorgi, and X. Gao, "A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends," *Autom. Constr.*, vol. 101, pp. 127–139, May 2019.

[3] M. Shahinmoghadam and A. Motamedi, "Review of BIM-centred IoT Deployment–State of the Art, Opportunities, and Challenges," in *Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC 2019)*, 2019, pp. 1268–1275.

[4] S. Tafraout, N. Bourahla, Y. Bourahla, and A. Mebarki, "Automatic structural design of RC wall-slab buildings using a genetic algorithm with application in BIM environment," *Autom. Constr.*, vol. 106, p. 102901, Oct. 2019.

[5] C. Musella, M. Serra, C. Menna, and D. Asprone, "BIM & AI: advanced technologies for the digitalisation of seismic damages in masonry buildings," in *International fib Symposium on Conceptual Design Of Structures. International fib Symposium on Conceptual Design Of Structures. Madrid, September*, 2019.

7 Conclusions

This thesis has focused on the use of BIM and novel technologies in structural engineering. The aim of this work has been to develop novel processes to digitise workflows in structural engineering and, consequently, perform structural engineering information lifecycle management. In Chapter 2, I present the first account of the contemporary experience on the use of BIM in structural engineering. In my opinion, research on the use of BIM in structural engineering has a prominent role to play in mitigating shortcomings that originate from the typical cultural background of structural engineers: they often lack, indeed, an aptitude for process identification, multidisciplinary collaboration, and information management. In this regard, it is worth noting that while the BIM approach has no own agenda for only research purposes, it is the focus of applied research with the purpose of aiding professional practice. In fact, there are fundamental differences between the BIM and traditional approaches, with the former enabling the development of standardised information processes and the management of information flows. Consequently, the research proposed in this thesis can be a valuable reference starting point for both practitioners and researchers who are interested in the adoption of BIM in structural engineering. However, the case of new buildings is the most mature and is where structural engineers can currently best apply the BIM approach and tools. The case of BIM for existing buildings deserves further attention from a structural engineering point of view because appropriate BIM-based methodologies are needed to replace traditional work processes and reducing their deficiencies. In the next future, it is expected that the integration between BIM and the IoT will enable the digital twin era in the AEC industry [88], i.e., information models become digital twins of real as-built assets, with their performance (e.g., temperature, energy consumption, structural functioning) monitored and updated in real-time. Research on the use of BIM in structural engineering would be fundamental to aid practitioners in adopting this framework where AI algorithms could be used to highlight possible issues and provide forecasts in relation to various maintenance scenarios [89], [90]. Additionally, digital twins could also be adapted to both new and existing buildings. Finally, additional developments are also expected in openBIM-based research in structural engineering that will focus mainly on the strategic infrastructures (such as bridges), with particular attention paid to the monitoring and maintenance phases. As an example, to overcome the limitations of the previous scheme, which was conceived for buildings [91], the buildingSMART community released IFC version 4.2 in 2019, which was conceived from the IFC bridge-extension project.

Research on using BIM in structural engineering has a prominent role to play in mitigating these shortcomings and fostering the adoption of BIM and other digital technologies. Therefore, the processes that this thesis proposes in Chapter 3, Chapter 4, and Chapter 5 are a first attempt to fill this gap, and may also be a valuable starting point for both practitioners and researchers in structural engineering who are interested in furthering this field. Figure 7.1 depicts the life cycle of a building and shows where the three processes that this thesis proposes are located with respect to the lifecycle phases.

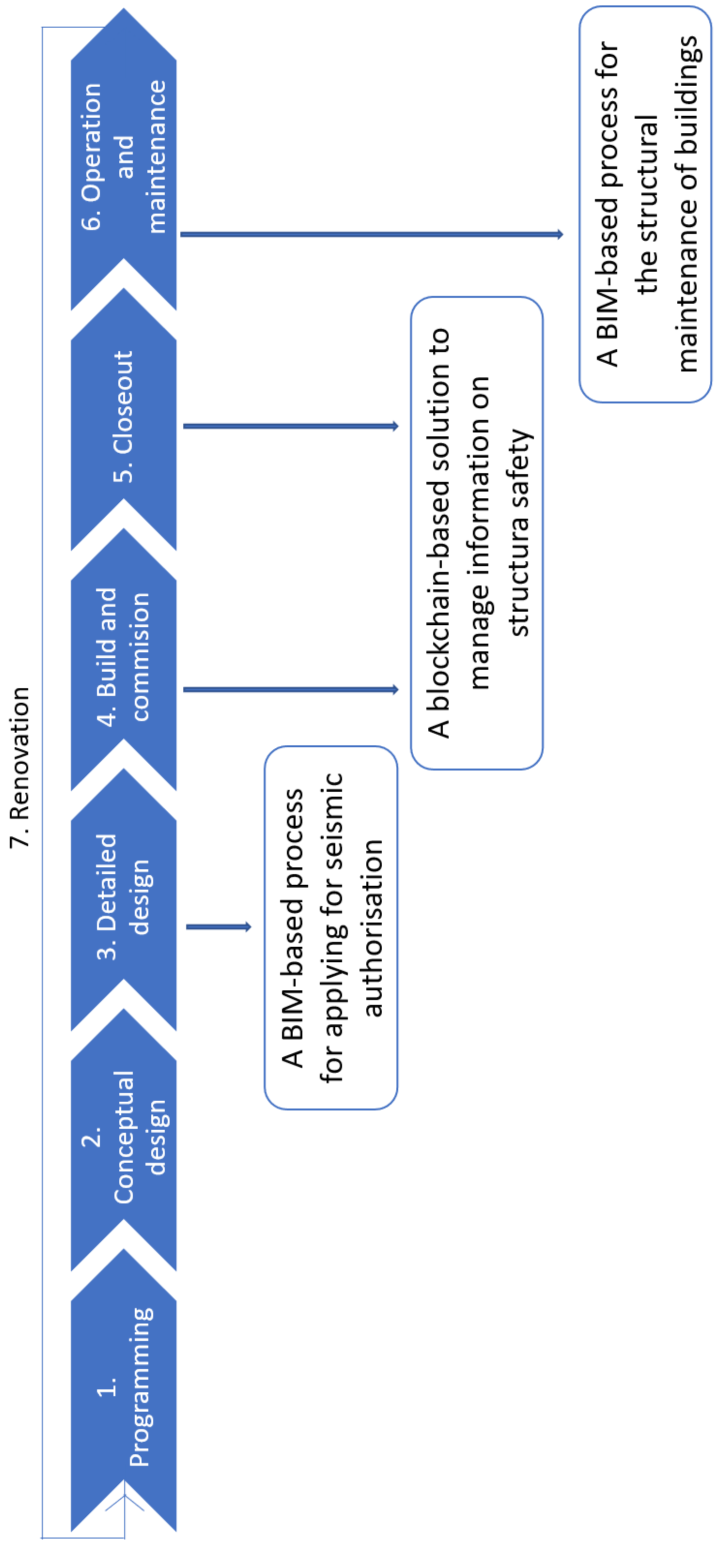


Figure 7.1: Relation between the lifecycle of a building and the three processes for information management that this thesis proposes.

The BIM-based process to apply for the seismic authorisation permit belongs to the detailed design phase, and proposes the use of IFC models of the structural discipline to interact with the building authorities.

In Chapter 3, the Str.E.Pe. process proposes the use of a dedicated IFC model to apply for seismic authorisation, and the research has focused on defining and standardising content that is integrated into IFC models for transfer to BAB officers. This approach (finally) makes a substantial change to traditional practices that are still based on delivery reports and technical specifications in simple digital, but unstructured, format, or even in paper format. The building authority of Avellino has proven that the use of integrated IFC models is feasible in the seismic authorisation process that its officers implement, provided that there is an initial phase of training on IFC format and the e-permitting platform. Opportunities for time saving are also possible if further automatic code-checking rules are implemented. Accordingly, officers support our intention to develop an MVD for the purpose of seismic authorisation; the advantages of this would include considerably improving the integration issues of the IFC format in relation to structural information, and preventing misunderstandings, and, as a consequence, enhancing the clarity of information exchanges between engineers and BABs. Unfortunately, deliverables in addition to BIM models in the IFC format are required for applications for structural engineering permits and approvals; for this reason, further research is required to define the information requirements of BABs according to the (recently released) EN 17412-1:2020 standard, which provides guidelines to clarify the depth of the data needed in relation to geometry, additional information, and documentation. BuildingSMART® has drawn attention to the existence of a higher level of information requirements: regulatory information requirements (RIRs), which would add and include the other information requirements of EIR, AIR, OIR, and their counterpart, regulatory information models (RIMs) [4]. It is our view that incorporating information into structural BIM models is pointless unless this data can be subjected to an automated code-checking process. Therefore, such research may be fundamental in attracting the attention of regulatory bodies when it comes to identifying RIRs and translating them into machine-readable rules with which to process standardised RIMs. Finally, this has been a starting point for outlining the content that a new (and under development) MVD will allow us to convey automatically. Once the MVD is ready, further proof-of-concept could be performed with BABs, and further automatic code checking will be implemented to support BAB officers.

In Chapter 4, a blockchain-based solution to managing information regarding the structural safety of buildings belongs to the build and commission and closeout phases. In detail, Chapter 4 proposes a proof-of-concept for integrating blockchain technology and smart contracts into the information flows deployed in various common data environments (CDEs). The proposal focuses on the structural system, in particular on reducing human error, and increasing the reliability and transparency of the decisions made on construction sites. To this end, the proof-of-concept introduces smart contracts with different levels of complexity: 1) basic – for certifying information flows; 2) intermediate – for also collecting multiparty signatures or consents; and 3) advanced – for comparing information exchanged automatically with data gathered by IoT sensors on site. The preliminary testing of the proof-of-concept involved comparing this new workflow to the traditional approach, particularly in relation to the criticalities that can arise in exchanges of information, the reliability of this information, and the transparency of any decision making. The proposed process reduces the risk of such problems, as well as issues that can arise from human error when transmitting data. To this end, further research and development of the proposed tool could enable some checks to be conducted automatically using a combination of smart contracts and AI algorithms. It is worth noting that the proposal will enable the blockchain technology to be integrated into construction-site activities both today and in the long term. This is an important step forward because, even when the BIM approach is applied, the construction process relating to structural systems uses a huge amount of paper documentation to trace human activities on site. Accordingly, blockchain technology has the potential to legally certify construction site documents and end the dependence on paper. Additionally, increased reliability and the traceability of information flows that are certified on the blockchain make it possible to use tools to trace the construction process back at any time. These features will soon be even more valuable when innovative IoT, 3D printing and additive-manufacturing technologies become available for work on construction sites. These new construction practices will require suitable checking processes and the adequate storage of data. Our proof-of-concept meets this need by using advanced smart contracts and AI applications. This will make it possible to "close the circle" by integrating the use of BIM to manage all the information that arises from construction site 4.0.

In Chapter 5, the BIM-based process for the structural maintenance of buildings belongs to the operation and maintenance phase; this hinges on the wider framework of the electronical building logbook that the BIM-to-CIM project has identified. A building logbook is the register that should facilitate the management of the building by the administrator of the condominium or whoever deals with real estate management in general. In the traditional approach, this is only a set of documents to update manually during the operation and maintenance phase. The BIM-to-CIM project proposes the use of interoperable IFC-model-based platforms to ease the management of the building logbook, to implement the maintenance plan and to transfer the building information to the territorial level (geoportal). In this way, the reference IFC model of the building would always be the same, and any changes made to this on one of the platforms would occur on all the other platforms as well. However, the lack of structured information has required the definition of specific datasheets, for both the electronic building logbook and the maintenance platform, in order to link to the BIM objects that constitute the IFC model. The platform allows one to link the origin document of information that datasheets include to IFC models as well. From a structural engineering perspective, this represents the first proof-of-concept for digitising the building logbook of the structure and moving to a data-driven maintenance platform. In fact, there is currently a proliferation of collaborative model-centred platforms that allow one to manage facility management operations, such as ordering a replacement component in the event this has been damaged or has broken, or requesting ordinary maintenance operations, directly from BIM models (usually in open IFC format). From a structural engineering perspective, these collaborative platforms may be the first step towards achieving, in future, the integration of BIM and IoT technology in order to extend the BIM-based lifecycle information management of structural information to structural monitoring information.

In conclusion, the novel process proposed by this thesis addresses the open research field of renovating and digitising workflows in structural engineering. Additionally, the lifecycle management of information in structural engineering would enable, in the near future, the deployment of efficient *digital twins* to support structural engineers and allow them to perform better-informed activities in the designing, constructing, maintenance and monitoring of structures.

APPENDIX A – Summary-sheet of the structural project of the school of Montemarano

Summarysheet of the structural project of the school of Montemarano

	ID	Requested information specification	Data type	Value
1. Description of the work	1.1	short description of the work	string	Demolition and reconstruction of an existing school in the Council of Montemarno
	1.2	land register data	string	-
	1.3	name of the owner	string	Council of Montemarano
	1.4	geographical coordinates (latitude;longitude)	number	lat. 40.9203 long. 14.9975
	1.5	peak ground acceleration at the site of the work (a_g)	number	0,269 g
	1.6	existence of any prescription and/or urban constraint	Boolean	no
	1.7	kind of work	string	public
	1.8	type of work	string	school
	1.9	construction system	string	reinforced concrete
	1.9.1	existence of any seismic device (isolators/dampers)	Boolean	no
	1.10	type of bearing structure	string	frame (beams-columns)
	1.11	type of foundation	string	piles
	1.12	contruction category of use: residential, commercial, offices, parking, etc.	string	category C1 according to §2.5.2 NTC 2018
	1.13	contruction geometrical information: total plan surface [m^2]; total volume[m^3]; basement floors[n°]; storeys[n°]; max floor span[m]; max depth of the footings [m]; max height of the roof [m]; other (...).	chart	BIM structural model
...n soil	2.1	ground investigation type	string	geotechnical tests
	2.2	ground type accounting for the influence of local ground conditions on the seismic action	string	category B according to §3.2.2 NTC2018

APPENDIX A

2. Foundatc	2.3	ground type parameters: v_{s30}[m/s]; N_{spt30}, [-]; c_u [kPa]	chart	-
	2.4	ground type accounting for topographical conditions	string	category T1 according to §3.2.2 NTC2018
	2.5	existence of liquefation phenomena	Boolean	no
	2.6	data of ground stratigraphical profile: soil layers[n°]; soil layer depth[m]; soil weight ϒ[kN/m^3]; N_{SPT}[n°]; $q_{c,CPT}$[kN/m^2]	chart	See appendix's bottom
	2.7	existence of aquifer	Boolean	yes
3. Design actions	3.1.1	definition of all design actions involved: type (self-weight, imposed by the category use, wind, quake, snow, thermal, ect.); name; brief description.	chart	See appendix's bottom
	3.1.2	characteristic values of design actions in kN/m^2 with respect to: storeys, stairs, roof, foundation, other.	chart	See appendix's bottom
	3.1.3	load combinations considered: load combination name; list of loads involved; notes.	chart	See appendix's bottom
seismic actions	3.2.1	nominal service life of the structure v_N [years]	number	50y
	3.2.2	structure importance class and factor	string and number	1,5 (class III according to §2.4.3 NTC 2018)
	3.2.3	design service life of the structure v_R [years]	number	75y
	3.2.4	existence of a local seismic response study	Boolean	no
	3.2.5	Elastic response spectra data according to the limit states	chart and plot	See appendix's bottom
ssumptions	4.1	geometrical data	chart	BIM structural model
	4.2	existance of secondary structural elements	Boolean	no
	4.3	existance of noteworthy second order effects	Boolean	no
	4.4	type of base restraints for primary structural elements	string	fixed restraints
	4.5.1	Type of structural analysis in case of seismic actions	string	linear dinamic with behaviour factor
	4.5.2	Ductility class	string	high (class A)
	4.5.3	Satisfied structural regularity in plan	Boolean	yes

Section	No.	Description	Type	Value
4. Design criteria and modelling a	4.5.4	Satisfied structural regularity in elevation	Boolean	no
	4.5.5	Capacity design	Boolean	yes
	4.5.6	r.c. structural element capacity assessment taking into consideration confinement effects (accornding to §7.4.1 NTC2018)	string	no
	4.5.7.1	structural type of reinforced concrete building (§7.3.1 - Table 7.3.II NTC2018)	string	frame structure
	4.5.8.1 4.5.8.2	behaviour factors for horizontal seismic actions according to each state limit	chart	q(ULS/SLV)=4,68 q(SLS/SLD)=1,5
	4.5.9	assumption of diaphragmatic behaviour at storey level	Boolean	yes
	4.5.10	existance of discontinued vertical structural elements	Boolean	no
	4.5.11	existance of noteworthy vertical seismic actions	Boolean	no
5. Material properties	5.1	foundation concrete properties: concrete class; characteristic compressive strength; Young modulus; design compressive strength.	chart	See appendix's bottom
	5.2	building concrete properties: concrete class; characteristic compressive strength; Young modulus; design compressive strength.	chart	See appendix's bottom
	5.3	reinforcing steel properties: steel type; characteristic yield tensile strength; characteristic ultimate tensile strength; Young modulus; design tensile strength.	chart	See appendix's bottom
6. Methods of structural analysis and outcomes (Linear dinamic with behaviour factor)	6.2.1	number of modes taken into account for which the sum of the the effective modal masse amounts to at least 85% (§7.3.3.1 NTC2018)	number	15
	6.2.2	taking into account accidental torsional effects (§7.3.3 NTC2018)	Boolean	yes
	6.2.3	summary chart concerning modal information: foundamental periods in the main horizzontal directions of the building, effective modal masses and maximum roof displacements.	chart	See appendix's bottom
	7.1.1	safety checks required for each limit state according to the importance class of the building	chart	available options according to §7.3.6 NTC 2018- See appendix's bottom

7.1 Safety checks	7.1.2.1	ultimate limit state (ULS) WITHOUT seismic actions: performed safety checks on cross sections of primary structural elements such as beams, columns, walls, etc.	chart: each type of check(*) is associated with a minimum value of capacity demand ratio (C/D) and ID of the corrisponding element	**axial load/ bending moment/ shear**
	7.1.2.2	ultimate limit state(ULS - life safe) in case of seismic actions: performed safety checks on cross sections of primary structural elements such as beams, columns, walls, etc.		**axial load/ bending moment/ shear**
	7.1.2.3	ultimate limit state (ULS - near collapse) in case of seismic actions: performed safety checks on cross sections of primary structural elements such as beams, columns, walls, etc.		**ductility checks**
	7.1.3	existance of performed safety checks on secondary structural elements (§7.2.3 NTC2018)	Boolean	**no**
	7.1.4	existance of performed safety checks on non-structural elements (§7.2.3 NTC2018)	Boolean	**no**
	7.1.5	existance of performed safety checks on systems (§7.2.3 NTC2018)	Boolean	**no**
	7.1.6.1	serviceability limit state (SLS) WITHOUT seismic actions: performed safety checks on cross sections of primary structural elements such as beams, columns, walls, etc.	chart: each type of check(*) is associated with a minimum value of capacity demand ratio (C/D) and ID of the corrisponding element	**axial load/ bending moment**
7.1 Safety checks	7.1.6.2	serviceability limit state (SLS - immediate occupancy) in case of seismic actions: performed safety checks on cross sections of primary structural elements such as beams, columns, walls, etc.		**Inter storey drift**
	7.1.6.3	serviceability limit state (SLS - operational) in case of seismic actions: performed safety checks on cross sections of primary structural elements such as beams, columns, walls, etc.		**Inter storey drift**
	7.1.7	checks on available distance between adjacent conctructions (§7.2.1 NTC2018)	Boolean	**no**
sments	8.1	footing assessment procedure and corresponding safety factors for actions, materials and capacities	string	**according to §6.2.4.1 NTC 2018**

8. Foundation safety assess	8.3	performed safety checks in case of deep foundations at ultimate and serviceability limit state (ULS and SLS)	chart: each type of check(*) is associated with a minimum value of capacity demand ratio (C/D) and ID of the	**(*)bearing resistance/sliding resistance/overall stability/structural/ settlements/other**	
	8.4	performed checks on the horizontal connections at foundation level	Boolean	**yes**	
9. Special details	9.1	satisfied geometrical constraints for beams, columns, walls and beam-column joints according to §7.4.6.1.1-4 NTC2018	Boolean	**yes**	R.C. structures
	9.2	type of reinforcement constraint satisfied for each primary structural element inside and outside the critical region	chart: each type of constraint(*) is associated with a minimum value of required/effective ratio of the requested quantity	-	
	9.3	critical region minimum length satisfied (with respect to each structural element) according to §7.4.6.1.1-4 NTC2018	Boolean	**yes**	

2.6 Data of ground stratigraphical profile: soil layers[n°]; soil layer depth[m]; soil weight ϒ[kN/m^3]; N_{SPT}[n°]; $q_{c/CPT}$[kN/m^2]

Terreni

N_{TRN}	γ_T	K1			ϕ	c_u	c'	E_d	E_{cu}	A_{S-B}
		K_{1X}	K_{1Y}	K_{1Z}						
	[N/m³]	[N/cm³]	[N/cm³]	[N/cm³]	[°]	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	
Sabbia Limosa										
T001	18.000	60	60	300	30	0,000	0,010	800	0	0,000
Arenaria sciolta										
T002	18.000	100	100	1000	37	0,000	0,000	10.000	0	0,000
Arenaria										
T003	18.000	100	100	1000	44	0,000	0,000	60	0	0,000
Riporto di materiali di risulta										
T004	18.000	80	80	800	36	0,000	0,000	1.000	0	0,000

LEGENDA:

N_{TRN} Numero identificativo del terreno.
γ_T Peso specifico del terreno.
K1 Valori della costante di Winkler riferita alla piastra Standard di lato b = 30 cm nelle direzioni degli assi del riferimento globale X (K_{1X}), Y (K_{1Y}), e Z (K_{1Z}).
ϕ Angolo di attrito del terreno.
c_u Coesione non drenata.
c' Coesione efficace.
E_d Modulo edometrico.
E_{cu} Modulo elastico in condizione non drenate.
A_{S-B} Parametro "A" di Skempton-Bjerrum per pressioni interstiziali.

STRATIGRAFIE

Stratigrafie

N_{TRN}	Q_i	Q_f	Cmp. S.	Add	ΔEd
	[m]	[m]			
[S001]-Stratigrafia Centro					
T001	0,00	-1,50	incoerente	sciolto	lineare
T002	-1,50	-3,50	incoerente	sciolto	lineare
T003	-3,50	INF	incoerente	sciolto	nulla
[S002]-Stratigrafia Valle					
T004	0,00	-4,00	incoerente	sciolto	lineare
T001	-4,00	-6,00	incoerente	sciolto	lineare
T002	-6,00	-9,00	incoerente	sciolto	lineare
T003	-9,00	INF	incoerente	sciolto	lineare
[S003]-Stratigrafia Monte					
T001	0,00	-1,00	incoerente	denso	lineare
T002	-1,00	-2,00	incoerente	sciolto	nulla
T003	-2,00	INF	incoerente	sciolto	nulla

LEGENDA:

N_{TRN} Numero identificativo della stratigrafia.
Q_i Quota iniziale dello strato (riferito alla quota iniziale della stratigrafia).
Q_f Quota finale dello strato (riferito alla quota iniziale della stratigrafia). INF = infinito (profondità dello strato finale.
Cmp. S. Comportamento dello strato.
Add Addensamento dello strato.
ΔEd Variazione con la profondità del modulo edometrico.

3.1.1 Definition of all design actions involved: type (self-weight, imposed by the category use, wind, quake, snow, thermal, ect.); name; brief description.

TIPOLOGIE DI CARICO

Tipologie di carico

N_{id}	Descrizione	F+E	+/- F	CDC	ψ_0	ψ_1	ψ_2
0001	Carico Permanente	SI	NO	Permanente	1,00	1,00	1,00
0002	Permanenti NON Strutturali	SI	NO	Permanente	1,00	1,00	1,00
0003	Scuole	SI	NO	Media	0,70	0,70	0,60
0004	Autorimessa <= 30kN	SI	NO	Media	0,70	0,70	0,60
0005	Scale, balconi, ballatoi (Cat. C)	SI	NO	Media	0,70	0,70	0,60
0006	Coperture accessibili solo per manutenzione	SI	NO	Media	0,00	0,00	0,00
0007	Carico da Neve <= 1000 m s.l.m.	SI	NO	Breve	0,50	0,20	0,00
0008	Sisma X	-	-	-	-	-	-
0009	Sisma Y	-	-	-	-	-	-
0010	Sisma Z	-	-	-	-	-	-
0011	Sisma Ecc.X	-	-	-	-	-	-
0012	Sisma Ecc.Y	-	-	-	-	-	-

LEGENDA:

N_{id} Numero identificativo della Tipologia di Carico.
F+E Indica se la tipologia di carico considerata è AGENTE con il sisma.
+/- F Indica se la tipologia di carico è ALTERNATA (cioè considerata due volte con segno opposto) o meno.
CDC Indica la classe di durata del carico.
NOTA: dato significativo solo per elementi in materiale legnoso.
ψ_0 Coefficiente riduttivo dei carichi allo SLU e SLE (carichi rari).
ψ_1 Coefficiente riduttivo dei carichi allo SLE (carichi frequenti).
ψ_2 Coefficiente riduttivo dei carichi allo SLE (carichi frequenti e quasi permanenti).

3.1.2 characteristic values of design actions in kN/m² with respect to: storeys, stairs, roof, foundation, other.

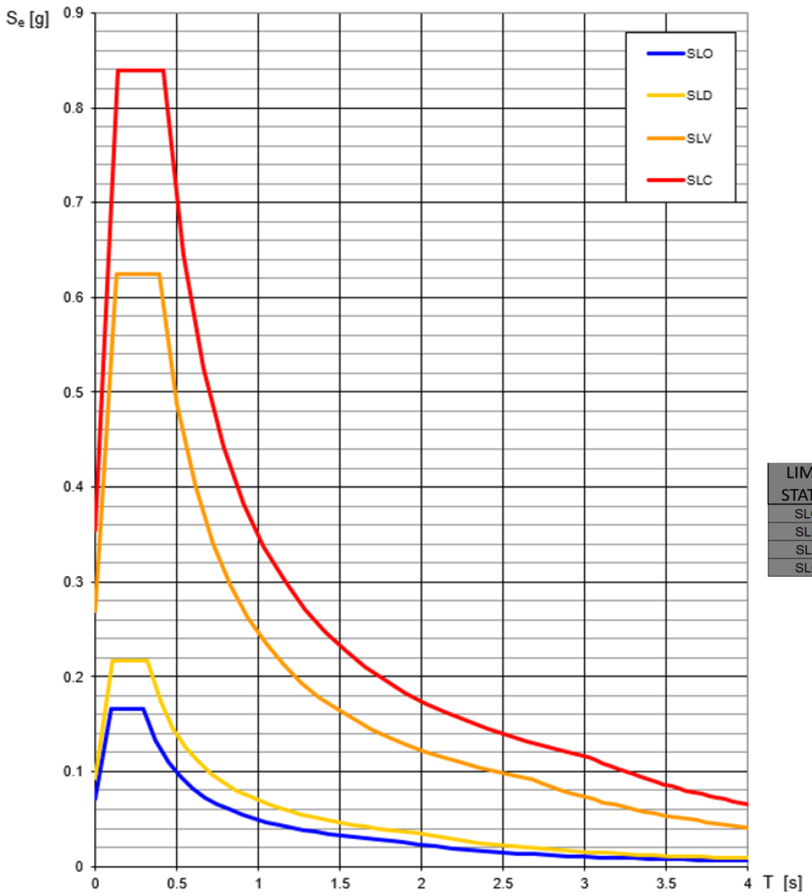
Analisi carichi

N_{id}	T. C.	Descrizione del Carico	Tipologie di Carico	Peso Proprio Descrizione	PP	Permanente NON Strutturale Descrizione	PNS	Sovraccarico Accidentale Descrizione	SA	Carico Neve [N/m²]
001	S	Doppia fodera 30cm (12+8)	Carico Permanente	Fodera esterna (12 cm) e fodera interna (8 cm)	1.600	Intonaco interno, intonaco esterno, isolante poliuretano espanso	740		0	0
002	S	Platea	Autorimessa <= 30kN	**vedi le relative tabelle dei carichi*	-	Sottofondo e pavimento di tipo industriale in calcestruzzo	2.000	Rimesse, aree per traffico, parcheggio e sosta di veicoli leggeri (peso a pieno carico fino a 30 kN) (Cat. F – Tab. 3.1.II - DM 17.01.2018)	2.500	0
003	S	Scala	Scale, balconi, ballatoi (Cat. C)	**vedi le relative tabelle dei carichi*	-		0	Balconi, ballatoi e scale comuni (Cat. C – Tab. 3.1.II - DM 17.01.2018)	4.000	0
004	S	LatCem Scuole H25	Scuole	Solaio di tipo tradizionale latero-cementizio di spessore 25 cm (20+5)	3.530	Pavimentazione e sottofondo, incidenza dei tramezzi e intonaco inferiore	2.360	Scuole (Cat. C1 – Tab. 3.1.II - DM 17.01.2018)	3.000	0
005	S	Copertura in Legno	Coperture accessibili solo per manutenzione	Orditura secondaria e tavolato in legno	300	Manto di tegole e coibentazione	600	Coperture e sottotetti accessibili per sola manutenzione (Cat. H – Tab. 3.1.II - DM 17.01.2018)	500	2.305
006	S	Balcone - Sbalzo in ca	Scale, balconi, ballatoi (Cat. C)	**vedi le relative tabelle dei carichi*	-	Pavimento, sottofondo e intonaco inferiore	1.360	Balconi, ballatoi e scale comuni di abitazioni (Cat. C – Tab. 3.1.II - DM 17.01.2018)	4.000	0

LEGENDA:

N_{id} Numero identificativo dell'analisi di carico.
T. C. Identificativo del tipo di carico: [S] = Superficiale - [L] = Lineare - [C] = Concentrato.
PP, PNS, SA Valori, rispettivamente, del Peso Proprio, del Sovraccarico Permanente NON strutturale, del Sovraccarico Accidentale. Secondo il tipo di carico indicato nella colonna "T.C." ("S" - "L" - "C"), i valori riportati nelle colonne "PP", "PNS" e "SA", sono espressi in [N/m²] per carichi Superficiali, [N/m] per carichi Lineari, [N] per carichi Concentrati.

3.2.5 Elastic response spectra data according to the limit states



LIMIT STATES	T_R [anni]	a_g [g]	F_o [-]	T_C^* [s]
SLO	45	0.071	2.340	0.295
SLD	75	0.093	2.333	0.321
SLV	712	0.269	2.317	0.393
SLC	1462	0.355	2.361	0.415

5.2	building concrete properties: concrete class; characteristic compressive strength; Young modulus; design compressive strength.

MATERIALI CALCESTRUZZO ARMATO

Caratteristiche calcestruzzo armato

N_{id}	γ_k [N/m³]	$\alpha_{T,i}$ [1/°C]	E [N/mm²]	G [N/mm²]	C_{Erid} [%]	Stz	R_{ck} [N/mm²]	R_{cm} [N/mm²]	$\%R_{ck}$	γ_c	f_{cd} [N/mm²]	f_{ctd} [N/mm²]	f_{cfm} [N/mm²]	N	n Ac
Cls C25/30_B450C - (C25/30)															
002	25.000	0,000010	31.447	13.103	60	P	30,00	-	0,85	1,50	14,11	1,19	3,07	15	003

LEGENDA:

- N_{id} Numero identificativo del materiale, nella relativa tabella dei materiali.
- γ_k Peso specifico.
- $\alpha_{T,i}$ Coefficiente di dilatazione termica.
- **E** Modulo elastico normale.
- **G** Modulo elastico tangenziale.
- C_{Erid} Coefficiente di riduzione del Modulo elastico normale per Analisi Sismica [E_{sisma} = EC_{Erid}].
- **Stz** Tipo di situazione: [F] = di Fatto (Esistente); [P] = di Progetto (Nuovo).
- R_{ck} Resistenza caratteristica cubica.
- R_{cm} Resistenza media cubica.
- $\%R_{ck}$ Percentuale di riduzione della R_{ck}
- γ_c Coefficiente parziale di sicurezza del materiale.
- f_{cd} Resistenza di calcolo a compressione.
- f_{ctd} Resistenza di calcolo a trazione.
- f_{cfm} Resistenza media a trazione per flessione.
- **n Ac** Identificativo, nella relativa tabella materiali, dell'acciaio utilizzato: [-] = parametro NON significativo per il materiale.

5.3	reinforcing steel properties: steel type; characteristic yield tensile strength; characteristic ultimate tensile strength; Young modulus; design tensile strength.

MATERIALI ACCIAIO

Caratteristiche acciaio

N_{id}	γ_k [N/m³]	$\alpha_{T,i}$ [1/°C]	E [N/mm²]	G [N/mm²]	Stz	$f_{yk,1}$/ $f_{yk,2}$ [N/mm²]	$f_{tk,1}$/ $f_{tk,2}$ [N/mm²]	$f_{yd,1}$/ $f_{yd,2}$ [N/mm²]	f_{td} [N/mm²]	γ_s	γ_{M1}	γ_{M2}	$\gamma_{M3,SLV}$	$\gamma_{M3,SLE}$	γ_{M7} NCnt	γ_{M7} Cnt
Acciaio B450C - (B450C)																
003	78.500	0,000010	210.000	80.769	P	450,00 -	-	391,30 -	-	1,15	-	-	-	-	-	-
S235 - (S235)																
004	78.500	0,000012	210.000	80.769	P	235,00 215,00	360 360	223,81 204,76	-	1,05	1,05	1,25	-	-	-	-

LEGENDA:

- N_{id} Numero identificativo del materiale, nella relativa tabella dei materiali.
- γ_k Peso specifico.
- $\alpha_{T,i}$ Coefficiente di dilatazione termica.
- **E** Modulo elastico normale.
- **G** Modulo elastico tangenziale.
- **Stz** Tipo di situazione: [F] = di Fatto (Esistente); [P] = di Progetto (Nuovo).
- $f_{tk,1}$ Resistenza caratteristica a Rottura (per profili con t = 40 mm).
- $f_{tk,2}$ Resistenza caratteristica a Rottura (per profili con 40 mm < t = 80 mm).
- f_{td} Resistenza di calcolo a Rottura (Bulloni).
- γ_s Coefficiente parziale di sicurezza allo SLV del materiale.
- γ_{M1} Coefficiente parziale di sicurezza per instabilità.
- γ_{M2} Coefficiente parziale di sicurezza per sezioni tese indebolite.
- $\gamma_{M3,SLV}$ Coefficiente parziale di sicurezza per scorrimento allo SLV (Bulloni).
- $\gamma_{M3,SLE}$ Coefficiente parziale di sicurezza per scorrimento allo SLE (Bulloni).
- γ_{M7} Coefficiente parziale di sicurezza precarico di bulloni ad alta resistenza (Bulloni - NCnt = con serraggio NON controllato; Cnt = con serraggio controllato). [-] = parametro NON significativo per il materiale.
- $f_{yk,1}$ Resistenza caratteristica allo snervamento (per profili con t <= 40 mm).
- $f_{yk,2}$ Resistenza caratteristica allo snervamento (per profili con 40 mm < t = 80 mm).
- $f_{yd,1}$ Resistenza di calcolo (per profili con t = 40 mm).
- $f_{yd,2}$ Resistenza di calcolo (per profili con 40 mm < t = 80 mm).
- **NOTE** [-] = Parametro non significativo per il materiale.

6.2.3 Summary chart concerning modal information: foundamental periods in the main horizzontal directions of the building, effective modal masses and maximum roof displacements.

DATI GENERALI ANALISI SISMICA - FATTORI DI COMPORTAMENTO

					Fattori di comportamento	
Dir	q'	q	q_0	k_R	α_u/α_1	K_w
X	-	4,680	5,85	0,8	1,30	-
Y	-	4,680	5,85	0,8	1,30	-
Z	-	1,500	-	-	-	-

LEGENDA:

- **q'** Fattore di riduzione dello spettro di risposta sismico allo SLU ridotto (Fattore di comportamento ridotto - relazione C7.3.1 circolare NTC).
- **q** Fattore di riduzione dello spettro di risposta sismico allo SLU (Fattore di comportamento).
- **q_0** Valore di base (comprensivo di Kw).
- **k_R** Fattore riduttivo funzione della regolarità in altezza.
- **α_u/α_1** Rapporto di sovraresistenza.
- **K_w** Fattore di riduzione di q_0.

Stato Limite	T_r	a_g/g	Amplif. Stratigrafica		F_0	T^*_C	T_B	T_C	T_D
			S_S	C_C					
	[t]					[s]	[s]	[s]	[s]
SLO	45	0,0701	1,200	1,401	2,339	0,298	0,139	0,418	1,880
SLD	75	0,0912	1,200	1,379	2,337	0,323	0,148	0,445	1,965
SLV	712	0,2629	1,155	1,324	2,328	0,395	0,174	0,523	2,652
SLC	1462	0,3468	1,072	1,309	2,367	0,419	0,183	0,548	2,987

LEGENDA:

- **T_r** Periodo di ritorno dell'azione sismica. [t] = anni.
- **a_g/g** Coefficiente di accelerazione al suolo.
- **S_s** Coefficienti di Amplificazione Stratigrafica allo SLO/SLD/SLV/SLC.
- **C_c** Coefficienti di Amplificazione di Tc allo SLO/SLD/SLV/SLC.
- **F_0** Valore massimo del fattore di amplificazione dello spettro in accelerazione orizzontale.
- **T^*_c** Periodo di inizio del tratto a velocità costante dello spettro in accelerazione orizzontale.

PRINCIPALI ELEMENTI ANALISI SISMICA

Dir	M_{Str}	M_{SLU}	$M_{Ecc,SLU}$	M_{SLD}	$M_{Ecc,SLD}$	$\%T.M_{Ecc}$	$\Sigma V_{Ed,SLU}$
	[N□/m]	[N□/m]	[N□/m]	[N□/m]	[N□/m]	[%]	[N]
X	2.651.435	1.936.689	1.929.282	1.936.689	1.929.282	99,62	1.962.124
Y	2.651.435	1.936.689	1.918.156	1.936.689	1.918.156	99,04	2.439.511
Z	2.651.435	0	0	0	0	100,00	0

LEGENDA:

- **Dir** Direzione del sisma.
- **M_{Str}** Massa complessiva della struttura.
- **M_{SLU}** Massa eccitabile allo SLU.
- **$M_{Ecc,SLU}$** Massa Eccitata dal sisma allo SLU.
- **M_{SLD}** Massa eccitabile della struttura allo SLD, nelle direzioni X, Y, Z.
- **$M_{Ecc,SLD}$** Massa Eccitata dal sisma allo SLD.
- **$\%T.M_{Ecc}$** Percentuale Totale di Masse Eccitate dal sisma.
- **$\Sigma V_{Ed,SLU}$** Tagliante totale, alla base, per sisma allo SLU.

RIEPILOGO MODI DI VIBRAZIONE MODI DI VIBRAZIONE N.15

Sptr	T	$a_{g,o}$	$a_{g,v}$	Γ	CM	%M.M	M_{Ecc}
	[s]	[m/s²]	[m/s²]			[%]	[N□/m]
Modo Vibrazione n. 1							
SLU-X	0,651	1,192	0,000	1.343,910	14,4193	93,26	1.806.094
SLU-Y	0,651	1,192	0,000	-7,698	-0,0826	0,00	59
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,651	1,716	0,000	1.343,910	14,4193	93,26	1.806.094
SLD-Y	0,651	1,716	0,000	-7,698	-0,0826	0,00	59
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	1,716	0,000	-	-	-	-
Elast-Y	-	1,716	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 2							
SLU-X	0,509	1,482	0,000	3,846	0,0253	0,00	15
SLU-Y	0,509	1,482	0,000	928,309	6,1015	44,50	861.757
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,509	2,193	0,000	3,846	0,0253	0,00	15
SLD-Y	0,509	2,193	0,000	928,309	6,1015	44,50	861.757
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	2,193	0,000	-	-	-	-
Elast-Y	-	2,193	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 3							
SLU-X	0,482	1,482	0,000	7,406	0,0435	0,00	55
SLU-Y	0,482	1,482	0,000	873,380	5,1355	39,39	762.793
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,482	2,318	0,000	7,406	0,0435	0,00	55
SLD-Y	0,482	2,318	0,000	873,380	5,1355	39,39	762.793
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	2,318	0,000	-	-	-	-

Sptr	T	$a_{g,O}$	$a_{g,V}$	Γ	CM	%M.M	M_{ecc}
Elast-X	-	2,318	0,000	-	-	-	-
Elast-Y	-	2,318	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 4							
SLU-X	0,290	1,482	0,000	2,034	0,0043	0,00	4
SLU-Y	0,290	1,482	0,000	-392,865	-0,8365	7,97	154.343
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,290	2,510	0,000	2,034	0,0043	0,00	4
SLD-Y	0,290	2,510	0,000	-392,865	-0,8365	7,97	154.343
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	2,510	0,000	-	-	-	-
Elast-Y	-	2,510	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 5							
SLU-X	0,157	1,635	0,000	-0,099	-0,0001	0,00	0
SLU-Y	0,157	1,635	0,000	283,247	0,1760	4,14	80.229
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,157	2,510	0,000	-0,099	-0,0001	0,00	0
SLD-Y	0,157	2,510	0,000	283,247	0,1760	4,14	80.229
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	2,510	0,000	-	-	-	-
Elast-Y	-	2,510	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 6							
SLU-X	0,235	1,482	0,000	227,813	0,3178	2,68	51.899
SLU-Y	0,235	1,482	0,000	0,823	0,0011	0,00	1
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,235	2,510	0,000	227,813	0,3178	2,68	51.899
SLD-Y	0,235	2,510	0,000	0,823	0,0011	0,00	1
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	2,510	0,000	-	-	-	-
Elast-Y	-	2,510	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 7							
SLU-X	0,256	1,482	0,000	209,164	0,3462	2,26	43.750
SLU-Y	0,256	1,482	0,000	3,409	0,0056	0,00	12
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,256	2,510	0,000	209,164	0,3462	2,26	43.750
SLD-Y	0,256	2,510	0,000	3,409	0,0056	0,00	12
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	2,510	0,000	-	-	-	-
Elast-Y	-	2,510	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 8							
SLU-X	0,143	1,754	0,000	-0,225	-0,0001	0,00	0
SLU-Y	0,143	1,754	0,000	-133,398	-0,0688	0,92	17.795
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,143	2,451	0,000	-0,225	-0,0001	0,00	0
SLD-Y	0,143	2,451	0,000	-133,398	-0,0688	0,92	17.795
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	2,451	0,000	-	-	-	-
Elast-Y	-	2,451	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 9							
SLU-X	0,210	1,482	0,000	-2,114	-0,0024	0,00	4
SLU-Y	0,210	1,482	0,000	-124,886	-0,1392	0,81	15.596
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,210	2,510	0,000	-2,114	-0,0024	0,00	4
SLD-Y	0,210	2,510	0,000	-124,886	-0,1392	0,81	15.596
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	2,510	0,000	-	-	-	-
Elast-Y	-	2,510	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 10							
SLU-X	0,091	2,202	0,000	-0,525	-0,0001	0,00	0
SLU-Y	0,091	2,202	0,000	-123,842	-0,0257	0,79	15.337
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,091	1,951	0,000	-0,525	-0,0001	0,00	0
SLD-Y	0,091	1,951	0,000	-123,842	-0,0257	0,79	15.337
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	1,951	0,000	-	-	-	-
Elast-Y	-	1,951	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 11							
SLU-X	0,162	1,585	0,000	119,216	0,0797	0,73	14.212
SLU-Y	0,162	1,585	0,000	3,230	0,0022	0,00	10
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,162	2,510	0,000	119,216	0,0797	0,73	14.212
SLD-Y	0,162	2,510	0,000	3,230	0,0022	0,00	10
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	2,510	0,000	-	-	-	-
Elast-Y	-	2,510	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 12							
SLU-X	0,088	2,224	0,000	-3,429	-0,0007	0,00	12
SLU-Y	0,088	2,224	0,000	100,531	0,0197	0,52	10.106
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,088	1,926	0,000	-3,429	-0,0007	0,00	12

Sptr	T	$a_{g,O}$	$a_{g,V}$	Γ	CM	%M.M	M_{Ecc}
SLD-Y	0,088	1,926	0,000	100,531	0,0197	0,52	10.106
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	1,926	0,000	-	-	-	-
Elast-Y	-	1,926	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 13							
SLU-X	0,130	1,861	0,000	-88,399	-0,0380	0,40	7.814
SLU-Y	0,130	1,861	0,000	6,423	0,0028	0,00	41
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,130	2,336	0,000	-88,399	-0,0380	0,40	7.814
SLD-Y	0,130	2,336	0,000	6,423	0,0028	0,00	41
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	2,336	0,000	-	-	-	-
Elast-Y	-	2,336	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 14							
SLU-X	0,127	1,887	0,000	58,201	0,0239	0,17	3.387
SLU-Y	0,127	1,887	0,000	8,559	0,0035	0,00	73
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,127	2,306	0,000	58,201	0,0239	0,17	3.387
SLD-Y	0,127	2,306	0,000	8,559	0,0035	0,00	73
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	2,306	0,000	-	-	-	-
Elast-Y	-	2,306	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-
Modo Vibrazione n. 15							
SLU-X	0,135	1,820	0,000	45,122	0,0208	0,11	2.036
SLU-Y	0,135	1,820	0,000	-2,113	-0,0010	0,00	4
SLU-Z	0,000	0,000	1,785	0,000	0,0000	0,00	0
SLD-X	0,135	2,381	0,000	45,122	0,0208	0,11	2.036
SLD-Y	0,135	2,381	0,000	-2,113	-0,0010	0,00	4
SLD-Z	0,000	0,000	0,365	0,000	0,0000	0,00	0
Elast-X	-	2,381	0,000	-	-	-	-
Elast-Y	-	2,381	0,000	-	-	-	-
Elast-Z	-	0,000	1,785	-	-	-	-

LEGENDA:

Sptr	Spettro di risposta considerato.
T	Periodo del Modo di vibrazione.
$a_{g,O}$	Valore dell'Accelerazione Spettrale Orizzontale, riferita al corrispondente periodo.
$a_{g,V}$	Valore dell'Accelerazione Spettrale Verticale, riferita al corrispondente periodo.
Γ	Coefficiente di partecipazione.
CM	Coefficiente modale del modo di vibrazione.
%M.M	Percentuale di mobilitazione delle masse nel modo di vibrazione.
M_{Ecc}	Massa Eccitata nel modo di vibrazione.
SLU-X	Spettro di progetto allo S.L. Ultimo per sisma in direzione X.
SLU-Y	Spettro di progetto allo S.L. Ultimo per sisma in direzione Y.
SLU-Z	Spettro di progetto allo S.L. Ultimo per sisma in direzione Z.
SLD-X	Spettro di progetto allo S.L. di Danno per sisma in direzione X.
SLD-Y	Spettro di progetto allo S.L. di Danno per sisma in direzione Y.
SLD-Z	Spettro di progetto allo S.L. di Danno per sisma in direzione Z.
Elast-X	Spettro Elastico per sisma in direzione X.
Elast-Y	Spettro Elastico per sisma in direzione Y.
Elast-Z	Spettro Elastico per sisma in direzione Z.

7.1.1 safety checks required for each limit state according to the importance class of the building

Tab. 7.3.III – *Stati limite di elementi strutturali primari, elementi non strutturali e impianti*

STATI LIMITE		CU I	CU II			CU III e IV		
		ST	ST	NS	IM	ST	NS	IM(*)
SLE	*SLO*					RIG		FUN
	SLD	RIG	RIG			RES		
SLU	*SLV*	RES	RES	STA	STA	RES	STA	STA
	SLC		DUT(**)			DUT(**)		

(*) Per le sole CU III e IV, nella categoria Impianti ricadono anche gli arredi fissi.
(**) Nei casi esplicitamente indicati dalle presenti norme.