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PH.D. PROGRAM IN STRUCTURAL, GEOTECHNICAL
ENGINEERING AND SEISMIC RISK
COORDINATOR: PROF. ING. LUCIANO ROSATI

XXXIII Cycle

CHRISTIAN MUSELLA

Ph.D. Thesis

Digital workflows for the management of existing structures in the pre- and post-earthquake phases: BIM, CDE, drones, laser-scanning and AI

TUTOR: PROF. ENG. DOMENICO ASPRONE
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2021

Ringraziamenti

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San Sebastiano al Vesuvio, 5 luglio 2021

Christian Musella

Summary

Figures summary

Tables summary

ABSTRACT

The BIM methodology, developed in America in the 1970s, has revolutionized the AEC industry by introducing the principles of innovation and digitization for project management, in a production sector too tied to traditional logics. The numerous digital processes that have been developed since then have largely concerned the design of new buildings, and are mainly related to the discipline of construction management. Some first experiments carried out over time have shown how the extension of this methodology to existing buildings involves many difficulties, which have been the subject of this thesis.

In this panorama, the thesis work is focused on the management of structures in the pre- and post-earthquake phases, with the objective of developing digital processes based on the use of innovative technologies applied to both ordinary and historic buildings.

The first workflow developed, pertaining to the pre-earthquake phase, has been named scan-to-FEM, and it aims to particularize the classic scan-to-BIM process in the field of structural engineering, thus analyzing all the steps from the survey of the building with the digital techniques of photogrammetry and laser-scanning up to the structural analysis and the calculation of the seismic safety index. Although the application of this process has proved to be very convenient on ordinary buildings, the same cannot be said of historical buildings, where the presence of many unique objects and decorations limits its application, which sees its level of automation reduced.

The post-earthquake structure management processes are instead focused on the estimation of the safety of the structure and the definition of intervention strategies, and are based on the analysis of the intrinsic characteristics of the structure and of the damages induced by seismic events. The entire process of assessing the operative level of a building has therefore been reviewed in the light of modern digital technologies. In detail, Convolutional Neural Networks (CNNs) have been developed for the inspection of cracks, and the extraction of numerical information associated to them, then managed thanks to BIM models. The cracks were then digitalized by defining a new object "crack" (currently not encoded in the IFC standard), to which was added a set of parameters partly evaluated with CNNs and partly qualitative.

During the development of these processes, any expedients were used several times to force existing BIM authoring software. For this reason, thanks to the collaboration with ACCA software, new ad-hoc tools have been developed for the management of existing buildings. In particular, any specifications have been defined for the development of digital damage datasheets, and any others for the creation of a new BIM object "crack".

The management processes for damaged buildings, thanks to the technological developments carried out, have been applied for the digitization of the historical building of the San Pietro in Vinculis church, damaged after seismic events, thanks to which the maximum benefits in terms of time reduction and resources saving have been experienced thanks to the contribution of digital technologies.

INTRODUCTION

Preliminary remark

The activities I have carried out in this three-year period of industrial PhD were part of the Programma Operativo Nazionale (PON) Ricerca e Innovazione 2014-2020, with reference to Asse I “Investimenti in Capitale Umano”, Azione I.1 “Dottorati Innovativi con caratterizzazione industriale”.

This program supports the promotion and strengthening of higher education and post-graduate specialisation at doctoral level in line with the needs of the national production system, including also the specific needs related to Industry 4.0 and skills in the "big data" sector, for those disciplinary areas with a strong scientific-technological vocation in the less developed Italian regions (Basilicata, Calabria, Campania, Puglia and Sicily, Abruzzo, Molise, Sardinia). In this context, doctoral training is characterized by a strong industrial interest and the involvement of companies that carry out industrial activities aimed at the production of goods or services. During this course, a period of study and research was also carried out at the company ACCA software S. p. a. and a period of study and research in Germany to qualify the training and research experiences "in an industrial sense".

In the context of this program, the research direction that I have pursued is characterized by a strong applicative feature given by the use of theoretical knowledge already known but not widespread for practical purposes, aimed at the development of new products in the technological field, and therefore departs from the traditional "fundamental research" whose objective is the advancement of theoretical knowledge and does not necessarily involve applicative outcomes. In fact, the Associazione Italiana per la Ricerca Industriale (AIRI) defines applied research as a mix between industrial research and experimental development. In detail, the first of them consists of planned research supported by critical surveys aimed at acquiring new knowledge and skills, to be used to develop new products, processes or services or to make a significant improvement of existing ones. It is aimed at the creation of complex products and may include the construction of prototypes in a laboratory environment, software applications in a computer environment and the development of guidelines for the use of innovative techniques and technologies.

Experimental development, on the other hand, consists of the acquisition, experimentation and combination of existing scientific, technological, commercial and other knowledge and skills in order to develop new or improved products, processes or services. Experimental development includes the construction of prototypes, demonstration, pilot product development, testing and validation of new or improved products, processes or services, carried out in an environment that reproduces real operating conditions with the primary objective being to bring about further technical improvements to products, processes and services. Experimental development may therefore include the development of a prototype or pilot product that can be used for commercial purposes whose manufacturing cost is too high to be used for demonstration and validation purposes only.

The main objective of industrial research is technological innovation, i.e. the improvement of existing technologies or processes and in some cases their overcoming, thanks to the rising of new technologies that replace those that belong to a past technology unprofitable and obsolete for the times. Technological innovation can be incremental, if it results in minor changes to existing products

and processes, or radical, if it results in technological implementations that significantly change the way products are designed and implemented or processes are thought about.
For this reason, during my PhD I provided support for the definition of the requirements of an openBIM platform for the management of the Common Data Environment (CDE), i.e. the formative environment in which all the stakeholders of a building process exchange information. This platform has then been expanded with new computer applications that make it suitable for extending the application of the BIM methodology to existing buildings, including the historic ones, despite it has been developed only for the design of new buildings.
Several tests of the computer applications have been carried out with numerous case studies, so that they will be analyzed more in depth in the body of this thesis work. Taking advantage from them, many improvements have gradually been defined that have led to the development of beta versions of the applications, but which may be ready for commercialization in the short term.

Description of the Ph.D program

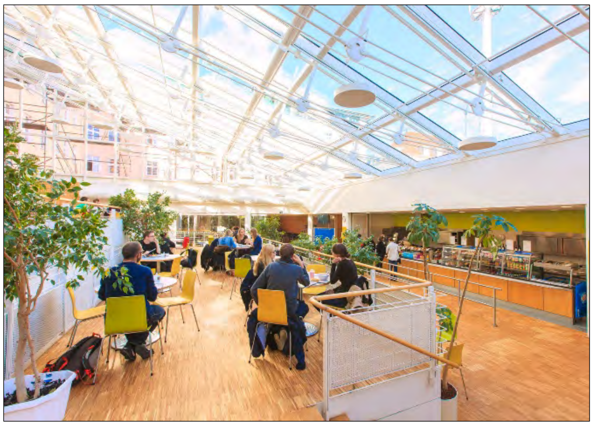
The PhD program was comprehended 3 phases:

- 2 years of study at the University of Naples Federico II;
- 6 months of study abroad in the German city of Leipzig, at the Hochschule für Technik, Wirtschaft und Kultur (HTWK);
- 6 months of internship in the company ACCA software.

In carrying out the activities, I have also expanded my cooperation with other companies, i.e. Deutsche Bahn Immobilien and the Stress S.c.ar.l. consortium.
During the first year, in the period spent in Naples, I studied the current applications of the BIM methodology, while in Germany I acquired some of the skills that allowed me to deepen the case studies carried out in the following years. In particular, I tested the use of laser scanners for digital surveys of existing buildings. Also significant was the collaboration with the German company Deutsche Bahn, which allowed me to carry out the first application pertaining the use of collaborative platforms for the information management of ordinary existing buildings. This collaboration was the first experience of a program that brought me closer to the industrial sector and also allowed me to "challenge myself" because the task of the activity was not defined from the beginning but it was an idea that evolved over time to get closer and closer to the needs expressed by the company.
During the second year, in the period spent in Naples I deepened the use of collaborative platforms for the information management of historical buildings, focusing on the case study of Palazzo Penne, in collaboration with ACCA software and Stress S.c.ar.l. Since this is a real case study (with the survey activities and the design of retrofit intervention already performed when my activity begun), I was able to analyze in detail the processes that were performed with traditional logic based on the documents produced and available, so that I could develop the new digital processes, optimized thanks to the introduction of new software applications. During the time spent in Germany, however, I continued to deepen my knowledge of digital surveying techniques, so that I tested low-cost technologies such as time-of-flight (ToF) cameras for the acquisition of three-dimensional geometries.
During the last year, in the period I spent in Naples I deepened the application of digital processes to existing buildings taking advantage of the most advanced technologies, with a focus on the

applications in the field of structural engineering. These processes included the scan-to-FEM method for the survey and the structural analysis of masonry buildings and the application of Artificial Intelligence for crack detection. During the internship period spent in the company ACCA software I had the opportunity to define the specifications for the development of new software applications, integrated in the usBIM management system, which simplify and make actually convenient the extension of the BIM methodology even for challenging application, such as for historical buildings. Therefore, beta applications have been developed and tested to be improved and made more and more suitable for use in real applications.

YEAR	**ISTITUTION/ COMPANY**	**ACTIVITIES**
I	Federico II	Study of the state of the art about BIM methodology (application on the design of new structures)
	HTWK Leipzig	Study and application of laser-scanning and photogrammetry techniques for the digital survey of existing buildings
	Deutsche Bahn	Use of digital platforms for the management of existing ordinary buildings
II	Federico II	Use of collaborative platforms for the management of BIM models and digital archives of existing buildings
	HTWK Leipzig	Study and application of low-cost digital surveying techniques
III	Federico II	Use of the scan-to-FEM method for the survey and structural analysis of masonry buildings and artificial intelligence methods for seismic damage detection
	ACCA software	Study of international open standards and development of innovative software applications for the information management of existing buildings



Hochschule für Technik, Wirtschaft und Kultur Leipzig campus (Germany)

ACCA software s.p.a. headquarters in Bangoli Irpino

Research questions

The objective of Ph.D program was to define guidelines for the application of the BIM methodology to structural analysis, documentation, retrofit and management of existing buildings, both ordinary and historical. The questions that have been the subject of study and investigation in this thesis work, basing on the evidence of the tests carried out, can be summarized as follows:

- Can the BIM methodology be applied for the management of masonry existing buildings despite the many difficulties involved?
- Up to which level of maturity and with which differences from the applications that are currently made for new buildings?
- Which are the BIM processes related to structural engineering that can be applied in the pre- and post-earthquake phases and how the structural information can integrate into the BIM model, taking advantage of the openBIM standards?

Methodology

The Ph.D program have been characterized by a significant applicative component. In fact, many innovative technologies and digital software tools have been experienced with the aim of understand how they can fit the construction processes and effectively improve the productivity of the AEC sector. Numerous case studies have been carefully documented and described in this thesis, reporting for each of them the tests carried out and the conclusions reached. Given the specificity of the object of the study, a distinction has been made between the processes for the management of buildings in the pre- and post-earthquake phases in order to define which of the digital techniques experienced can be applied to each of them and with what effectiveness.

The activities carried out have been supervised by experts with very different cultural and technical backgrounds, both in Italy and in Germany, including engineers (structural engineers and not), architects, archeologists and professionals belonging to the productive sector. This have allowed me to always have a very broad view of the problems faced and to expand my knowledge with very specific skills.

Contents

In discussing the research topics covered in this thesis work, numerous tests and applications have been carried out. Although all the case studies are focused on existing buildings, they have different peculiarities, depending on the health state of the building investigated, that were damaged or undamaged, the features of the buildings, that were ordinary or historic, their susceptibility to being retrofitted and the availability of information before at the beginning of the processes. All these differences required the development of different workflows to suit each case study.

Among the 5 application included in this thesis work, the last one concerns the church of San Pietro in Vinculis and represents the case study in which the maximum contribution of technologies has been made in order to get the maximum benefit, thanks to the experience gained in all the previous applications.

In each chapter are described in detail the methodologies, techniques and tools experienced, with critical considerations pertaining each of them and are explained the solutions to the problems that have arisen.

In the following table summarizes the intrinsic peculiarities of the different buildings used as case studies, which led to the definition of different workflows useful to manage a large number of existing masonry buildings.

Thesis contents

Case study	Type of building	Healthy state	Chapter	Role in the thesis	Documentation available	Survey and investigations	Model	Damage survey and implementation in the BIM model	Seismic vulnerability assessment
Knut's house	Ordinary	Healthy	3	Test and developement of a digital workflow for the vulneravilty assessment of masonry existing structures	-	Static laser-scanning	Semi-automatic modelling from point+cloud	Undamaged building	Static non-linear analysis
Marche building	Historical	Damaged by earthquake, to be repaired	4	Test and development of a semi-automatic methodology for seismic damage management and implementation in H-BIM models	CAD drawings	Survey on-site and visual investigations	Not-automatic from pointcloud	Automatic detection with CNNs and implementation in the model in its precise shape (high detail)	Empirical
Deutsche Bahn building	Ordinary	Degraded, to be repaired	5	Implementation of digital tools for damage management in ordinary buildings	Reports with the damages detected and paper drawings	Survey on-site and visual investigations	From CAD files	Implementation in the model with dedicated #TagBIM (low detail)	-
Palazzo Penne	Historical	Damaged by earthquake, to be repaired	5	Rethinking a real traditional workflow in a digital way, thanks to the use of CDE; development of BIM authoring tools for H-BIM modeling and management	Documental reports, reports of investigations, damage datasheets, CAD drawings	Static laser-scanning, destructive and non-destructive tests	From CAD files	Implementation in the model in its precise shape with dedicated tools (high detail)	Static non-linear analysis
San Pietro in Vinculis	Historical	Damaged by earthquake	6	Implementation of the tools developed for H-BIM modeling and management	Documentation of the epigraphs in the church	Dynamic laser-scanning + aerophotogrammetry	Not-automatic from pointcloud	Implementation in the model in its precise shape with dedicated tools (high detail)	Empirical

Thesis outline

This thesis consists of 6 chapters and 3 annexes.

In detail, *chapter 1* describes the background to the BIM methodology, with particular reference to the field of structural engineering. The low productivity that characterize the AEC sector are then described, and how these are related to the lack of digitalization, as could be observed with the comparison with other productive sectors. In particular, it is described how the lack of digitalization can be related to two causes, consisting in a lack of skills in the use of digital technologies and a lack of methodology capable of connecting them in well-designed workflows; it is emphasized that the latter cannot be separated from the openBIM standards developed by buildingSMART with the aim of making all the processes inclusive towards all the actors in the construction industry and minimizing the loss of information that occurs during the life cycle of an asset. Through the description of any case studies developed by different research groups, it is illustrated how the new technologies are significantly promising for structural engineering.

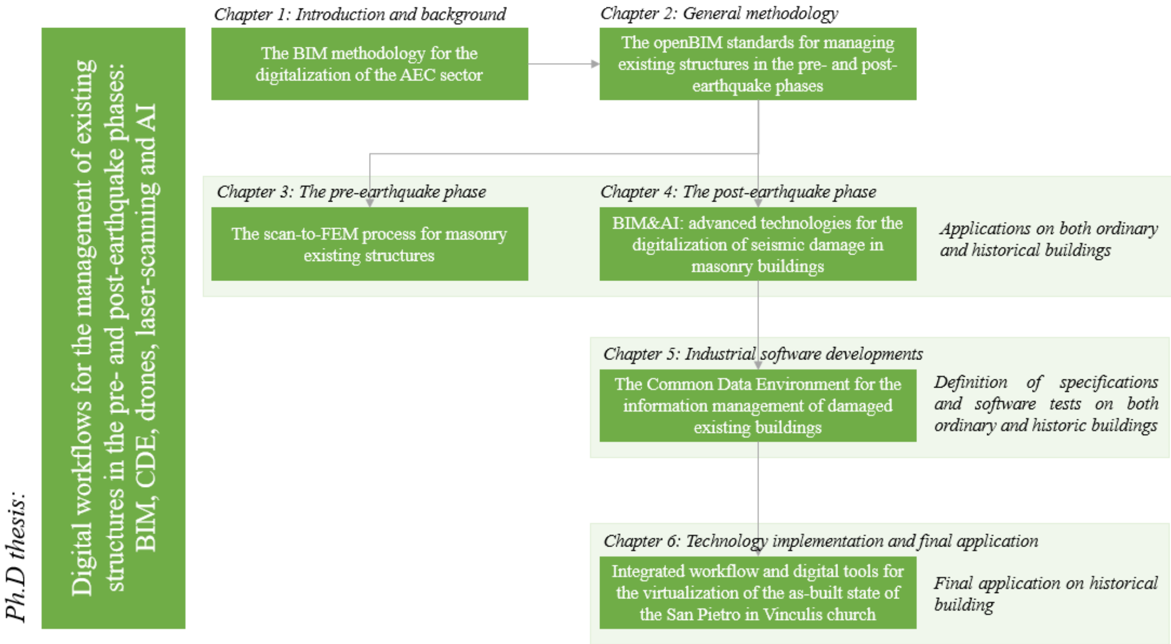
In *chapter 2* the general objective of the thesis is outlined, i.e. the definition of digital processes for the management of existing structures, in terms of preventive actions and processes that are triggered in the post-earthquake phase, up to the moment before reconstruction. It is evident that the actions that are implemented in these two phases are completely different from each other and therefore require separate analysis and discussion. The workflow for these processes were defined in an Information Delivery Manual and Process Maps, i.e. openBIM standards introduced for the description of processes and their information requirements. Then, in *chapters 3 and 4* are focused on applications carried out for the implementation of such processes on masonry structures. More in detail, *chapter 3* focuses on preventive actions, which consist in the survey and structural analysis, up to the seismic vulnerability assessment. In order to test the role that digital technologies offer in this regard, the scan-to-FEM method is discussed, which includes all the phases from the scanning of structures with the aid of photogrammetric and laser-scanner surveys, to the management of data and information through a software ecosystem that allows the definition of an analytical model saving time and resources.

In *chapter 4* the support that digital techniques offer to the management of buildings in the post-earthquake phase is explored. Applications have been carried out on the implementation of image-based Artificial Intelligence techniques, which have allowed the crack detection and the automatic extraction of damage information on masonry buildings, which has then been managed in a BIM environment.

While the study of the digital management of preventive actions led to the development of the scan-to-FEM method, which can be implemented with existing software applications, the post-earthquake methods are affected by more difficulties due to the lack of supporting BIM objects and to technological gaps, which were partly filled thanks to the collaboration with the software house.

In *chapter 5* it is then illustrated how information management can be greatly improved by the use of the Common Data Environment, implemented through collaborative platforms that are equipped with tools that make all useful information always available, and that drastically reduce non-productive working time. In addition, digital damage datasheets and BIM objects have been developed which are suitable to reference information about damages and mechanisms activated (or that can be activated) in masonry structures directly on the BIM model.

On the basis of all the techniques and technologies listed above, in the *final chapter* all the phases for the virtualization of the as-built state of existing buildings belonging to the cultural heritage are covered. This type of building are affected by the greatest difficulties so that a specific focus has been dedicated; in fact, the analysis of historical buildings has revealed peculiarities that make the digital management of these assets particularly difficult, which led to the birth of a specific branch of BIM, called Heritage-BIM (H-BIM). In particular, the BIM method has been applied to the case study of the San Pietro in Vinculis church, which is representative of a wide category of buildings located in the historical center of Naples, and which constitutes a useful reference for their possible digitization.



Thesis outline

List of the acronyms

ACDat	Ambiente di Condivisione dei Dati
AEC	Architectural, Engineering and Construction
AI	Artificial Intelligence
ANN	Artificial Neural Network
BEP	BIM Execution Plan
BIM	Building Information Model
CDE	Common Data Environment
CNN	Convolutional Neural Network
DL	Deep Learning
FCN	Fully Convolutional Network
FEA	Finite Element Analysis
FEM	Finite Element Model
GLCM	grey level co-occurrence matrix
H-BIM	Historic Building Information Model
ICT	Information and Communication Technologies
KL	Knowledge Level (trad. Livello di Conoscenza)
L	Livello Operativo
LC	Livello di Coordinamento
LOD	Level Of Develompment
LOIN	Level Of Information Need
LV	Livello di Verifica
R-CNN	Region-based Convolutional Neural Network
SHM	Structural Health Monitoring
SLD	Stato Limite di Danno
SLV	Stato Limite di Salvaguardia
TLS	Terrestrial Laser Scanning
ToF	Time of Flight
UAV	Unmanned Aerial Veichle

AUTHOR’S ACHIEVEMENTS

Skills acquired

In carrying out the activities many skills have been acquired in the use of numerous software, such as Edificius, Revit and ArchiCAD for BIM modeling, Edilus and Midas for structural analysis, Navisworks for clash detection, usBIM.platform for CDE, pix4D, VisualSFM and Agisoft Photoscan for photogrammetry, CloudCompare and other numerous applications for pointclouds post-processing.

Moreover, many skills have been acquired in the use of digital surveying instruments; in particular, during the time spent in Germany I was educated on the use of static laser-scanner devices, which I then continued to deepen during my research at the University in Naples. In particular, I have experienced the use of innovative mobile systems such as the Mobile Mapping System (MMS), which consists in mounting the laser scanner on a mobile devide in order to exploit the speed of movement to speed up the acquisition, and the Simultaneous Localization and Mapping (SLAM) technology that allows individuals in motion to survey an environment by drastically reducing the use of markers for point cloud recording. I then learned how to use time-of-flight cameras (ToF) to capture the 3D geometry of objects and environments.

I also licensed to become an UAV operator in open A1, A2 and A3 missions by passing the respective theoretical tests.

During the period spent in Germany, I also improved my English language skills, especially in the field of civil engineering, and acquired basic German language skills. I also achieved the BULTAS certification for business English with a B2 level in speaking, listening, reading and comprehension and C1 level in writing.

Industrial developments

Part of the studies of the training course has been focused on the application of the BIM methodology to applicative case studies, with the continuous collaboration of industrial partners in order to test and improve the working methods and the software tools.

More in detail, during the collaboration with the company Deutsche Bahn AG, the staff were shown the potential that innovative digital tools can bring to the practices carried out every day, with the aim of providing them with new methodologies that can simplify their working practices.

Then, significant was the collaboration with the company ACCA Software S.p.a., to which was provided support in defining specifications for the management of existing buildings with the collaborative platform usBIM.platform and the BIM authoring software Edificius. In detail, the new application usBIM.data has been implemented in the usBIM management system, for the creation of digital datasheets and the referencing of information as metadata directly on the objects of the BIM model. Moreover, specifications were provided for the creation of BIM "crack" objects, including the definition of the set of parameters, the methods of introducing them into the model and the methods of displaying them in two-dimensional views. It follows that with the Edificius software it is now possible to digitalize the crack pattern, an operation which is currently not allowed by other BIM authoring software.

Awards

The activities carried out for the industrial research project BIM ReCulT (Il metodo BIM per il Recupero del patrimonio CulTurale) have been included in the project "HBIM tools. Web-based collaborative platform & HistoricBIM Toolbar", focused on the case study of San Pietro in Vinculis and presented at Digital&BIM Italy 2020 together with DiARC, Sress s.c.ar.l and ACCA software. This project was the winner in category 7 "Digital technology for the constructive process", whose award ceremony was held on December 15, 2020. Annex C shows the report and the drawings of the project submitted for the competition, elaborated in collaboration with DiARC. A more extensive description of the activities can be found in Chapter 6.

Bibliographic production

During my PhD I took part in national and international conferences presenting the following contributions:

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- Musella C., Serra M., Menna C., Asprone D. - *BIM & AI: advanced technologies for the digitalization of seismic damages in masonry buildings* – Proceedings of the conference International fib Symposium on Conceptual Design of Structures, Madrid, September 2019
- Musella C, Di Stasio S., Asprone D. – *A workflow for structural tasks with digital tools – a case study in the Philippines hazard-prone area* – Proceedings of the 1st conference Drones - Systems of Information on culTural hEritage D-SITE, Pavia, June 2021
- Musella C., Serra M., Salzano A., Menna C., Asprone D. - *H-BIM – Innovative and digital tools to improve the management of the existing buildings* – Proceedings of the 4th International Conference on Protection of Historical Constructions PROHITEC, Athens, July 2021
- Lanzara, E., Scandurra, S., Musella, C., Pulcrano, M., Palomba, D., Asprone, D. and di Luggo, A.- *Parametric Modelling of vaults and shared implementation of the data in HBIM system*- Proceedings of the conference 3D Modelling&BIM. Digital Twin. Roma, April 14, 2021.
- Lanzara, E., Scandurra, S., Musella, C., Palomba, D., Pulcrano, M., Palomba, D. di Luggo, A., Asprone, D. - *Documentation of structural damage and material decay phenomena in H-BIM systems* – Proceedings of XXVIIIth CIPA Symposium Beijing 28 August-1 September 2021 (under submission and review process)

I have contributed to the following journal articles:

- Musella, C.; Serra, M.; Salzano, A.; Menna, C.; Asprone, D. - *Open BIM Standards: A Review of the Processes for Managing Existing Structures in the Pre- and Post-Earthquake Phases*. CivilEng, November 2020, 1, 291-309. https://doi.org/10.3390/civileng1030019
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- Musella, C, Serra, M, Menna, C, Asprone, D. - *Building information modeling and artificial intelligence: Advanced technologies for the digitalisation of seismic damage in existing buildings* - Structural Concrete. 2021; 1– 14. https://doi.org/10.1002/suco.202000029

Chapter 1:

THE BIM METHODOLOGY FOR THE DIGITALIZATION OF THE AEC SECTOR

Abstract

The construction industry is currently suffering inefficiencies due to the use of obsolete techniques. The advent of digitization represents an opportunity to change traditional working methods and rethink them in a completely new way with the aim of avoiding errors and optimizing resources. New technologies such as Building Information Modelling and the Common Data Environment provide valuable support in this direction by promoting collaboration and integration around a project. In the following paragraphs, their fundamentals are analyzed, highlighting the peculiarities of openBIM, which is designed to ensure maximum independence between working methods and specific software applications. More in detail, are here investigated digital applications that are increasingly affecting structural engineering, both through the interoperability of BIM models with structural analysis tools, and through investigations that involve further innovative technologies. The topics and themes covered in the section will be further discussed and development in later chapters.

1.1. The problem of productivity in the construction sector

While labor productivity across industries has increased by 25 percent in the past 20 years, in the construction industry, it has only grown by 5 percent. Interestingly, in the manufacturing industry, productivity has increased by nearly 60 percent (Fig. 1.1). This low labour productivity in the construction industry is one of its biggest showstoppers, effectively putting a brake on further innovation. It has become increasingly difficult for the industry to meet growing demand in the market. If productivity does not increase, more people will need to be hired and finding and retaining them remains a challenge. It also leads to higher prices, making it harder for construction incumbents to compete with new entrants.

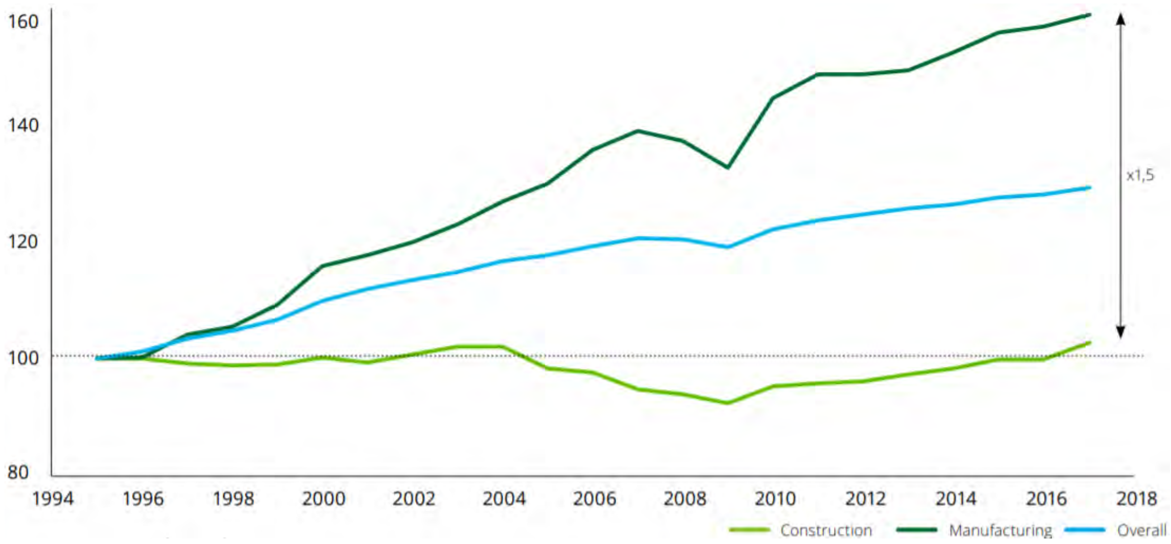


Figure 1.1: Standardized labor productivity growth 1995 - 2018 [1]

Innovations in IT are driving increased productivity in other industries. Many organizations, for instance, have shifted their ERP systems to a cloud environment and started working paperless in an effort to become more agile. One possible explanation for the low productivity in construction is that the industry is spending the least amount of money on IT compared to other industries. On average, IT spending is 3.5 percent of revenue and 4.6 percent of operating expenses. In construction, these percentages are respectively 1.2 and 1.3 percent. Tight margins in construction possibly contribute to low IT spending. The margins in the construction industry are under pressure. Companies are taking on projects at low prices, but most projects take longer to finish than scheduled, and some of them are up to 80 percent over budget. Migration and management of risk needs further attention in the industry.

During times of challenges, opportunities arise. Digital Construction is defined as utilizing digital technologies to construct more efficiently with higher quality. Many of the emerging technologies have already proven themselves and they offer numerous opportunities for the construction industry throughout the entire construction life cycle (Fig. 1.2). A recent example of new technologies aiding the construction industry is the renovation of one of the world's major landmarks: Notre Dame. After the devastating fire, discussions regarding its renovation sparked inspiration from unexpected corners. Back in 2015, an Art History professor had 3D scanned the entire cathedral, generating over a billion data points and creating a high-resolution digital blueprint. His work will aid in mapping the building with great precision, allowing for detailed and careful decision-making [2].

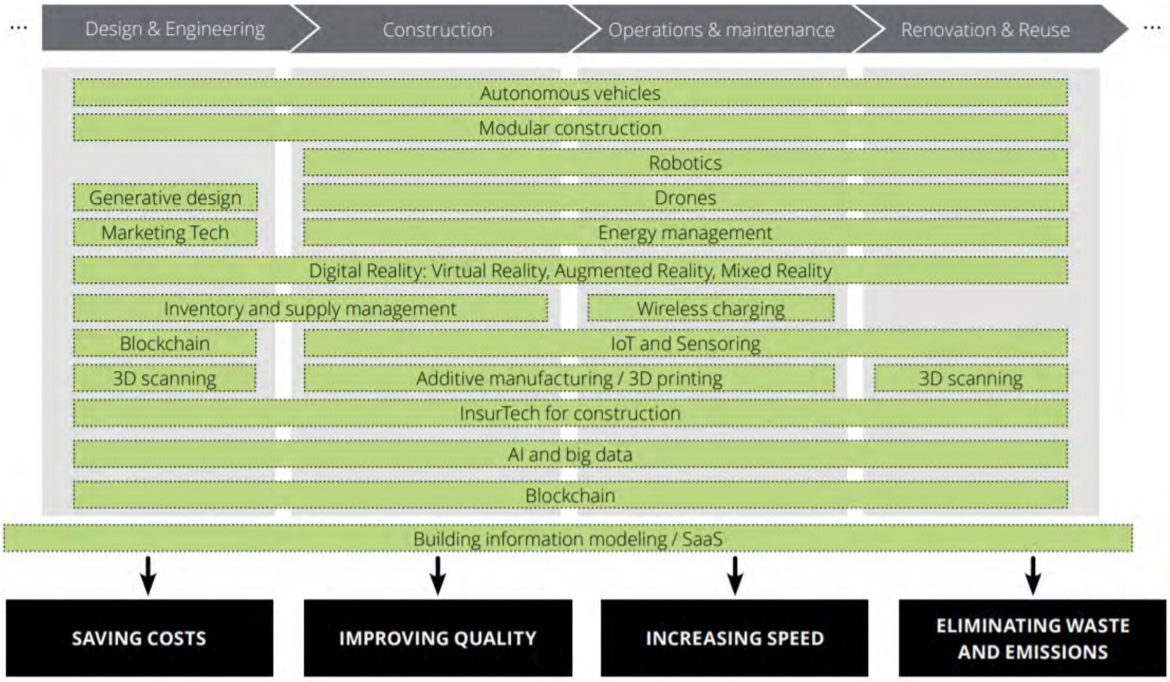


Figure 1.2: Digital technologies throughout the construction lifecycle [3]

1.2. Ecosystem of digital technologies for the construction industry

The technologies identified in Fig. 1.2 represent fragmented portions of a more complex concept that goes under the name of the digital ecosystem. Actually, the concept of ecosystem has been introduced in the field of biology, and identifies all living organisms and non-living matter that interact in a given environment constituting a self-sufficient system in dynamic equilibrium. Bringing up the term in the context of digitization, for "digital ecosystem" we mean the whole of computer environments and community of people who interact, exchange information, combine, evolving in terms of knowledge, skills, contacts, in order to improve the business and meet the needs [4].

In this regard, Blanco et al. [5] have carried out studies aimed at analysing the emerging trend of digital technologies and the way they are being taken up by the productive sector of companies. They found that after decades of under-digitization, the engineering and construction (E&C) sector is making bold moves in a new era evolutionized by digital technologies.

In the continuous mapping of the construction technology landscape, occurred the concept of different “constellations” of connected solutions emerging around established use cases, which serve as indicators of what technologies are gaining the most traction and where their impact can be expected to rapidly increase in the near future. Today, the most prominent constellations include 3-D printing, modularization, and robotics; digital twin technology; artificial intelligence (AI) and analytics; and supply chain optimization and marketplaces.

Within each constellation are three or more use cases that span the three use case clusters: on-site execution (“field”), digital collaboration (“team”), and back-office and adjacencies (“office”). For example, the digital twin technology constellation includes drone-enabled yard inspection, which is an on-site execution use case, as well as several digital collaboration use cases: laser scanning, virtual learning, and design simulation. In Fig. 1.3 the thickness of the lines connecting various use cases indicates use cases that are often addressed together; in the digital twin technologies constellation, design simulation and virtual learning are strongly linked given the increasing amount of solutions offering these two uses cases in combination.

In particular, three of the constellations—3-D printing, modularization, and robotics; twin models; and artificial intelligence and analytics—are poised to be transformational for the industry. A fourth constellation, supply chain optimization and marketplaces, is notable due to its quick rise, as dozens of smaller players have entered into this market over the past year.

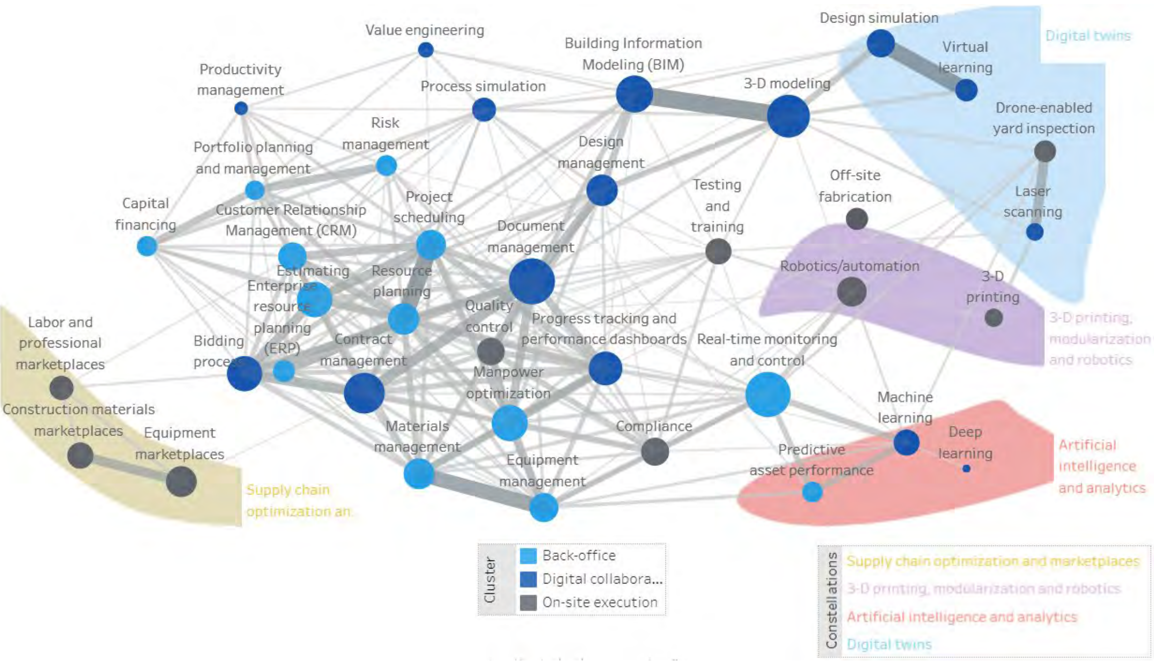


Figure 1.3: Mapping the construction technology ecosystem [6]

Artificial intelligence and analytics

In the long-term, AI and analytics have boundless potential use cases in E&C. Machine learning is gaining some momentum as an overarching use case (i.e., one applicable to the entire construction life cycle, from preconstruction through O&M), particularly in reality capture (for example, in conjunction with computer vision) as well as for comparison of in situ field conditions with plans (for example, supporting twin models). Indeed, by applying machine learning to an ongoing project, schedules could be optimized to sequence tasks and hit target deadlines, and divergences from blueprints could be caught closer to real time and corrected using a variety of predetermined potential scenarios.

In the immediate future, AI’s proliferation in the E&C sector is expected to be modest. Few leaders have the processes, resources, and existing data strategies in place to power the necessary algorithms and meaningfully implement this technology. However, the potential impact is so large that the industry can no longer afford to ignore it. AI methods are increasingly able to work across industries, elevating the threat of competition from nontraditional market entrants and a narrow set of start-ups are already gaining market traction using AI-focused approaches [7].

3-D printing, modularization, and robotics

Parts of the construction industry are moving toward a manufacturing-like system of mass production, relying on prefabricated, standardized components that are produced off-site. Our research finds that consistent use of these techniques, on projects where they are economically feasible, could boost the sector’s productivity by five- to tenfold. Such a system would include applications such as fully automated prefabrication processes that turn a 2-D drawing or 3-D model into a prefabricated building component, or fabrication directly off a 3-D model or shop drawings; construction robotics such as bricklaying or welding robots; self-driving heavy machinery to make construction safer, faster, and more affordable; exoskeletons and wearable robotics to improve the mobility of workers with injuries or to harness the strength of robotic arms; and metal 3-D printing of long-lead components such as joints, enabling the production of high-performing components and, ultimately, more efficient, cost-effective parts.

On the robotics side, the E&C industry is at the beginning of its journey to embrace the hardware innovations that enable field augmentation with exoskeletons and drone-enabled yard. These advances are particularly important given a labor shortage in many geographies as well as the natural ceiling of human physical productivity. Pairing humans with robots can assist in tasks that would take a human worker more effort (for example, lifting heavy objects and placing them in exact coordinates).

Digital twin technology

In E&C, productivity gains are directly driven by transparency and proactive problem resolution. Digital twin platforms and reality-capture solutions enable stakeholders to minimize rework in the field by allowing a dynamic view of the project and real-time comparison of progress to design blueprints—and the ability to adapt those blueprints as the work progresses and inevitably results in changes. Drones and satellite imagery, as well as LiDAR and photosphere based-solutions are key components of many reality-capture efforts.

The most exciting applications of twin models can be found in the seamless integration of 3-D models generated by drone imagery, turbocharged by live key performance indicators that are monitored using Internet of Things sensors. This approach creates an exact digital replica of a project’s physical reality, allowing us to rapidly advance data accuracy and incorporate as-built data into 3-D models for automated, real-time progress updates. It also enables users to virtually interact with “mixed reality” models that combine 3-D design and as-built configurations. What is truly exciting about these applications is the ability to reduce decision-making cycles in a construction project from a monthly basis to a daily basis through full automation of the project’s scheduling and budgeting updates.

Supply chain optimization and marketplaces

Currently, procurement of materials, equipment, and labor is a largely manual and cumbersome process. However, start-ups that offer marketplace platforms for the buying and selling of goods as well as hiring have begun to gain traction in certain regions. Some of these start-ups have been acquired by large suppliers, which have quickly deployed these platforms at scale. By enabling players to match supply with demand, these marketplaces have huge potential to optimize the supply chain—much the way such marketplaces have revolutionized industries such as retail—improving productivity and profitability. In construction, these marketplaces can also enhance competitive bidding by improving transparency on costs and availability of materials, labor, and equipment for both future and ongoing projects. They will also become increasingly important given the rising use of prefabricated components that are manufactured off-site. Despite the progress, this constellation is nascent and limited to North America. Also interesting, is the analysis on what is the evolutionary trend of the market as a function of the technologies that are gradually emerging. Mapping the number of transactions in 38 use cases against the number of new companies in the past five years in that space reveals a detailed picture of the current construction market (Fig. 1.4). Four features emerge:

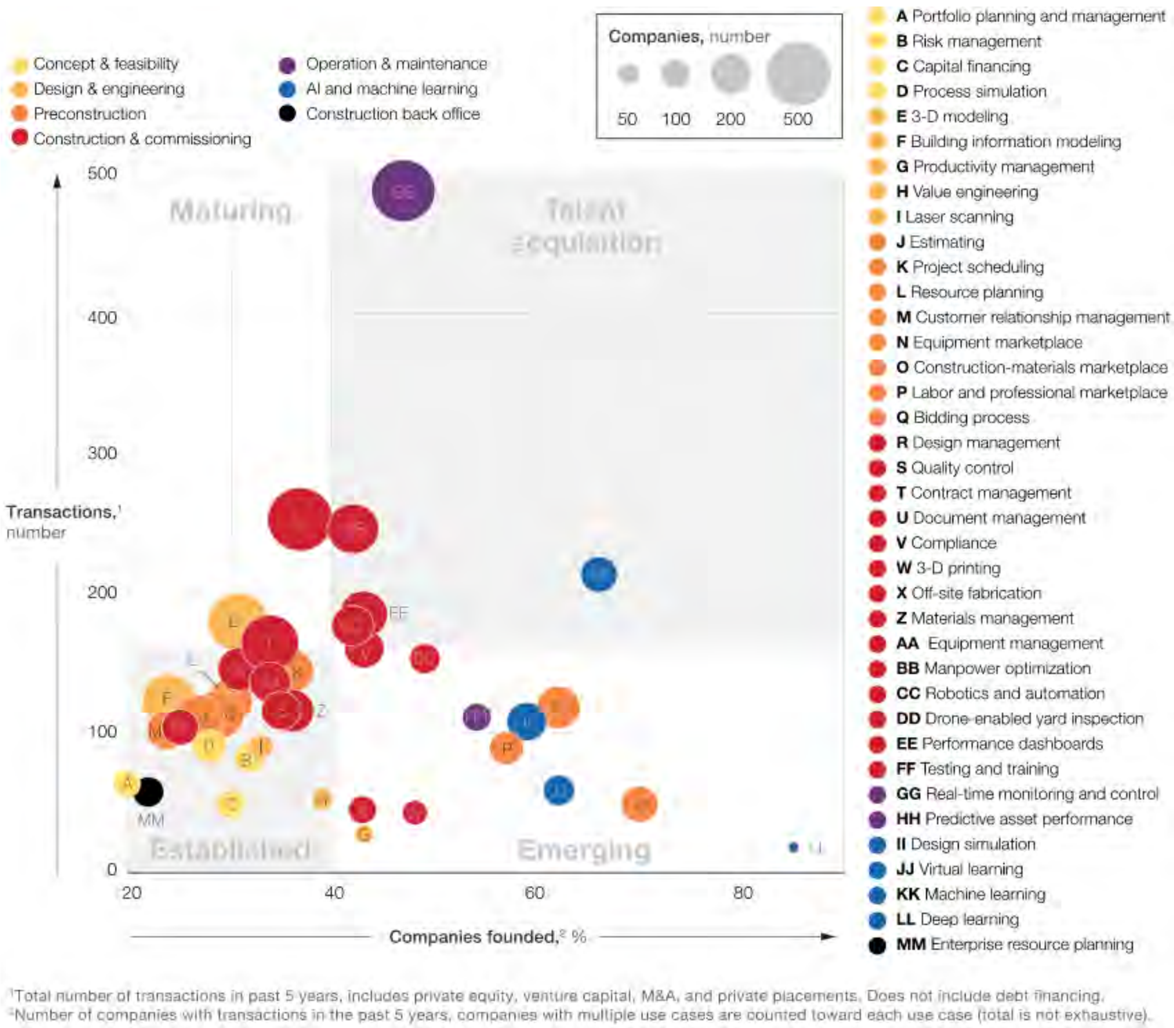


Figure 1.4: Mapping the number of transactions in use cases against the number of new companies in the past five years [8]

1. *Talent acquisition*. In the upper right quadrant, there are both a high concentration of new companies and a high number of transactions in machine learning, among several other use cases. This quadrant can be described as "talent grab," which means that companies are using acquisitions to onboard new talent and skills.
2. *Emerging*. In the lower right quadrant, we find use cases, such as deep learning, where there are many new companies but not a lot of transactions, suggesting these use cases are primed to emerge into the tech investment space in the next few years.
3. *Maturing*. In the upper left quadrant, we find use cases, such as document management, with many transactions but relatively fewer new companies, suggesting that relatively established companies operating in a fragmented market dominate these use cases. These areas may thus be facing consolidation in the near future.
4. *Established or unproven*. Finally, in the lower left quadrant we find established or unproven use cases, such as enterprise resource planning, where few new companies and few transactions are underway. These markets may be saturated—but for the exception of some use cases, such as laser scanning, that have simply not yet realized momentum.

The fragmentation of technology offerings will continue to be an issue. In the analysis conducted in 2017 by Blanco et al., just 13 percent of the companies we studied had engaged a technology solution that addressed more than one of the three clusters (on-site execution, digital collaboration, and back-office and adjacencies)—meaning that most companies are engaging solutions that address a very specific, narrow application rather than solutions that are more integrated. This year's research confirms that more than half of companies are still engaging a solution that addresses just 1 or 2 use cases out of the 38 (Fig. 1.5).

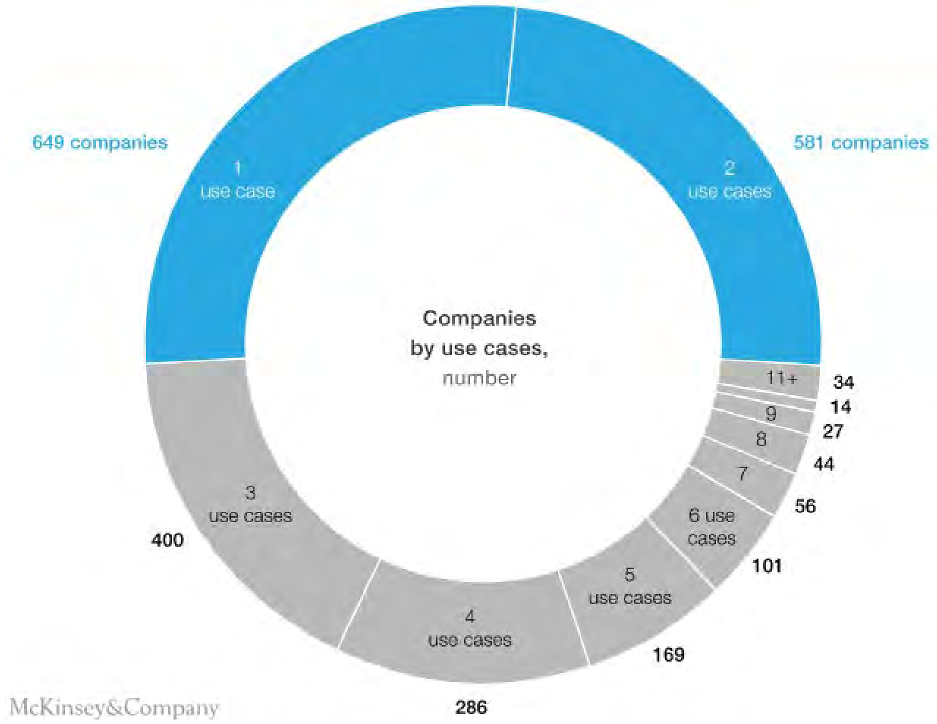


Figure 1.5: Multiple use cases for integrated solutions in 2018 [5]

There are two aspects that need to be considered as a challenge in the innovation process, that are the fragmentation of the technologies ecosystem and finding workers with digital skills.

About the first of them, this fragmentation is one of the biggest challenges that companies want to engage with technology solutions. Many are older, venerable companies using legacy systems and various information-collection methods. For these companies, integration may sound more like it is yet another solution to layer in on the top of all the other processes and solution on hand—when in fact, technology can be used to cut down on the number of solutions and methods being used. The lack of use case integration is one of the drags on technology adoption at scale. As such, more companies are exploring the potential to consolidate solutions that address multiple use cases. While integration will not "grease the wheels" of every aspect of technology adoption, it certainly represents a viable path forward to bring more layers up to speed.

About the second aspect, finding digital talent is a prominent concern for executives across the industry. It will be critical to digitization: according to research by McKinsey's Digital Academy, investing in talent makes increases the odds of digitization success by 2.5 times. Investing in talent requires balancing the entrepreneurship DNA, industry knowledge, and business acumen to build business unit from scratch—but the talent pool is small when it comes to balancing these three skill sets. Among the digital technologies recently implemented in established practices is that of BIM, which also aims to create connections between the several technologies reviewed.

1.3. The acronym BIM: building information model, modeling and management

The National Building Information Model Standard Project Committee defines BIM as:

"Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition."

A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder.

The National Institute of Building Science (NIBS), a non-profit organization authorized by the U.S. Congress to conduct research in the construction industry, coined the neologism BIM^3 (cubed), where the acronym BIM has 3 meanings [9]:

1. Building Information Modeling: Is a BUSINESS PROCESS for generating and leveraging building data to design, construct and operate the building during its lifecycle. BIM allows all stakeholders to have access to the same information at the same time through interoperability between technology platforms;
2. Building Information Model: Is the DIGITAL REPRESENTATION of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onwards;

3. Building Information Management: Is the ORGANIZATION & CONTROL of the business process by utilizing the information in the digital prototype to effect the sharing of information over the entire lifecycle of an asset. The benefits include centralized and visual communication, early exploration of options, sustainability, efficient design, integration of disciplines, site control, as built documentation, etc.– effectively developing an asset lifecycle process and model from conception to final retirement.

1.4. BIM adoption in Europe and in the world

The need to standardize processes and to regulate all the procedures established for the BIM methodology have led to the institution of BuildingSMART, an international organization that groups together twenty-seven Countries with the aim of developing openBIM standards and carrying out development policies and disclosure. The Italian chapter of buildingSMART is chaired by Anna Moreno. The main industrialized states that are part to the project are: USA, Canada, China, Japan, Korea, Singapore, Australia, Holland, France, Germany, Spain, Norway, Sweden, England and Italy. BuildingSMART's main objective is to standardize in a single format the data that can be used with the BIM methodology in order to ensure interoperability among different disciplines and different data. Each individual country is, however, developing its own strategies for the inclusion of BIM in the construction chain following the guidelines laid down by that organization.

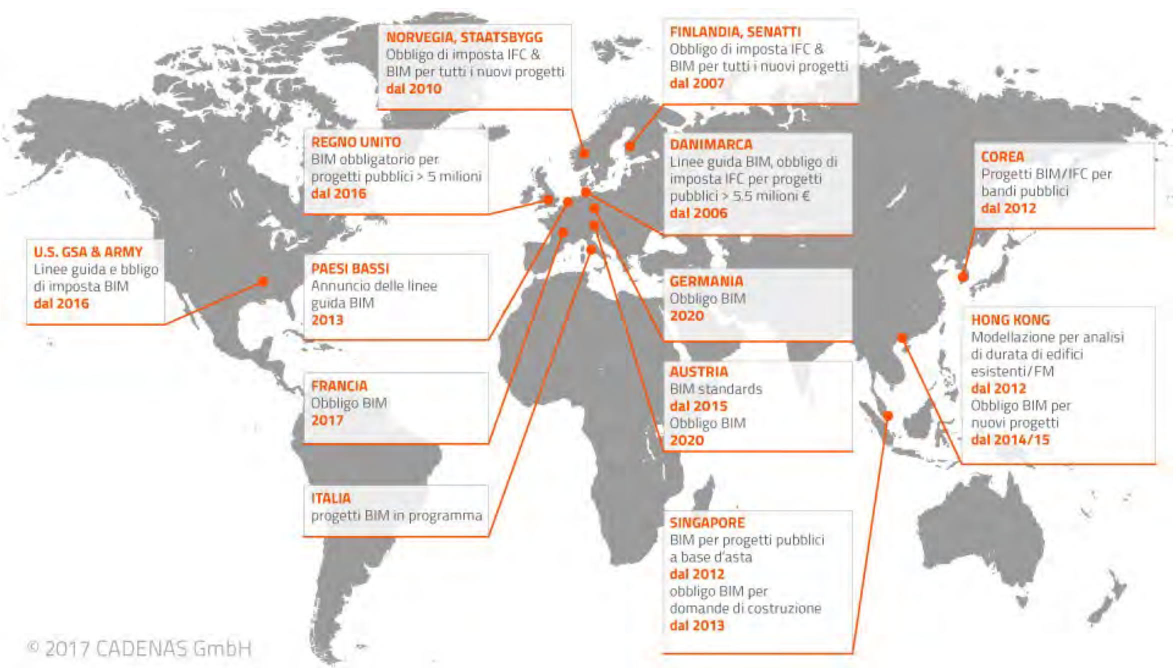


Figure 1.6: Main BIM countries and standards in the world [10].

The Scandinavian countries and the United Kingdom represent European excellence in BIM.

In *Finland* BIM is at a very advanced stage and there are already companies that use it for the management of the entire life cycle of the work; it represents the state of the art on the diffusion of BIM standard for design of new buildings. For example, a public institution responsible for real estate, the Senate Properties, has promoted the use of BIM models and the IFC format through some pilot projects since 2001 and has published the Common series BIM Requirements 2012, the result of an extensive research project on the topic, strongly required by the associations of entrepreneurs and building materials manufacturers to standardize the project processes and, above all, the methodologies of data exchange between the various interlocutors involved. In a few years, almost of 70% of the projects ere managed according to the BIM approach, thus quickly becoming a standard. The Finnish government authorities have been requesting a BIM model in public tenders since 2007.

With very complex infrastructure projects (such as the E4 Stockholm Bypass) and some large scaled building projects (including the largest public / private hospital project in the world), *Sweden* shows many similarities with the Finnish model. In this regard, a very important project is the New Karolinska Solna Hospital (NKS), the largest public-private partnership in the hospital sector in the world, involving an overall investment of 3 billion dollars. The project demonstrated how the BIM model and prefabrication could increase the speed and quality of construction as well as environmental sustainability.

Similarly, both in Denmark and in Norway, its use has been promising since the beginning of the new millennium.

In *Norway*, the Norwegian Directorate of Public Construction and Property Management drove the dissemination and use of the standardized methodology has reached very high levels. There has been a great deal of awareness on the subject, which has led to the publication, among other things, of the Statsbygg BIM Manual, which has become a reference point for bodies and designers who want and must adhere to the standards dictated by the public building management body.

Denmark approached to this new reality during 2006, when the 3D Working Method and the 3D CAD Manual have been published concerning the methods of creation, exchange and reuse of three-dimensional models in the different design phases. A further contribution to the dissemination of the integrated work methodology came from the three public institutions owning properties (the Palaces and Properties Agency), the Danish University and the Defense Construction Service. They imposed the BIM approach for the facility management of their goods as well as for the design and construction of new buildings, thereby affecting the entire real estate market.

In the *United Kingdom*, on the other hand, the government set up a "BIM Task Group" with the objective to bring the use of BIM at Level 2. The British Government aims to achieve a reduction in the costs of public works and carbon emissions by 20%. For the purpose, in 2011 public projects were established to become mandatory by 2016. The Cabinet Office of the Government published in May 2011 the policy document that set these goals, i.e. the Government Construction Strategy. Among the several institutions that aim to raise awareness in the construction industry on the issue of BIM, the National Building Specification (NBS) is certainly one of the most dynamic. In close synergy with the Royal Institute of British Architects, the NBS is working on improving communication between manufacturers, companies and designers.

In *France*, the Plan Transition Numèrique dans le Bàtiment (PTNB), launched in 2014 and completed in 2017, has provided funding of €20 million to support national policies for the digital development of construction. The purpose of the plan was to allow the "transition" of the sector, from enterprises to institutions, to the new working methods based on BIM, without, however, making compulsory its use. For the purpose, a series of major projects, infrastructures and public works were launched, in which all the potential offered by BIM was immediately applied in the field. The adoption of this ambitious program has also allowed the construction of 500,000 new homes, designed and built with BIM tools. The French BIM strategy has also been supported through the national project Modélisation des INformations INteropérables pourr les INfrastructures Durables (MINnD) coordinated by IREX and including almost 60 national partners (divided between companies, institutions, universities, etc.). The next major public project with the application of BIM, is the "Europa City" plan which is being developed in Paris over an area of 800,000 m² with: 500 shops, green spaces, hotels, recreational and sports areas. The completion of all works is scheduled for 2021.

Germany has promoted construction innovation with a bottom-up approach. Starting from the associations and local working groups, the national strategy called "Stufenplan Digital Planen und Bauen" was developed and started in 2015 with the economic support of the Ministry of Infrastructure and Digital Construction. The strategy is based on the implementation, by 2020, of several pilot projects used to test the benefits of BIM environments. Futurium Berlin is one such pilot project, an essential reference to understand the level of diffusion/adoption of BIM in Germany. Promoted by a public-private partnership, the plan covers an area of 8,000 m² and has a budget of 58 million euros: work began in 2017 and was completed towards the end of 2019. Currently in Germany the use of BIM for public projects with investments of more than 5 million euros is now an established practice, so the country is now ready to make the use of this digital tools mandatory for the design and construction of all public works.

In *Ireland*, despite the absence of regulatory obligations on BIM, the need for digital and sustainable innovation in the construction sector is a priority for the government. Both from an economic point of view, with the financing of specific training courses, and thanks to the research of techniques and work processes in the AEC sector; BIM is already a consolidated reality, widely acquired, in the Irish academic and university world. As far as public plans are concerned, it should be noted that since 2014, the construction strategy for 2020, published by Enterprise Ireland, has financed BIM based construction plans with 200 million euros. NBC Ireland has also been established, the Strategic Council that will coordinate, plan and draft new policies aimed at developing digital design and achieving BIM Level 2. The NHC-New Children's Hospital is the largest, most complex and significant BIM project ever undertaken in the Irish health sector. The BIM model/project has made it possible to better design the spaces, optimize the use of unused areas and allow a rapid/practical sharing of data and information between the entire technical team. Another key project for the development of Ireland's BIM was the Corrib Onshore Gas Pipeline Compound tunnel, an energy infrastructure that covers the country's total energy needs for the next 20 years: a work started in 2011 and finished in 2016. The project has also been awarded as best Engineering Project in the world in 2016.

Spain has quickly integrated a high level of BIM adoption by technical agents and designers. The Spanish national strategy on BIM is called esBIM. Starting from 2019 it foresees the total inclusion of Building Information Modelling in the construction sector aligned with the Digital Agenda of Public Administrations. Recently, the inter-ministerial commission on BIM has been established with the aim of optimizing and speeding up the innovation process in this sector.

One of the main challenges that *Iceland* had to face through its construction digitization process was to adapt BIM strategies to small, medium and large companies. In 2008 the Government Construction Contracting Agency – GCCA signed the “Statement of Intention to support Building Information Modeling with open standards”. The Ministry of Finance has established that building projects by Ministries and government agencies should mandatory implement BIM processes in design and constructions since 2011. “BIM Iceland”, a council of public procurers, was later established to develop a common strategy and update the guidelines for the advancement of BIM in the public sector. Some infrastructure projects and large public projects have strongly influenced the Icelandic BIM strategies, such as the National University Hospital and the “Burfell II” hydroelectric plant. Burfell II is an underground hydroelectric power station, costing 212 million euros, which is created as an extension of 100 MW of the alreday existing Burfell plant. It was one of the first infrastructural projects built using BIM in Iceland. The project generated 42 BIM models and 4 point clouds for as built [11].

The European Community, with the approval on 15 January 2014 of the European Union Public Procurement Directive (EUPPD), clearly introduced the BIM methodology in the new European public procurement directive: "*For public works contracts and design contests, Member States may require the use of specific electronic tools, such as of building information electronic modeling tools or similar*" can be read in the text of the aforementioned directive.

Beyond the ocean, the *United States of America* represent the reference point in the sector, in both research field (theoretical and applied) and in professional practice. The United States, through the Public Building Service (PSBS) and the General Service Administration (GSA) have established the national program for 3D and 4D BIM by publishing guides which describe the methodology of work in the construction industry. The American Institute of Architects (AIA) in 2013 released guidelines that aim to correct use of BIM in civil works and that even today represent the reference protocols on the scale international.

Also in *Australia*, BIM is already a widely used tool for works in the national territory and, consequently, used by Australian companies for work abroad. In addition, a working group has been set up with the aim of improving construction processes, called National Specification System (NATSPEC), in which take part professional orders, constructors, owners and government groups. NATSPEC, in fact has drawn up and published the National BIM Guide Documents, as a reference point for stakeholders. Another document drawn up by NATSPEC and used as a valid reference on a worldwide scale is the NATSPEC BIM Scheduling guidelines, which defines the working methodology for the computerization of BIM objects and therefore the model for planning and programming purposes.

In *China*, similarly, BIM-Union has been established for promoting and coordinating the development of BIM and, in 2013, Technology the "China Industry Technology Innovation Strategic Alliance" was approved by the Minister of Science and focused on the development of BIM in the construction industry.

In *Hong Kong* was founded the Hong Kong Institute of Building Information Modeling (HKIBIM) which, together with the CIC (Construction Industry Council), aims to disseminate guidelines and train experts within each engineering discipline in BIM.

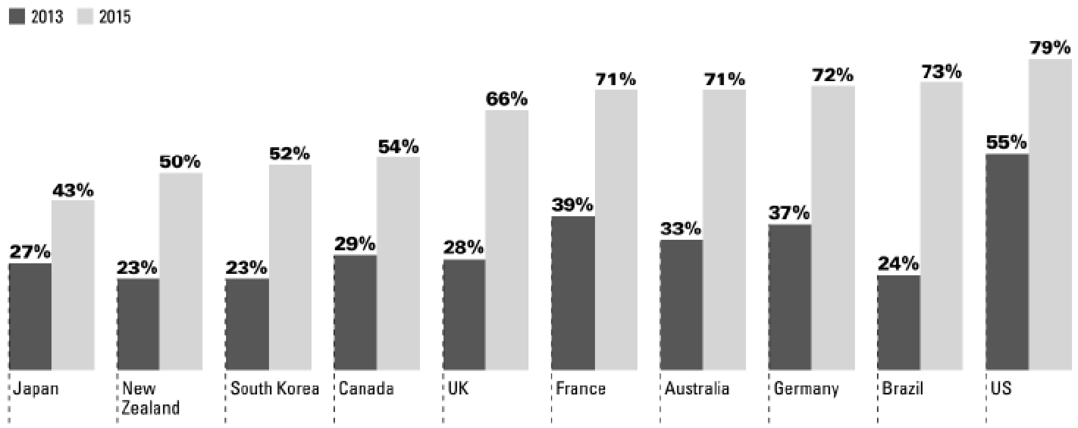


Figure 1.7: Percentage of Contractors at High/Very High BIM implementation levels (by Countries) [12]

Within this concise summary of the state of diffusion of BIM in the world, it is also necessary to mention countries in continuous evolution in the construction world such as the Arab Emirates, India and Singapore which require more and more BIM managers' skills in order to conform, as soon as possible, to the most advanced realities in the sector.

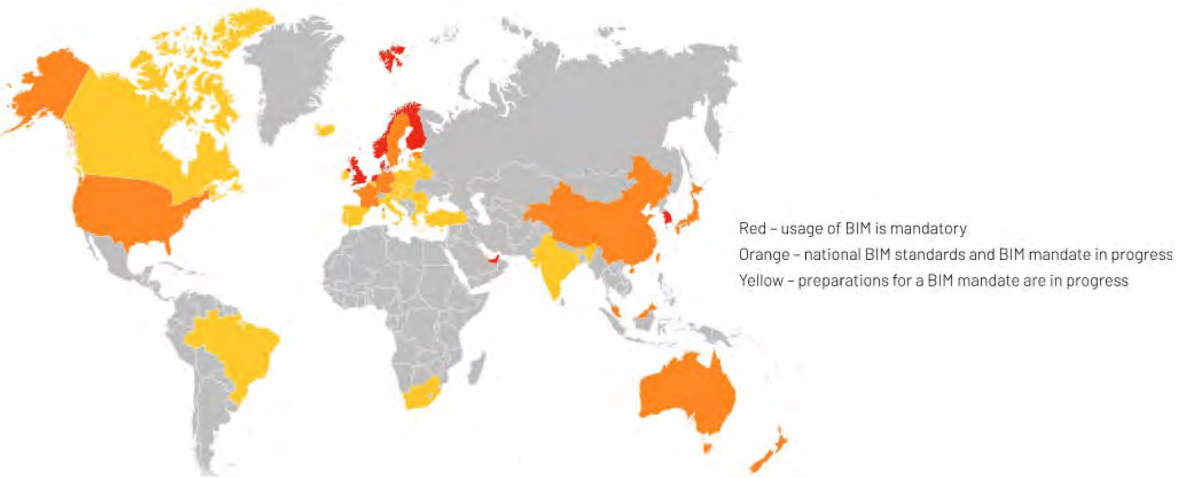


Figure 1.8: BIM diffusion in the world [13]

1.5. BIM adoption in Italy

In Italy, large engineering and construction companies, especially for large works, use BIM while it is not yet widespread in the fabric of SMEs. The Italian construction industry, unlike other productive sectors, still fails to take advantage of Information Communication Technology (ICT). The XIX CRESME Report (Centro Ricerche Economiche Sociali di Mercato) for the Building and Territory, considering the continuing crisis of the economic model of market, identifies precisely in innovation the obligatory path that must lead to redefine new strategies of the industrial construction system oriented to an overall redesign of products (real estate, cities, infrastructures), processes and offer models. Certainly, there is resistance to change; moving from unstructured, uncoordinated and almost never efficient information exchanges to an integrated supply chain based on collaborative working in BIM requires a big change [14].

Quoting the words of Machiavelli, in "Il Principe": "*E debbasi considerare come non è cosa più difficile a trattare, né più dubia a riuscire, né più pericolosa a maneggiare, che farsi a capo ad introdurre nuovi ordini. Perché lo introduttore ha per nimici tutti quelli che delli ordini vecchi fanno bene, et ha tepidi defensori tutti quelli che delli ordini nuovi farebbono bene…*"

Unfortunately, in Italy there are few Professional Orders, associations of Research Institutions and Universities that invest resources to spread this new digital culture, but above all organizational, of the building process. One of the first extensive research projects in the field of Building Information Modeling is InnovANCE, promoted by the National Association of Building Constructors and financed by the Ministry of Economic Development in partnership with other companies and public and private bodies that gravitate in the construction industry (such as ENEA, CNR and UNI) as well as the Polytechnics of Milan and Turin and the University of Naples "Federico II".

" Nel nostro Paese l'adozione del BIM è ancora agli inizi. Anzi, no: è 'prima dell'inizio" are the words of Luca Ferrari, chairman of the association Ingegneria Sismica Italiana (ISI) and manager of Harpaceas (a company that is currently one of the first Italian BIM experts). The adoption of BIM in Italy is still far from being a widespread and shared practice. The current working model is based on traditional methods and the exchange of information mostly through paper-based documents. It lacks a cultural background and a vision necessary to initiate a real change, based on integrated and shared ways of working, and a transition to digital infrastructure, despite the fact that BIM represents a long-term investment capable of allow for a reduction in time, thanks to the efficiency of the construction process, and of the management of the work, and would undoubtedly lead to a rationalization of expenditure.

The beginning of 2017, however, brought with it a number of interesting innovations. First of all, the publication of the first three parts of the new UNI 11337, the Italian technical regulation on "Gestione digitale dei processi informativi delle costruzioni". Of this standard, conceived in several parts (twelve parts are currently planned, but they could still increase in number), have been released Parts 1, 4, 5, 6 and 7. Secondly, one of the innovations introduced by the Nuovo Codice dei Contratti Pubblici (D.Lgs. n. 50, 18/04/2016) is the use of BIM models for design of new works. Its entry into force allows the Appointing Party to request their use for new works and design services, if the works are above the EU thresholds. The comma 13 of Article 23 of the Nuovo Codice dei Contratti Pubblici has delegated to a decree of the Ministry of Infrastructure to establish the modalities and timing of progressive introduction of the BIM for both administrations and enterprises. The Ministry of Infrastructure and Transport has set up a Commission for this purpose, made up of representatives from public administrations, academia and the national network of technical and scientific professions ("Commissione Baratono") in order to finalize the final text of the decree. Minister Graziano Delrio signed the so-called "decreto BIM" on 1 December 2017. It establishes the obligation to digitize public procurement contracts as of January 1st 2019 for complex works relating to works with a tender value of 100 or more million, with a gradual extension of the perimeter to smaller works, on 1 January 2025 for all new works. The measure also regulates the preliminary fulfilments of the contracting stations, which will have to adopt a staff-training plan, an acquisition plan or a plan of maintenance of hardware and software tools to manage decision-making and information processes and an organizational act that explains the control and management process, the data managers and the conflict management. The appointing parties shall be provided with interoperable platforms based on non-proprietary open formats for the use of the data and information produced and shared among all project participants.

The first virtuous example found in Italy is the call for tenders for the construction of the Ponte della Navetta in Parma, the first digital contract in Italy, published in the Gazzetta ufficiale of 28 July 2017. The final design, started in the traditional way after a competition of ideas, was carried out at the executive stage through the BIM by the Provveditorato Interregionale per le Opere Pubbliche di Lombardia e Emilia Romagna, led by Mr. Pietro Baratono (Chairman of the "Commissione ministeriale BIM"). The project involves the construction of a 70-meter walkway exclusively for pedestrians and bicycles on the Baganza stream (whose flood caused the historic bridge to collapse in 2014) at a cost of 1.34 million euros. The structural scheme is that of a lowered arch with steel ties (bowstring). The main feature of this work, beyond its importance in terms of mobility urban sustainable, is that it is a pilot project that will be developed by applying the provisions of the new Codice dei Contratti Pubblici. To the project documents has been added the Exchange Information Requirements (EIR), a real experimentation in the management of a BIM contract for a public work, which also contains the elements for an efficient data-sharing environment to support the implementation process, and management of the work. The informative models and the EIR have been built following the guidelines of the UNI11337 standard, published in February 2017. The EIR are an appendix to the Capitolato Speciale d'Appalto [15], in which are specified the requirements that the Appointing party requests for the information management of the entire supply chain, until the management of the asset. In order to achieve the purpose of the BIM experimentation, the Provveditorato required 3D modelling, with informative attributes, in support of the tender documents, drafted on the executive draft. The model has been requested in neutral and open format, so that it is available for any bidder, regardless of the instruments in use by the latter. Therefore, one of the constraints suggested by the new UNI 11337 standards is respected and, with the use of open IFC syntaxes, the UNI EN ISO 16739:2017 standard is used and recalled. The experimentation has also involved aspects that are not directly tangible, such as, for example, some traditionally dialectical processes between the works management and the construction company, with the aim of re-proposing them in a digital key imagining the use of a collaborative and archiving system that would configure itself as an "CDE" (Common Data Environment). The BIM process has allowed the highlighting of some issues related to the design inaccuracies and procedural flaws before they could turn into potential grounds for the contractors to retaliate against the client.

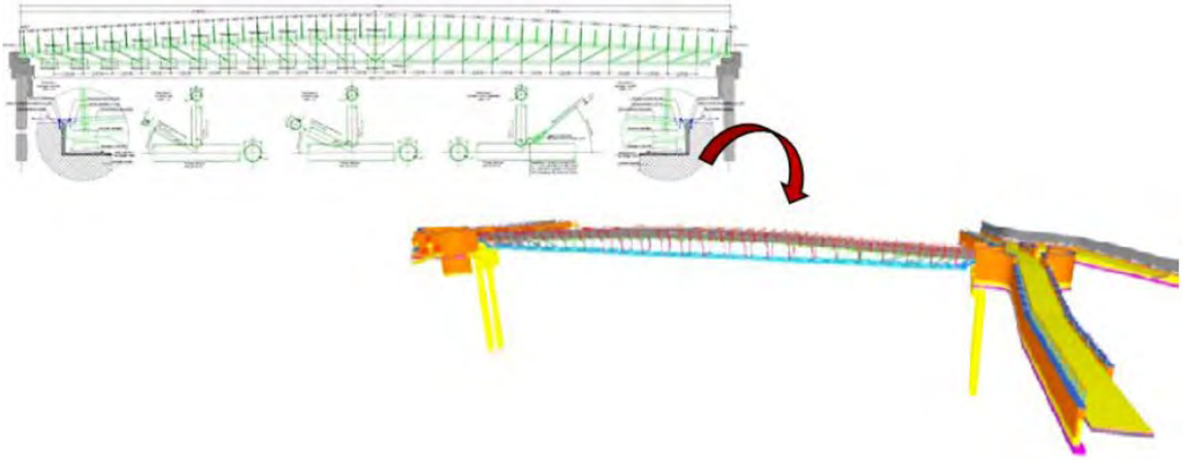


Figure 1.9: The traditional project (top) and the BIM model of thePonte della Navetta in Parma (bottom)

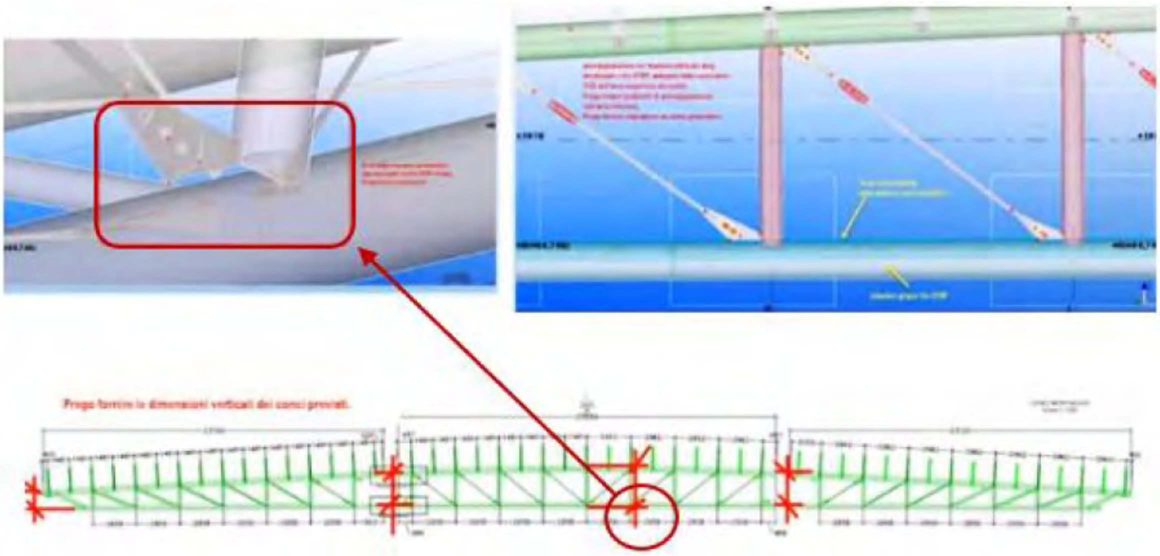


Figure 1.10: An example of design inaccuracy detected thanks to the model [16]

In conclusion, it is easy to see that the application of BIM in Italy will certainly be gradual in order to provide the time needed to reorganize the Appointing parties, train the people, the professionals and enterprises. The point is that organizations that decide to implement the methodology will not be able to do so only changing software or even by simply imposing new processes. The real change will happen when the people within the organization will embrace this methodology, adapting and changing the way they work. Many companies and firms, unfortunately, still believe that its introduction will involve additional costs and a lengthening of design time, especially because Italy is home to small and medium-sized companies that perhaps would not be able to cover the initial costs but would certainly gain an advantage, also in terms of competitiveness, in the medium to long term.

1.6. Little- big-, open-, closed-BIM

The concept of BIM can be interpreted differently depending on how it is implemented. For this reason, very often the term BIM is followed by four attributes, namely little-, big, open- and closed-BIM [17]. Among these, the first two refer to the dimensions involved, in terms of disciplines and project phases in which BIM is implemented, while the last two refer to how the information is exchanged.

More in detail, with reference to the dimension, it is defined:

- *little-BIM*, a BIM process in which a single planner for his specific planning uses only one BIM software. The BIM solution is used as an isolated solution in the specific field of activity of a specialist planner and communication with the outside world continues to be based on drawings. Efficiency gains can be achieved with little BIM, but the potential of a consistent use of digital building information remains untapped;
- *big-BIM*, a BIM process in which a collaborative, multidisciplinary model-based communication takes place between all participants over all life cycle phases of a building. Data exchange and coordination take place via Internet platforms and database solutions. Therefore, there is a systematic use of BIM and digital models throughout the entire life cycle and in all disciplines [18]

Both the size and complexity of the project influence the number of parties involved and the scope and frequency of the information exchange. The amount of data increases in proportion to the size of the project: the larger the project, the more consistent the amount of data and the more frequent the exchange of information needed. It follows that between little- and big-BIM there is a wide range of dimensions among which the 8 currently acknowledged are (Fig. 1.11):

- 3D: geometrical modeling - the building is displayed during the whole lifecycle so that the errors are reduced both during the design phase and the execution and maintenance;
- 4D: time model – it consists in the visualization the progress of the construction of the elements to have a better control of errors and changes that may occur during the project
- 5D: cost model - allows, through the 3D model and the BIM 4D, to have full control of costs over time. This enables efficient and cost-effective construction;
- 6D: energy model - consists in the analysis of the energy consumption of the building. Analyzing the energy performance right from the project phases, allows to adopt the most suitable technical solutions to ensure lower energy consumption in order to guarantee the sustainability of the project;
- 7D: facility management - consists in optimizing the management and maintenance of the asset’s components throughout the entire life cycle. It provides information on the individual components: from technical systems to finishes;
- 8D: safety model - the succession of the operations during the construction phases is planned. It can be intended as a time schedule of the phases with the aim of reducing the possibility of interferences during the construction of the asset.

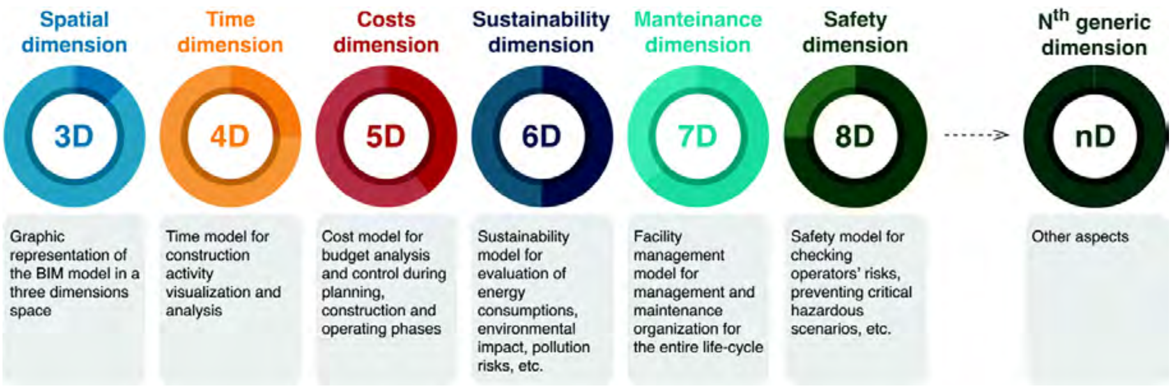


Figure 1.11: BIM dimensions [19]

With reference to the method for the exchange of information, it can be distinguished:

- *closed-BIM*, which describes a limited use of the BIM methodology within the project with the adoption of software and exchange formats of a single software provider in order to minimize the data conversion required;
- *open-BIM*, conversely, is promoted by an association of leading software providers in the construction industry with the aim of enabling and expanding interdisciplinary collaboration based on neutral and open standards. In this way every user can use the software of his choice and can access to a wide range of different products. The increasing number of open international standards also guarantees lasting communication between individual products.

In closed-BIM processes (Fig. 1.12), information exchange takes place through direct links that consist in an internal and direct exchange of information from architectural/structural modeling software to structural analysis tool. Within the structural discipline, an example is the dialogue between Revit and Robot Structural Analysis, both owned by Autodesk: in this case, the model can be transferred and updated directly, without the use of an interchange file format. It can be stated that the user is not aware of the operation. There is also the case in which the exchange takes place directly but between different software using the same proprietary format (this is the typical case of the program suites of the same manufacturer). Closed-BIM interoperability processes are called first level processes.

Figure 1.12: Direct link: information flow from BIM model to calculation result

Open-BIM processes (Fig. 1.13) are based on indirect links or add-on tools. Open-BIM interoperability processes are called second level processes.

Within the structural discipline, the use of indirect links consists of dialogue via a neutral file format (i.e. IFC) exported from the three-dimensional model, imported into the structural calculation software and reworked in order to correctly perform the structural analysis. This is a non-trivial operation due to the complexity of IFC files and the personal interpretation of the format by the different BIM software providers. The IFC standard takes into account the main structural elements such as beams, pillars, generic linear elements and also offers the possibility to transfer data concerning plates, walls, flat and inclined slabs. Once the structural design is complete, it is possible to export a file still in IFC format and integrate it into the architectural design. Although this procedure offers many advantages in terms of communication, productivity and quality, in the context of interoperability between the BIM model and the calculation program in practice these operations are not always completely effective because each structural object should be represented by a finite 1D-2D element congruent with the adjacent elements.

Figure 1.13: Indirect link: information flow from BIM model to calculation result

With reference to add-on tools (Fig. 1.14), the exchange of information takes place through links that allow a direct transfer of information between software that does not have the same proprietary format. Generally, the structural analysis software providers provide these links as add-in components can be installed in the modeling software; they carry out the transfer through specific interchange files optimized to locate the data needed for the structural analysis and then re-update the model with the information coming from the analysis. The choice of this kind of methodology can be found in the desire to minimize the loss of information when using specific programs for both modeling and structural calculation.

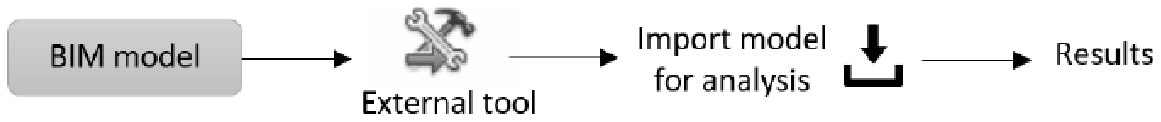


Figure 1.14: Add-on tools: information flow from BIM model to calculation result

By crossing the concepts of little/big with open/closed BIM, it is possible to define four possible combinations (Fig. 1.15):

- *little closed BIM*: the user (e.g. architect, engineer, building contractor, facility manager) works with a digital model, but only in his area and without exchanging the data with others. The software solutions used are uniform for all project participants;
- *little open BIM*: the user only works with the digital building model in his area, but he exchanges the resulting data with others in a neutral exchange format (IFC). The software solutions are still uniform;
- *big closed BIM*: several internal and / or external users from different disciplines work with digital models in a uniform software ecosystem and exchange data with proprietary exchange format;
- *big open BIM*: several users from different disciplines work with digital models, but the software solutions are different. The data exchange format are neutral [20].

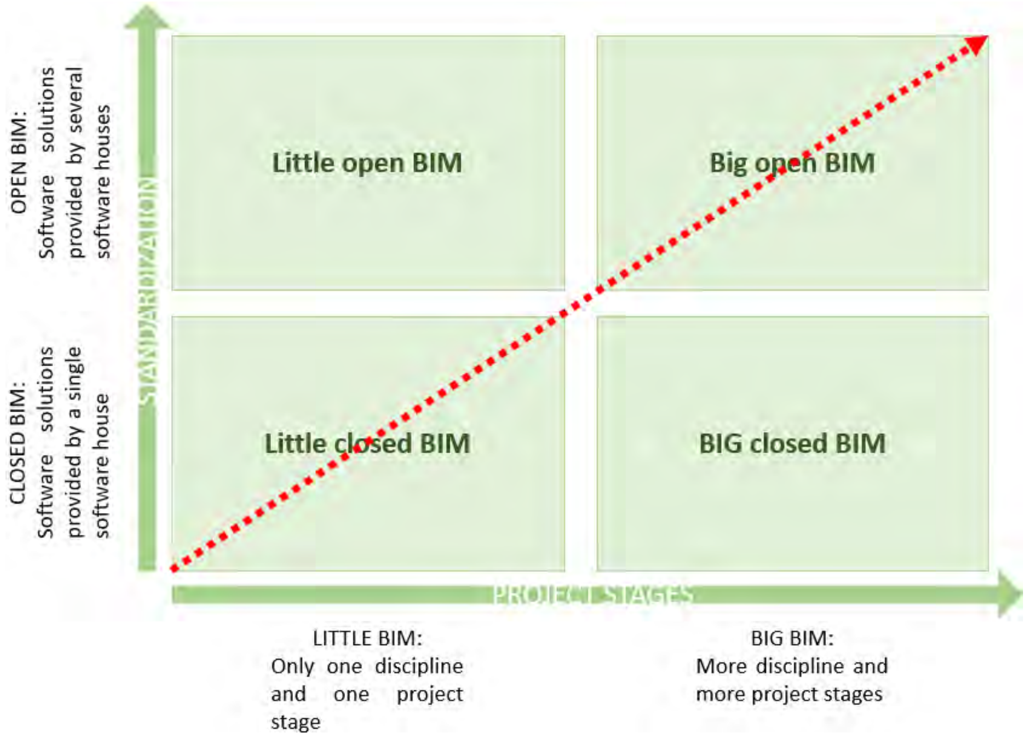


Figure 1.15: From "little closed BIM" towards "big open BIM"

Research developments often focus on the study of big open BIM processes, in which all information exchanges are managed through IFC and other neutral standards, integrating all phases of the life cycle. However, little closed BIM processes still have some application in the AEC sector, so the way BIM is implemented should always be carefully defined before starting each project in order to properly rationalize the resources to be allocated according to the specific objectives of the project.

1.6.1. Interoperability with the structural environment

It is necessary to set the practices for the exchange of information with all members of the project team in order to make interoperability efficient. The objective of these practices is to make the actors quickly operative. The optimization of the data exchange procedures leads to an immediate advantage: errors generated by the redesign of the structure are completely eliminated, as well as the loss of time in communicating any changes to the designers.

Within an integrated structural modeling three phases can be distinguished:

1. Pre-processing: in this phase the analytical modeling of the structure is elaborated by inputting all the information necessary for the structural model, such as materials, cross-sections of the elements and structural loads. In addition, design constraints and loads are inserted taking into account the technical codes;
2. Analysis: after modeling, the model is moved to a finite element tool that solves the matrix system associated to the structure, generating a solution in terms of stresses, displacements and everything necessary for structural checks;
3. Post-processing: represents the verification and judgement phase, in which a validation of the calculation is carried out and the executive design begins.

In order to optimize the process, a conscious modeling is necessary by adopting those expedients that orient the file to be moved to a structural software. A BIM modeling platform used as a pre-processing environment for calculation software represent the most efficient and modern way to transfer data. A professional who creates the calculation model directly in the structural analysis software simply composes a skeleton of one-dimensional or two-dimensional elements sufficient to capture the structural response; otherwise, in a BIM environment he works on a model full of details, relevant mostly for other disciplines. It is therefore essential to elaborate the model aimed at performing structural calculations, defining the elements that influence the static/dynamic response of the structure and paying great attention to the congruence of the elements. As a way of example, a wall has always to be divided at each floor so that the nodes that delimit the finite elements align at the floor level for the application of the diaphragm constraint.

In the author's opinion, in order to optimize the transfer to a structural analysis tool, the following steps should be taken into account:

1. Identify the main structural elements;
2. Simplify complex geometries;
3. Avoid inputting information that can be easily managed within the structural analysis software (constraints, loads, load combinations, etc.);
4. Pay attention when transferring non-structural objects such as rigid links to restore congruency;
5. Choose the position of the structural objects (the can be placed in a barycentric position or in compliance with fixed strands);
6. Check the analytical model created with the BIM modeler, as the consistency of the elements may be affected.

In addition, after each transfer it is necessary to pay close attention to the alerts that are reported and remedy them where possible. Subsequently, a systematic check must be made of the information transferred, both outward and return, taking into account geometry, constraints, loads and any other kind of transferable information. A typical structural workflow in BIM modeling is shown in Fig. 1.16:

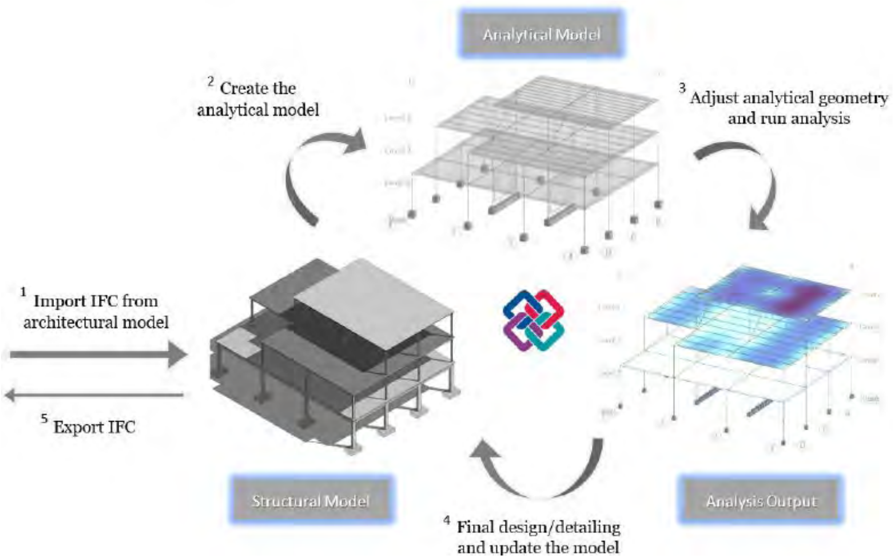


Figure 1.16: Example of a structural workflow in BIM processes

1.7. OpenBIM standards

OpenBIM standards exist to support the exchange of information between project parties and between software applications in a consistent and transparent way.

Information transfer, or more broadly 'communication', is at the core of all our business activities. Communication may be in the form of a verbal instruction, a set of plans, a technical specification, or a contract. BIM seeks to support project communication in the broadest sense. There are many other factors that are necessary to make communication effective.

Recognising this need, buildingSMART – the organization that helps asset owners and the entire supply chain to work more efficiently and collaboratively through the entire project and asset lifecycle – created a suite of standards that would support the entire communication cycle. A number of these are now ISO and European standards and the other standards are set to follow suit.

BuildingSMART promotes international consensus among stakeholders on specific standards to accelerate implementation and uptake. OpenBIM standards (Tab. 1.1) cover a wide range of process and information capabilities unique to the built environment industry, including:

- an industry-specific data model schema - Industry Foundation Classes [IFC]
- a methodology for defining and documenting business processes and data requirements - Information Delivery Manual [IDM]
- data model exchange specifications - Model View Definitions [MVD]
- model-based, software-independent communication protocols - BIM Collaboration Format [BCF]
- a standard library of general definitions of BIM objects and their attributes - buildingSMART Data Dictionary [bSDD].
-

Table 1.1: openBIM standards [21]

Name	Description (function)	Standard
Industry Foundation Classes (**IFC**)	Transfer data and information	ISO 16739
Model View Definition (**MVD**)	IFC View Filter	buildingSMART MVD
Information Delivery Manual (**IDM**)	Standardized Process Description	ISO 29481-1 ISO 29481-2
International Framework for Dictionaries (**bSDD**)	Mapping of Terms	ISO 12006-3
BIM Collaboration Format (**BCF**)	Reporting and Tracking	buildingSMART BCF

1.7.1. Industry Foundation Classes (IFC)

Basically, buildingSMART allows the entire sector of built assets to improve information sharing throughout the entire life cycle of the project or asset. By breaking down the barriers due to poor data interoperability, end users can collaborate and cooperate better regardless of the software application they are using. The technical core of buildingSMART is based on Industry Foundation Classes (IFC), ISO certified in 2013. IFC is a standardized digital description of the built asset industry. It is an open international standard (ISO 16739-1: 2018) and promotes vendor-neutral or agnostic features that can be used on a wide range of hardware devices, software platforms and interfaces for many different use cases. In general, IFC, or "Industry Foundation Class", is a standardized digital description of the built environment, including buildings and civil infrastructure. The IFC scheme specification is buildingSMART International's main technical product to achieve its goal of promoting openBIM. More specifically, the IFC schema is a standardized data model that logically encodes:

- identity and semantics (name, machine-readable unique identifier, type of object or function);
- the characteristics or attributes (such as material, color and thermal properties);
- relationships (including places, connections and properties) ...
    - Between objects (such as columns or slabs);
    - Abstract concepts (performance, costing);
    - Processes (installation, operations);
    - And people (owners, designers, contractors, suppliers, etc.).

The schema specification can describe how a structure or installation is used, how it is constructed and how it is managed. IFC is able to define the physical components of buildings, pre-fabricated products, mechanical / electrical systems, as well as the more abstract models for structural analysis, for energy analysis, for cost subdivision, for work planning and much more. Today, IFC is typically used to exchange information between two or more parties to a specific business transaction. For example, an architect can provide the owner with a model for the design of a new structure, an owner can send that building model to a contractor to request an offer, and a contractor can provide the owner with a model built with the details they describe the products installed and the manufacturer's technical information. The IFC can also be used for archiving project information, both incrementally during the design, procurement and construction phases, and as an "as-built" collection of information for long-term conservation and operations purposes. The desired IFC data can be encoded in various formats, such as XML, JSON and STEP (see IFC formats) and transmitted on web services, imported / exported to files or managed centrally or linked databases. More in detail:

- IFC-SPF is a text format in the EXPRESS data modelling language. It has a compact size and is the most widely used IFC format.
- IFC-XML is a format in the Extensible Markup Language, XML. Although XML is a more common programming language, IFC-XML has a larger file size than IFC-SPF and is less commonly used.
- IFC-ZIP is a ZIP compressed format of the IFC-SPF file. An .ifcZIP file usually compresses an .ifc down by 60–80 % and an .ifcXML file by 90–95 %.

Information modeling (BIM authoring) software vendors - including design, simulation, analysis, visualization, and more - provide end users with interfaces to export, import, and transmit data in certain IFC formats. Since 1997, IFC has been tried and tested through many iterations, gaining trust around the world as a means of delivering projects from around the world [22].

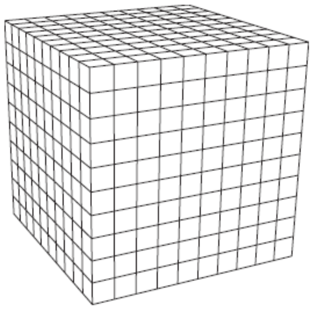


Figure 1.17: A simplified representation of the IFC schema [22]

1.7.2. Model View Definition (MVD)

A MVD, or “Model View Definition”, is a subset of the IFC schema that defines a data exchange for a specific use or workflow. MVDs can be as large as almost the entire scheme (eg. For archiving a project) or specific as a pair of object types and associated data (eg. For determining the price of a continuous wall). Documenting a MVD allows you to repeat the exchange across various projects and software platforms, providing consistency and predictability. In order to support BIM interoperability between hundreds of software applications, industries and regions around the world, the IFC scheme is designed to adapt to different configurations and levels of detail. Since IFC is a vendor-independent scheme, MVDs are focused on data rather than applications. This means that it is the workflow and information exchange requirements with the end user that determine the extent and shape of the model view, and do not depend on specific capabilities or limitations of the software available on the market. However, the specifications of an MVD should affect the capabilities or needs of the software. The parties involved in a project (architects, structural engineers, plant engineers, construction companies, facility managers, etc.) have different responsibilities, skills and needs in the creation and use of construction data. Ultimately, they must share this information with the other operators involved in the project life cycle to carry out different activities. Therefore, it is necessary to clarify which subset of all data needs to be exchanged for a particular use. These subsets of data can be defined by analyzing the overall IFC scheme in smaller "model views", which specify the information requirements necessary for the end user. An MVD will describe which objects, representations, relationships, concepts and attributes are necessary for the recipients to perform the desired activity with their software application.

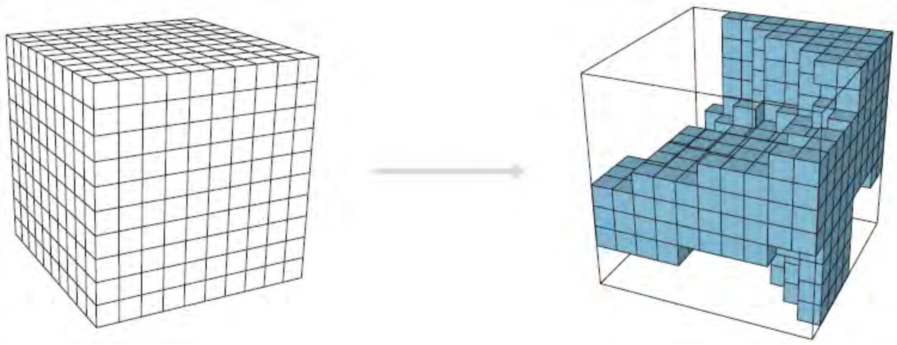


Figure 1.18: Generation of a specific view of the model, the MVD, (represented as the partial cube on the right) to meet a use-case requirement [22]

In Tab. 1.2 are listed the MVs currently developed or under development for IFC 2x3 and IFC 4.

Table 1.2: MVD database [Source: 23]

IFC	MVD Name	Status	Summary
IFC2x3	Coordination View	Official	Spatial and physical components for design coordination between architectural, structural, and building services (MEP) domains
IFC2x3	Space Boundary Addon View	Official	Identification and export of additional Space Boundaries (polygons which define the extents of a space's contact with directly adjacent surfaces [e.g. walls, floors, ceilings] and openings). Can be used for building energy analysis and quantity take-off.
IFC2x3	Basic FM Handover View	Official	Handover of model information from planning and design applications to CAFM and CMMS applications, as well as the handover of model information from construction and commissioning software to CAFM and CMMS applications
IFC2x3	Structural Analysis View	Official	The structural analysis model, created in a structural design application by a structural engineer to one or many structural analysis applications.
IFC4	Reference View	Official	Simplified geometric and relational representation of spatial and physical components to reference model information for design coordination between architectural, structural, and building services (MEP) domains
IFC4	Design Transfer View	Official	Advanced geometric and relational representation of spatial and physical components to enable the transfer of model information from one tool to another. Not a "round-trip" transfer, but a higher fidelity one-way transfer of data and responsibility.
IFC4	Quantity Takeoff View	Draft	Estimate and track construction materials and costs.
IFC4	Energy Analysis View	Draft	Estimate and track energy usage and costs.
IFC4	Product Library View	Draft	Manufacturer product information and configurations.
IFC4	Construction Operations Building Information Exchange	Draft	Lifecycle information for maintaining equipment and systems within buildings.

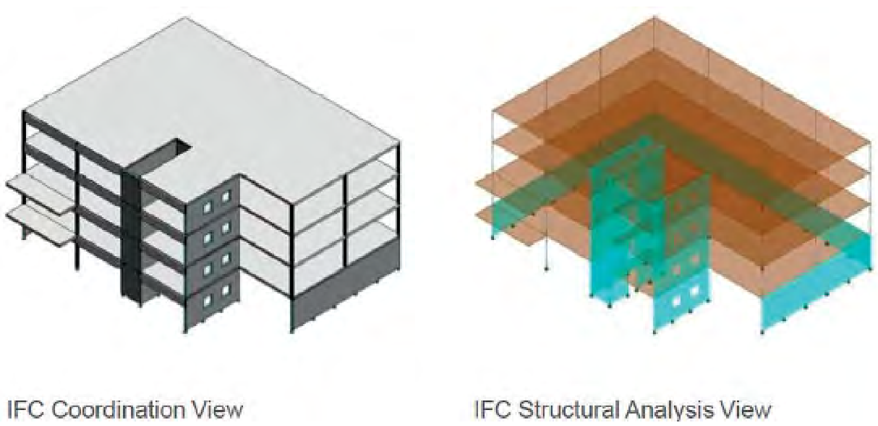


Figure 1.19: Examples of Model View Definition [22]

1.7.3. Information Delivery Manual (IDM)

The AEC industry (including buildings and civil infrastructure), in fact, is characterized by the cooperation of many companies and authorities in a specific organization for the project. In order to work efficiently, it is necessary that all participants in the organization know when and what different types of information must be exchanged. The problem is even more relevant when digital tools are introduced, because most of the digital tools have a very low tolerance threshold for the interpretation of data. The ISO 29481-1: 2010 standard "Creation of information models - Information delivery manual - Part 1: Methodology and format" was developed by buildingSMART in order to have a methodology to acquire and specify the processes and the flow of information during the life cycle of a facility. The methodology can be used to define new or existing processes and describe the associated information that needs to be exchanged between the parties. Subsequently, the output of the standard can be used for more detailed specifications which form the basis for software development. It is important to state that the development of an IDM is always aimed at defining the requirements of a software. The methodology is now accepted as an ISO standard. It is expected that some improvements will be applied to the standard to make it more specific in relation to the documentation of exchange scenarios, as well as to have well-defined phases in a communication process between the parties. Numerous IDM projects were launched simultaneously with the development of the methodology. Several IDMs have been further specified and tested in real projects and tenders. The concept is well explored today and collaborative efforts are being made to create usable IDMs. Despite advances, it is recognized that sometimes it is a real challenge to create IDMs as there is a lack of structured and well-documented processes. In such cases, it is necessary to initially agree on the processes, relevant activities and exchange requirements. In some cases it is necessary that the development work of an IDM is followed by a software development phase. This means that if software development is non-existent, the expected results cannot be achieved. It is therefore essential to ensure that those promoting an IDM have a clear strategy on how to implement the IDM in software solutions. For a clear documentation of the processes, all the activities that need to be performed are summarized in a Process Map (Fig. 1.20), where the sequence of the tasks are represented and assigned to the responsible party [24].

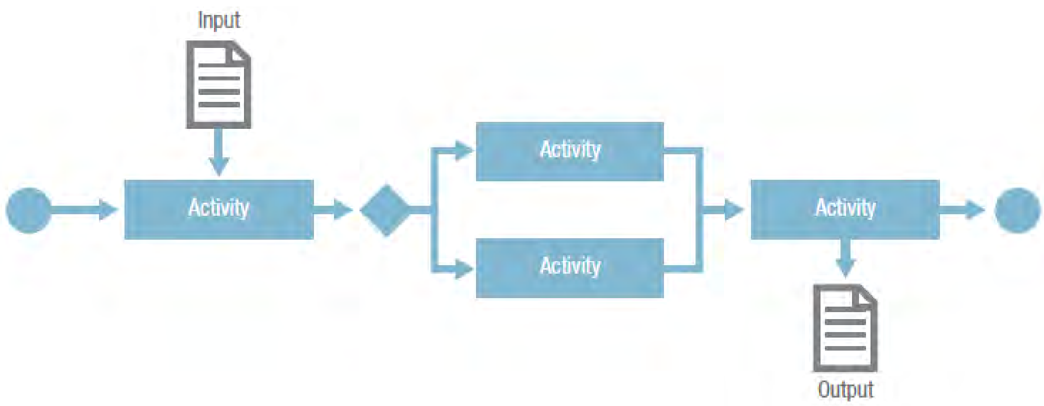


Figure 1.20: An example of schema illustrating n Information Delivery Manual [22]

1.7.4. BuildingSMART Data Dictionary (bSDD)

We know that IFC can transfer data from one application to the next in a standardised way. Because IFC is structured and static it makes the sorting (filing) and retrieving of information very easy. Specific information types will always be filed in the correct ‘folder’ regardless of the application used. What IFC does not do is checking the contents of the ‘folder’. It will transfer the information regardless of how it is inputted. Across multidisciplinary project teams, there are often different conventions used for naming the same object properties. An architect may use the property name ‘Fire Rating’ while a fire engineer may name the same property ‘Reaction to Fire’. Both are accepted conventions within their respective disciplines; however, they may not be mutually recognised. The same is true in multinational collaboration where different object classifications or different languages are used. To solve this problem, either all project members must use the same naming conventions – the same language and classification systems – or there must be a mapping of synonymous terms. In response to this issue, buildingSMART developed an application, the buildingSMART Data Dictionary (bSDD) to support multidisciplinary and multi-language terminology mapping. The Data Dictionary is not a standard but an application based on a buildingSMART and ISO standard called the International Framework for Dictionaries (IFD). The data dictionary is a cloud-based resource that hosts object listings, properties, and concepts relevant to the application of BIM. Each entry in the bSDD is mapped to all possible derivations of that concept in different contexts and languages. The data dictionary is like a “Google Translate” for BIM (Fig. 1.21). Like the IDM, the bSDD was not established for the average user; it is primarily for software developers and advanced users [22].

Figure 1.21: The buildingSMART Data Dictionary: the "Google Translate" for BIM [22]

1.7.5. BIM Collaboration Format (BCF)

The BIM Collaboration Format (BCF) allows different BIM applications to communicate problems with each other based on IFC models previously created and shared among the project participants. BCF was created to facilitate open communications and improve IFC-based processes, quickly identifying and exchanging information on model problems, bypassing proprietary formats and complex workflows. This can be done by using a file exchange between software platforms, or by using a RESTful service that directly connects the software platforms to each other or to a third party BCF server that acts as a hub for such communications.

More in detail, BCF works by transferring XML formatted data, which is problem information contextualized via a direct reference to a model view, acquired via PNG and IFC coordinates, and elements of a BIM model, as indicated via their IFC GUIDs, from one application to another. BCF development began in 2009 and was originally conceived by two members of the buildingSMART International Implementation Support Group (ISG), Solibri and Tekla, together with the Institute for Applied Building Infomatics (iabi) of the Munich University of Applied Sciences (Germany). Their desire to take advantage of open communication technology for IFC-based workflows led to prototyping the BCF. BCF is now an international buildingSMART openBIM standard. There are two different ways to use the BCF, either via a file-based exchange or via a web service. The file-based exchange workflow is relatively simple and is a process used by most people. A BCF file (.bcfzip) is transferred from one user to another, modified and returned. As an alternative to file-based workflow, there is the Web Services Based API (RESTful) mode. This involves the implementation of a BCF server, with the possibility that this is also the central BIM server, which stores all BCF data and allows project participants to synchronize the creation, modification and management of BCF topics in one single centralized location. There are numerous use cases that can benefit from BCF-enabled workflows, in which information can be derived from BIM and linked back to BIM for specific information on objects. These cases include may include:

- Design phase (document the quality assurance / quality control of BIM items, clash detection, annotation material selections);
- Procurement phase (elements of coordination of offers and clarifications, information on costs and suppliers for objects);
- Construction phase (Quality assurance / quality control records of installations with respect to BIM models, monitoring of the availability of items and coordination of replacements, collection of last-minute information for delivery to the owner / operator as part of COBie's final results);
- Operational phase (notations to the models delivered for commissioning when changes are made to the structure and its numerous elements during the occupation, owner's notes on necessary updates).

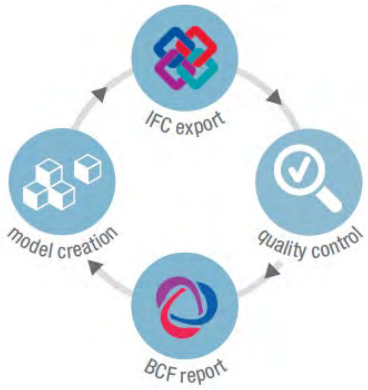


Figure 1.22: Workflow using the BIM Collaboration Format [22]

1.8. BIM Maturity Levels

The digital transition of the construction processes of the various stakeholders is taking place gradually, depending on their ability to adapt to this change. For this reason, the BIM task group introduced the concept of BIM Maturity Levels (Fig. 1.23) in PAS1192-2, recognizing that the BIM transition is done in a systemic and gradual way. In fact, thanks to this gradual transition, you can see more and more advantages. The BIM task group initially identified 4 levels of maturity, with the aim of bringing the United Kingdom quickly to maturity level 2, having recognized that this level corresponds to the first economic benefits of using BIM. The level of maturity has also been adopted by other countries, including Italy.

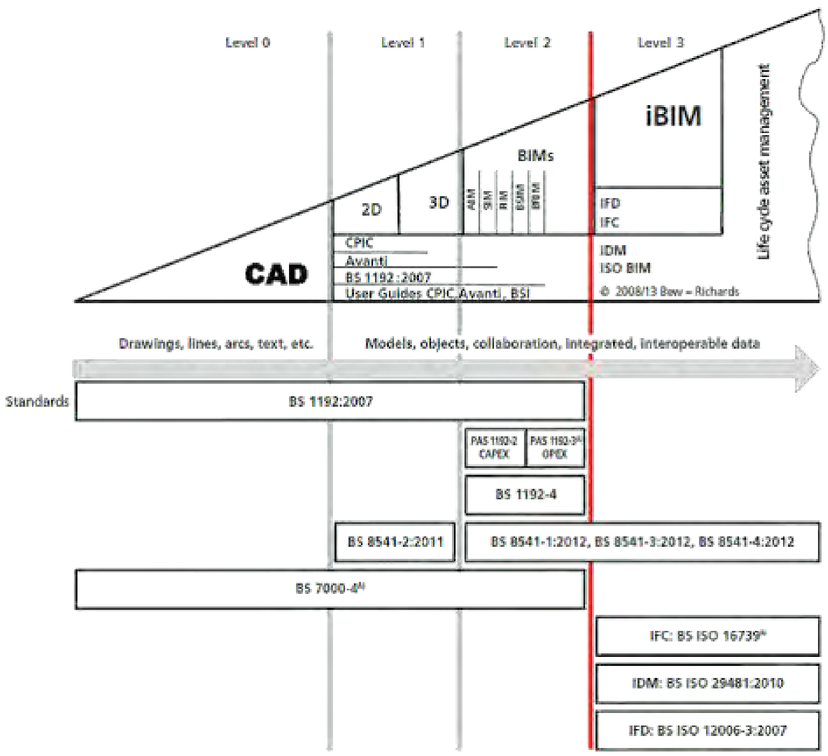


Figure 1.23: Bew triangle according to PAS1192-2 [25]

The *BIM Maturity Level 0* was introduced conventionally, and corresponds to the state of evolution of the processes before the introduction of BIM methodology. In fact, this level corresponds to the digitization of the graphical drawings, i.e. individual views. It is defined Level 0 precisely because BIM is not introduced, but is only a starting point for the introduction of digital processes.

The *BIM Maturity Level 1* is reached when the geometry of the asset is digitalized and then the digital model of the building is introduced. This transition actually began in the 90s with software like Archicad; in fact, Archicad is not an alternative to autoCAD, but differs substantially because it allows object modeling.

With BIM Maturity Level 2 we are witnessing the real BIM revolution. Two fundamental innovations are introduced:

1. Centrality of the data: the model of the asset is used to structure a database made up of not only geometric information. This allows the model to be used not only for the production of two-dimensional views, but also as a database of information, since data relating to the physical properties of each object is linked to it, and therefore changes from object to object. Indeed, in BIM Level 1 a structured database is built on the digital model. It follows that centrality is given to the information, which is produced only once and is not redundant. In order to better understand the importance of this innovation, it has to be noticed that with the conventional approach, for example, the compressive strength of a concrete is written several times both in drawings and in reports, which can lead to unintentionally commit errors related to the fact that the production of the information is not "optimized". If, on the other hand, the data is entered only once, the software will automatically always return the same information, thus reducing the opportunities for errors;
2. the standardization of the processes: besides the construction of the digital twin of the asset, standardized processes are introduced with the aim of planning the modality in which the information must be produced and input in the model. Since several stakeholders are responsible for the elaboration of the database, then the way in which the information must be processed has to be codified. Therefore, it can be affirmed that thanks to the standardization of the processes the production of the information is "industrialized". While the conventional way was based on common sense and experience, with the introduction of BIM it was realized that the complexity of the work, however, requires that we must proceed with the standardization of the way in which we exchange information and technical decisions. Since the data is centralized, the role of each stakeholder who interact with the database must be well defined and well-coordinated with the other roles. For this reason, new professional figures responsible for the data production process have been introduced. To summarize, level 2 is aimed at the evolution of the construction chain that takes care of the quality of data production.

In BIM Level 2 there is no single model of asset, but several models identified on the basis of the several disciplines to which they refer and which are federated among them. This separation of models takes the name of federated models. This concept has not to be considered as a software detail, but as a specific feature. It follows that each discipline works with its own languages, and when necessary, models are exchanged to transfer information to project team members from other disciplines.

With *BIM Maturity Level 3* software is so effective that there is no need to identify separate models, but all the data are collected in the same environment, not even distinguishing between architectural and structural models. Working in the same environment, clash detection is done continuously, differently from federated models where it is has to be scheduled (BIM Level 2). The model is openBIM, so that it is possible to work in a total data sharing environment, which does not depend on the use of a specific software platform, taking full advantage of non-proprietary formats. In addition, the consequence of the Level 3 approach is that if the model is centralized and powerful enough to hold all the data, then the need to produce drawings is minimized.

Finally, a *BIM Maturity Level 4* (not shown in the graph in Fig. 1.23) has also been assumed. According to this level, the BIM model is fully integrated with the real building. The building works and offers high performance because it works with its digital copy. The digital copy of the building becomes the database for the information in input and output of sensors placed in the real building so that users interacts with the building through its digital copy.

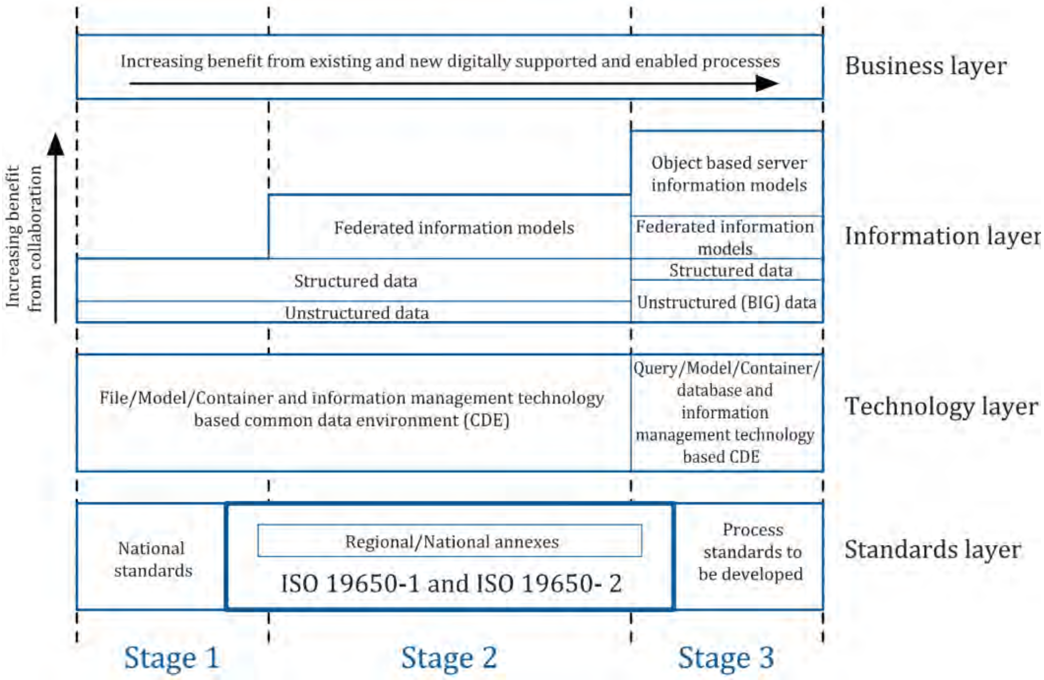


Figure 1.24: BIM Stages according to ISO19650-1 [26]

With the release of ISO19650-1 "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", the progression scheme and the definition of the levels is replaced by a scheme called "stages" in which three stages are outlined for different layers (Fig. 1.24):

- a *Standards layer*, which in Stage 1 is constituted by national standards, in Stage 2 is constituted by ISO 19650 and in Stage 3 will be supported by standards that do not yet exist;

- a *Technology layer*, which in Stage 1 and 2 will rely on Common Data Environment based on the management of files and models and in Stage 3 will provide databases where it is possible to directly access the information contained in the models;
- an *Information layer*, which in Stage 1 makes use mainly of both structured and unstructured data while in Stage 2 introduces the concept of federated information model. Instad, in Stage 3 it will make use of servers that allow the direct management of objects and, while maintaining federated models and structured information, for unstructured information it will be necessary to deal with the concept of BIG data.

1.9. Benefits and risks of integrated modeling

Every time an innovation, whether technological, process or regulatory, is adopted, it is necessary to carry out the risks and benefits assessments. The first point to take into account is the cost associated to the adoption of the BIM methodology compared to the traditional one.

It is useful to make a premise in this regard; following the assumptions of MacLeamy, the construction, maintenance and demolition costs of a work should be monitored at an early stage of the design. This statement seems to be logical, but it does not match the reality. Currently, the design process is divided into three distinct and sequential phases and only during the last one there is the effective integration of all disciplines (structures, facilities, energy efficiency, scheduling program, quantity take off, etc.). It should be noted, however, that if integration were to take place earlier, there would be a greater propensity to make informed and useful choices, thereby reducing the total costs of the asset. In addition to the design phases, there is also the construction phase, during which the greatest variations traditionally occur, due to the interferences that emerge when the work is carried out.

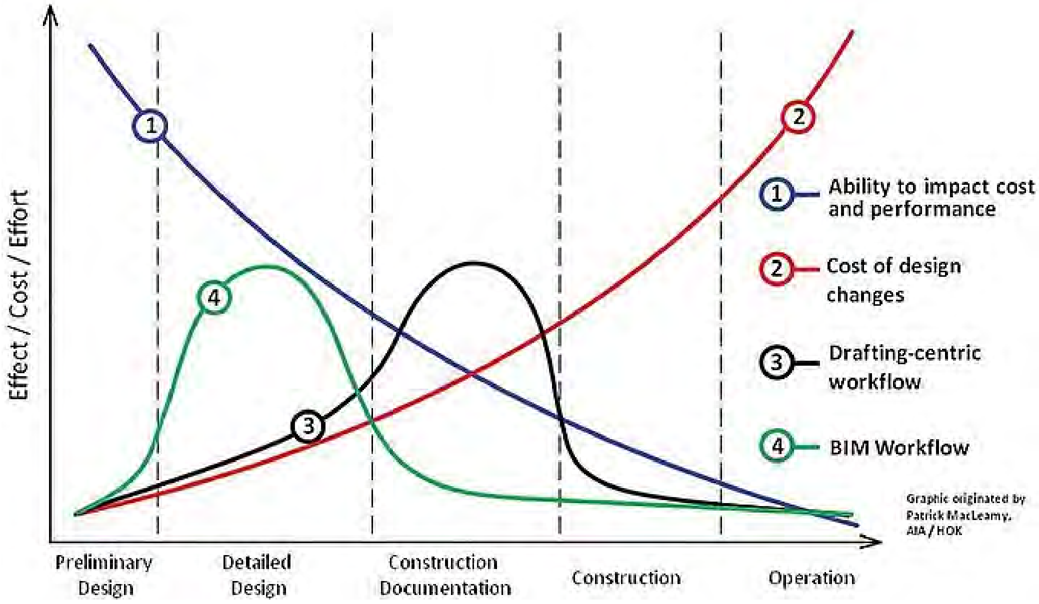


Figure 1.25: MacLeamy curve [27]

These conclusions can also be reached by analyzing the MacLeamy graph (Fig. 1.25). In detail, on the x-axis shows the flow of the life cycle of an assset, divided into successive phases, while the y-axis shows the effects, costs and efforts required to make the changes that may be necessary during the various phases. The graph shows four curves:

1. the ability to impact cost and performance, that decreases with the advancement of the life cycle of the asset;
2. the cost of design changes, that increases with the advancement of the life cycle of the asset;
3. the traditional design process;
4. the BIM design process.

The area underneath curves 3 and 4 represents the amount of efforts performed during the life cycle of the work. It can be observed that, according to the traditional methodology, the greatest efforts are concentrated in the construction documentation phase, in which it is possible to make variations to the asset but they involve considerable costs. In fact, the design is mainly based on 2D paper drawings, which require a lot of time to be prepared and great effort to be modified, as well as enormous difficulty to be understood by those who did not participate in their development; in addition, it is complicated to transmit more information than just geometry and space. This makes it difficult to share information between several stakeholders for integration so that even the optimization of the design process is hard to achieve, with numerous possibilities for mistakes and redundancies. With the advent of BIM technologies, on the other hand, the greatest efforts are made in the initial phases, when it is easier to make changes to the project with lower costs necessary to realize them. It opens up the possibility of involving all the experts from the preliminary stages, through rapid and effective data sharing, who will be able to contribute with their knowledge to optimize the project when it is possible and more convenient to do so. The exchange of data and information by those involved in the process is therefore continuous. The first design phase, i.e. the preliminary design, therefore plays a fundamental role since during this phase the spatial design of the building, the structural organisation, sustainability aspects, etc. are defined. Therefore, a greater commitment in terms of human and economic resources is necessary during the preliminary design phase. This is due to the fact that designers must set the work in a way to optimize the future calculations and the procedures for the development of the technical documentation, having already clear some aspects of the project. Each choice has the greatest impact when the process has not yet started, losing its capacity for impact as time goes on. The philosophy at the base is that of "*Begin with the end in mind*", which means having clear from the beginning the technological, performance and economic aspects. Once these parameters have been defined, any member of the team can, at any time and in a shared way, make changes, even substantial ones, to the project (and therefore to the model) as they will be cascaded on all aspects related to it.

This concept has been confirmed and further specified also by Sacks, Eastman et al. [28], as shown in the graph in Fig. 1.26, in which is illustrated the data losses both with the traditional and the BIM methodology over the lifecycle of an asset. As traditional processes are based on paper documents and due to poor insufficient integration during the design and construction phases, they turn out to be fragmented. In addition, since the phases can follow one another at different times and even with different working groups, there is frequently a loss of information, which must then be compensated for the continuation of the design. Consequently, the result is loss of value in information assets across phases, many opportunities for errors and omission, and increased effort to produce accurate project information (red line 2).

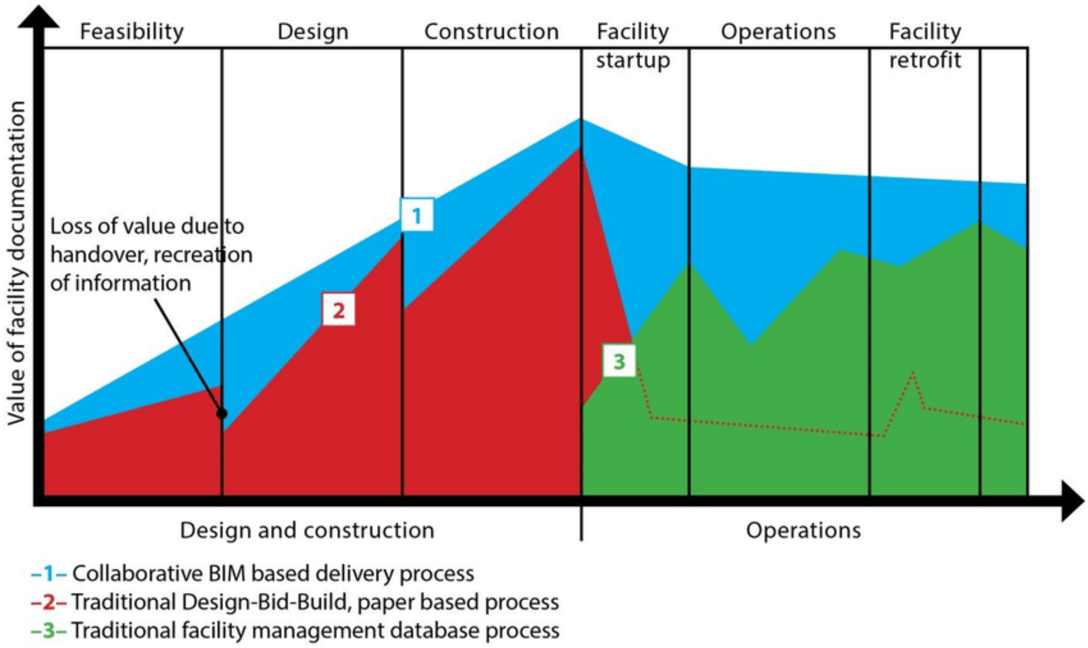


Figure 1.26: Data losses during the lifecycle of an asset [28]

The same happens in the following operations phase (green line 3). Instead, the BIM based process (blue line 1) support a collaborative approach that involve each member of the project. This collaboration builds trust and common goals for each team members, in contrast in contrast to the previous, improving integrated design and construction process, which increases the value of project information in each phase and allow greater efficiency for the project team. The result is that the several activities are carried out with less difficulties and the actors involved in the project develop the whole process with a greater awareness. Continuous information management, favours by the implementation of the BIM that is based on well-defined processes and standardized information, solvers the data losses. The importance of this derives from the cost associated to the losses (estimated in a NIST report in USA 2004) caused by an inadequate interoperability in the process, between the lifecycle stages and actors. These benefits make the BIM methodology, although yet a less common practice, particularly suitable for the operations of Facility Management (FM) of the existence buildings.

Smooth communication and the regular exchange of information and expertise are as much as important as transparency to ensure good project management. This is achieved if all parties can access the updated information from any anytime, anywhere. It is not only the communication between designers that is crucial, but also the communication with the clients and decision-makers is equally important. Decisions must be made quickly in the planning and construction process. The BIM coordination model provides all the information needed to make such decisions, regardless of whether they relate to a changes in the project, to detailed solutions or construction. The actors in the process can at any time query the database and receive the information they need, minimizing the use of paper documents, the timescales and misunderstandings.

The team members, in particular, are the main factor of success: everyone involved in the project must adopt the shared approach of work; they must be able to manage the documentation and communication technology; they must know the processes and regulations. Each company must build its own project team and ensure that all members are familiar with the work methodology.

BIM make possible to reduce errors, change orders and deadlines, since there is a higher consensus on models between all parties since the beginning of the design phase; it also helps to find interference between elements on a computer environment rather than on the construction site. Then, thanks to a digital recording of what has been done, you a higher experience can be learnt from what is being done. In addition, reduce order times and meet individual order deadlines by improving productivity and benefiting from higher profits.

Important companies like SKANSKA have implemented the BIM methodology on many types of projects including buildings, roads, bridges, tunnels and industrial plants. As a result, they have been able to benefit from a number of advantages including better communication between project stakeholders, increased efficiency, greater certainty for both planning and cost compliance and risk reduction. The BIM fully supports the important objectives of Skanska's "Five zeros vision" by improving safety, efficiency and allowing zero defects during the construction phase. Andreas Udd, Project Manager of the Swedish company, also saw a saving of more than 1000 working hours thanks to the use of specific software for the implementation of the BIM [www.skanska.com]. From an engineering point of view, the most important contribution of BIM is the increase in productivity, especially in the production of construction documents [29].

The production of 2D drawings, in fact, represents a laborious activity for civil engineers. This process is fully automatic when using an informative model. In most engineering firms, then, especially large ones, it is common to work with teams in different geographical locations. New technologies such as cloud servers greatly simplify the whole process. Being able to share all information through online cloud environments, where everyone working on a project can access and modify it, is an important advantage.

The main benefits of BIM implementation found by companies were analyzed in a market study conducted by McGraw Hill Construction and summarized in the graph in Fig. 1.27.

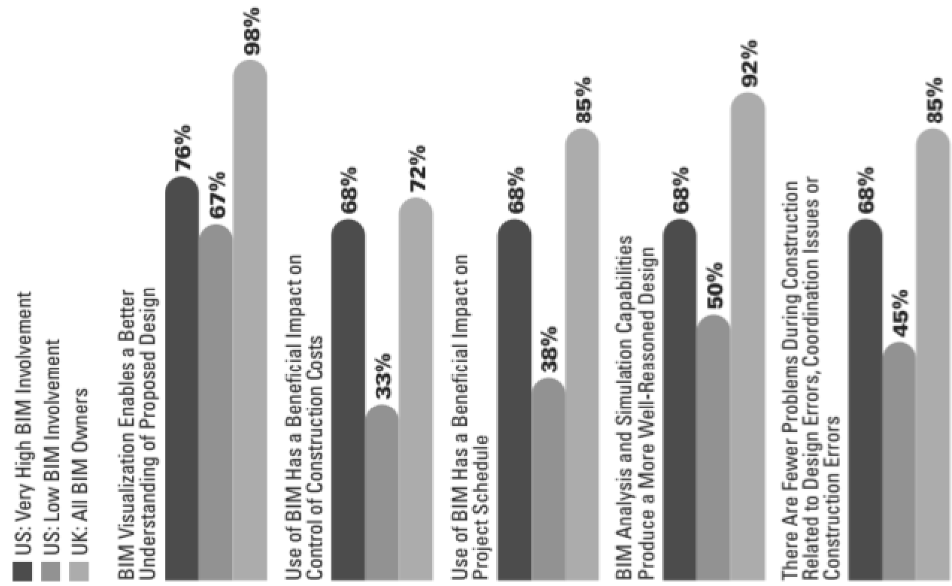


Figure 1.27: Benefits recognized by companies using the BIM methodology [30]

Surveys conducted by industry professionals who have already switched to BIM list several important business benefits found, such as:

- Up to 20% reduction in planning time (TSI Structures Case Study, United Kingdom, 2015);
- Reduction in rework;
- Conflict detection before construction;
- Increased profits;
- Collaboration in different geographical areas.

With reference to the possible risks, it is necessary to start with an observation: adopting the BIM methodology by a company involves an initial cost for training the designers, purchasing and updating hardware and software licenses. The initial training inevitably leads to a loss of productivity because it takes personnel away from the current activities, requiring time to be assimilated and put into current practice. Within the organization, employees may have to adapt to new working methods. If the firm has always used only 2D drawings, employees will need to expand their skills to implement the new business processes. It may be necessary to reformulate the standards applied, examine the existing hardware and software, the type of projects carried out, the project partners and the risks involved until the change of approach. In this way, it is possible to achieve the definition of processes and equipment techniques to be adapted by management to facilitate the transition to the new working methods. It is necessary to define a strategy that clearly sets out the objectives the implementation of BIM in the company and the processes and standards to be met. As the company increases its expertise, the strategy can always become more specific and personalized to constantly adapt to the new knowledge acquired. Large companies have equipped themselves in recent years with BIM Manager and have implemented a full of BIM solutions, including in relation to some regulations such as that of the United Kingdom. Another point to focus on are interoperability issues: for example, when companies use subcontractors, it is important that they work with the same methods and processes. The information required by subcontractors, if they use a different approach, could give rise to interoperability problems with contractors.

In addition, there is an issue related to a regulatory debate on the intellectual property of data and related copyrights. In contrast to the case where paper documentation is used as a contractual reference, with digital models all the team members involved in the project have access to the same information at the same time. This has important consequences, especially related to the protection/integrity of sensitive data and the control of information flows, with the adoption of specific technical standards. It is also necessary to point out that other types of information conveyed by the information models also represent confidential data: for example, the provision of the intrusion detection systems, the electrical, fire and gas systems must be accessible only to persons directly interested in the activities. Obviously, it is necessary to comply with the privacy standards (Codice in materia di protezione dei dati personali, D.lgs. 30 giugno 2003, n.196), allowing access to information only to those strictly concerned and for needs related to the fulfilment of the contract. It is also necessary to consider aspects related to the protection of industrial property, which, together with literary and artistic property, makes up intellectual property. The core of BIM consists especially on collaboration among the actors involved in the construction process, therefore in the availability of information and management of the information flow. It is necessary to define the ownership of each piece of information, in the sense of identifying who has the rights of access and modification and, consequently, the relative civil and criminal responsibilities. The ownership of these items will depend entirely on the organization and agreements of the clients. The common data environment is going to assume relevance and dignity in the process and has not to be seen as a simple information repository; it consists therefore in an IT environment where accesses and management methods acquire a relevance that goes beyond the important service of ensuring uniqueness and adequacy of information. Finally, there is a risk for small and medium-sized enterprises (SMEs) in the construction sector that risk being excluded from the market if they do not adapt to this methodology.

1.10. Seven structural engineering applications in a BIM environment

The transition of structural engineering to the use of BIM systems is becoming more extensive, covering more and more fields of applications. In the passages below, a state-of-art of some benchmark case studies that illustrate the potential of digital tools in the field of industrial engineering have been analysed. With the analysis of these experiences, the main focus of BIM in the field of structural engineering are reviewed, which have been useful to define the applications deepened in the following chapters. Specifically, they concern:

- interoperability between the structural BIM model and the structural analysis tool;
- the parametrization of the structural connections;
- the Structural Health Monitoring (SHM) systems;
- virtual reality (VR);
- augmented reality (AR);
- IFC schema extension;
- the safety assessment of existing structures.

In the study presented by Ren et al. [31], the authors conducted a preliminary literature review about BIM interoperability trying to identify topics and trends on the BIM interoperability problem with a focus on the structural analysis domain, from both the theoretic perspective and the application perspective. Based on the review and preliminary experimental analysis, research gaps were identified in the BIM interoperability with structural analysis area.

When an IFC model is exported from one software and imported into another, certain information may miss or become untraceable. Redefining information manually is time-consuming and human error-prone. But without a full interoperability these manual inputs cannot be avoided. In the structural analysis domain, for example, when a shell element is being analysed, loads and materials are needed but may not be successfully transferred using IFC models. To address this, any researchers have manually checked the potential information loss before file are exchange, in order to avoid/reduce unknown information missing during the file exchange.

Fig. 1.28 shows different types of files used in different software for the preliminary interoperability experiment, and their results of structural analysis. In this experiment, Revit files were imported into Autodesk Revit, and exported as IFC files. The IFC files were imported into different software, such as ETABS, SAP2000 and Autodesk Robot to conduct structural analysis. Four types of objects were used, i.e. beams, column, slab and wall. Beam and column models were created in Autodesk Revit Structure software directly, whereas slabs and walls models were downloaded from online sources. Tab. 1.3 shows the property representations of the models in different software for structural analysis, including material properties, section properties, degree of freedom, and load description. IFC file was used as the standard file to test the interoperability between architectural design and structural analysis. During this import/export process, a few problems occurred that caused unsuccessful import/export results. For example, when IFC files were created in the Autodesk Revit Structure and imported into Autodesk Robot for structural analysis, material property was missing and loads information could not be loaded. Autodesk Revit Structure is good for processing large building models, but for simple models, such as a beam or column, boundary conditions such as a pin on certain point/node/element cannot be directly loaded.

Secondly, when IFC files were imported, Autodesk Robot could not read material information from the IFC files. It caused information missing when IFC files were imported into Autodesk Robot. That was the reason why we had no structural analysis results for slabs and walls (Tab. 1.3) when using Autodesk Robot.

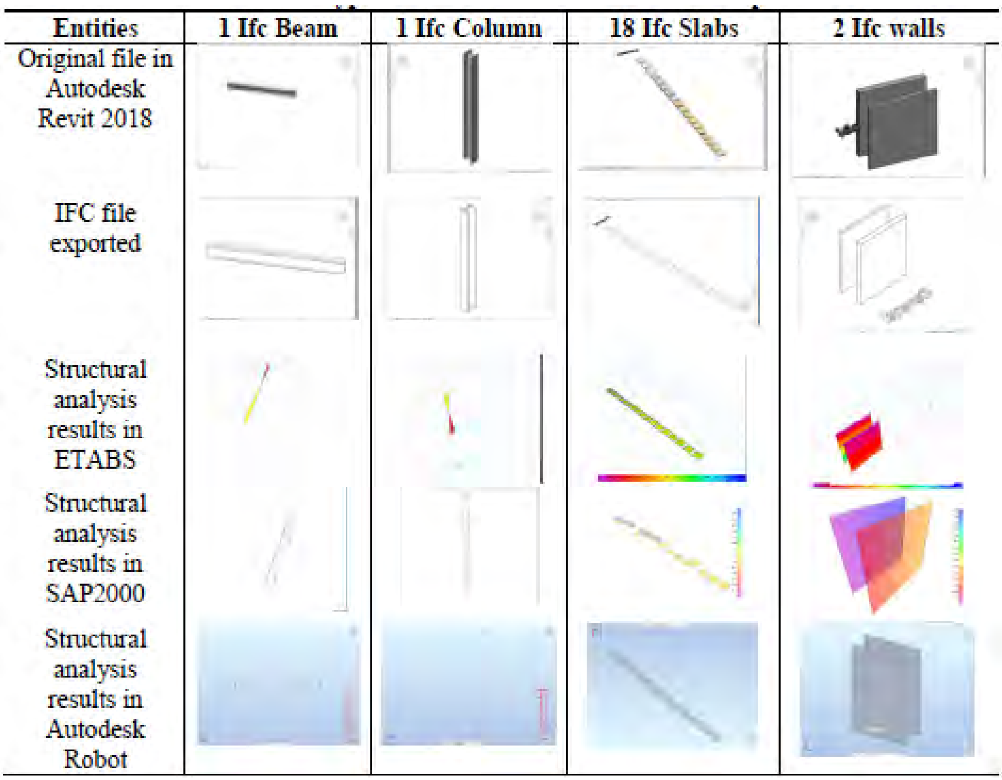


Figure 1.28: Import/export structural elements in several software [31]

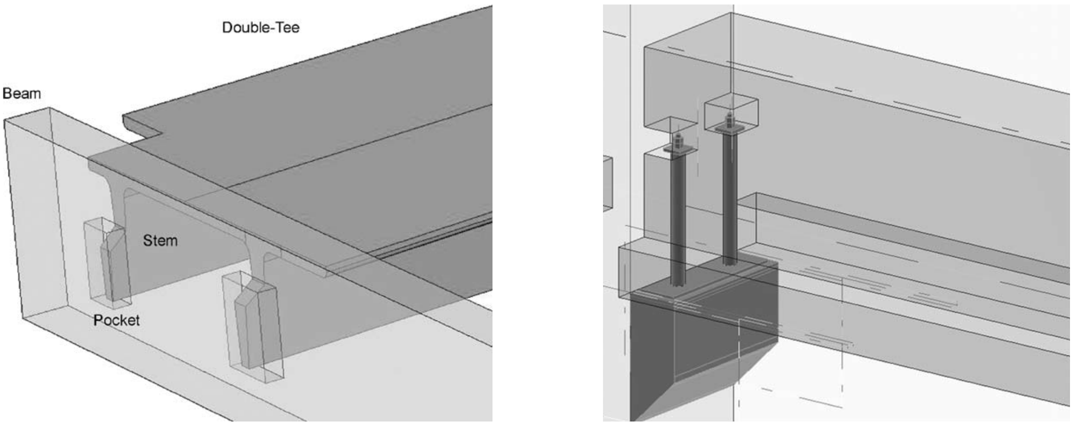
Table 1.3: Properties import/export in different software [31]

Software	Entities	Material properties	Section properties	Degree of freedom	Load
ETABS	1Ifcbeam	Steel ASTM A992	Frame W12*26	UX UY RX RY	Trapezoidal
	1Ifccolumn	Steel ASTM A992	Frame W10*49	UZ RZ	Trapezoidal
	18Ifcslabs	nbl_DeckBeamAndBlock150	Slab nbl_DeckBeamAndBlock150	UZ RZ	Uniform $2kN/mm^2$
	2Ifcwalls	nbl_concept	Wall nbl_concept150.000	UY UZ RY RZ	Uniform $2kN/mm^2$
SAP2000	1Ifcbeam	Steel ASTM A992	Frame W12*26	UX UY RX RY	Trapezoidal
	1Ifccolumn	Steel ASTM A992	Frame W10*49	UZ RZ	Trapezoidal
	18Ifcslabs	nbl_DeckBeamAndBlock150	Slab nbl_DeckBeamAndBlock150	UZ RZ	Uniform $2kN/mm^2$
	2Ifcwalls	nbl_concept	Wall nbl_concept150.000	UY UZ RY RZ	Uniform $2kN/mm^2$
Autodesk Robot	1Ifcbeam	Steel ASTM A992	Frame W12*26	UX UY RX RY	Trapezoidal
	1Ifcolumn	Steel ASTM A992	Frame W10*49	UZ RZ	Trapezoidal

In the study presented by Lee et al. [32] the theme of parametric modelling of construction details of structural connections is deepened in detail. Parametric modelling has been proposed as an effective means to embed domain expertise in models of buildings. As information technology becomes more powerful in terms of the ability to manipulate large parametric models, the potential grows to build increasingly sophisticated functional systems for designing, modelling and fabricating buildings. Implementing more powerful systems implies greater functional specificity, which requires elicitation and capture of increasingly detailed and complex domain-specific semantics and knowledge. In the study is described a protocol for designing, validating and sharing the design intent of parametric objects. In Fig. 1.29 are drawn examples for precast concrete. Fig. 1.29 (a) shows a precast concrete floor panel called a double-tee connected to a beam using a pocket-type connection. An expected behaviour pattern of the connection is that the pockets in the beam should be adjusted to the locations and the sizes of the stems (the bottom part of a double-tee). When the stems are too deep for the beam, they are dapped (cut back) over part of their height, leaving only the undapped parts to rest in the pockets. In order to define a pocket on a beam, at least five parameters are required: i.e., pocket depth, pocket width, pocket height, horizontal location and vertical location (assuming the beam and double-tees are horizontal—if not, a rotation would also be necessary). However, pocket width, depth, height and location are usually defined not by absolute values, but by relative values defined by load conditions, the shear strengths of the beam and of the stems, local shear strength below the pocket, the angle of the stem and so on. The number of independent parameters can be very large.

Fig. 1.29 (b) illustrates a typical connection between a precast column and a beam. All the components (pockets, bolts, nuts, joints, the haunch and the bearing pads) are designed to automatically adjust to any change to the beam or column cross-sections, orientations or locations.

Even this relatively simple geometric shape requires more than 160 parameters and relations between its constituent objects to maintain semantic integrity when adjacent objects are modified.



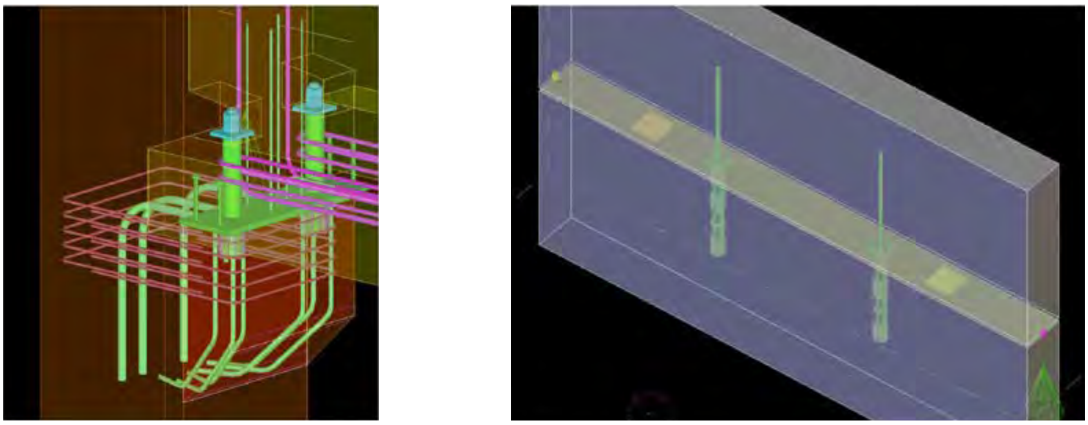
a) *b)*

Figure 1.29: Parametrization of the connection between a beam and a double tee (a) and between a precast column and a beam (b) [32]

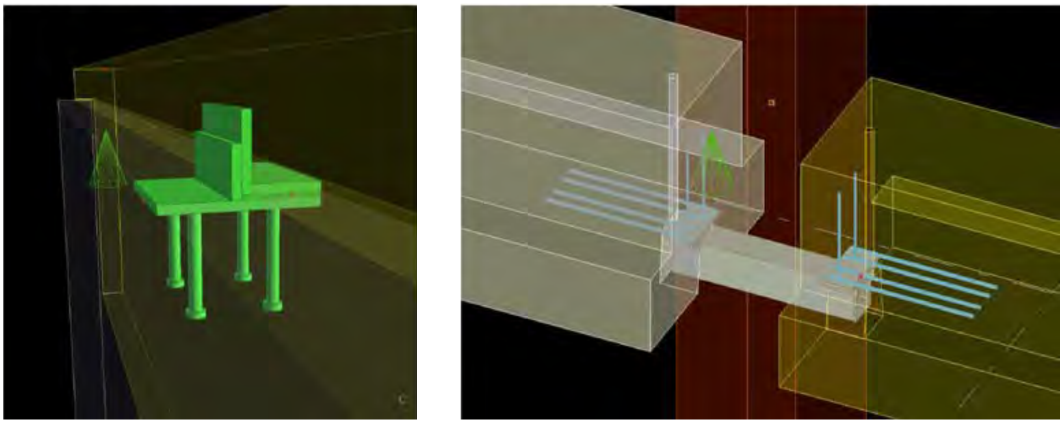
With the aim of parameterizing more and more connections, a procedure made up of for steps is proposed:

- In the knowledge elicitation phase, modelers should clarify design intent and identify expected object behaviour. The identified object behaviour in this phase is a description based on domain expertise and should be used as a guideline for verifying an implemented parametric object and its behaviour in the validation phase;
- In the design phase, modelers express object behaviour in terms of explicit parameters and geometric constraints;
- In the implementation phase, the translated object behaviour is implemented in a CAD system as a parametric model;
- In the validation phase, the implemented parameters and geometric constraints should be checked against the descriptions of initial design intent and should be optimized.

With this methodology some others structural connections have been parametrized, some of which are shown in Fig. 1.30.



a) *b)*



c) *d)*

Figure 1.30: BIM parametrization of a column-to-inverted tee corbel connection (a), of a wall-to-wall array connection (b), of a slab-to-wall connection (c), of a column-to-inverted tee connection (d) [32]

Another application presented by Zhang et al. [33] pertains a wireless structural condition scanning system that utilizes the building information modelling (BIM) and radio frequency identification (RFID) based wireless strain sensor technologies to enable non-contact scanning of structural deformation (Fig. 1.31).

In buildings, structural members are often hidden behind drywalls, and thus buckling or yielding in steel members are difficult to detect, often requiring removal of coverings and thus time consuming and costly. Fast and accurate assessment of structural conditions is important to the occupant safety and uninterrupted use after extreme load events such as strong earthquakes. BIM can integrate all types of structural and condition assessment information collected in the life cycle of civil structures and also provides the visual data displaying mechanism that makes the structural health monitoring information easily understandable and actionable. In the study is shown how a breakage-triggered (BT) strain sensor that uses RFID tag for non-contact scanning of structural deformation condition can detect the surpass of pre-set strain threshold corresponding to structural damage conditions such as yielding and buckling. This system can rapidly identify the spot where the pre-set strain threshold has been surpassed in the corresponding structural element in the BIM model. In the BIM user interface where the Revit structure model is shown, two colours were used to highlight the trigger strain level — blue or red. When the member concerned is marked with a blue colour bar, the lower level BT strain sensors is known to be triggered while if it's marked with a red colour bar, the higher level BT strain sensor has also been triggered. Through the validation test on truss member made of PVC tube, the performance of BT strain sensor for detection of pre-set threshold strain level was demonstrated on relatively large-scale structural members. The RFID sensor based non-contact structural deformation monitoring was validated through hybrid testing of a truss structure under monotonic loading. The trigger strain levels for each configuration were close to the design values. BIM user interface automatically highlights the trigger strain level on the concerned member and displays the updated properties of the selected member once the BT strain sensors are triggered.

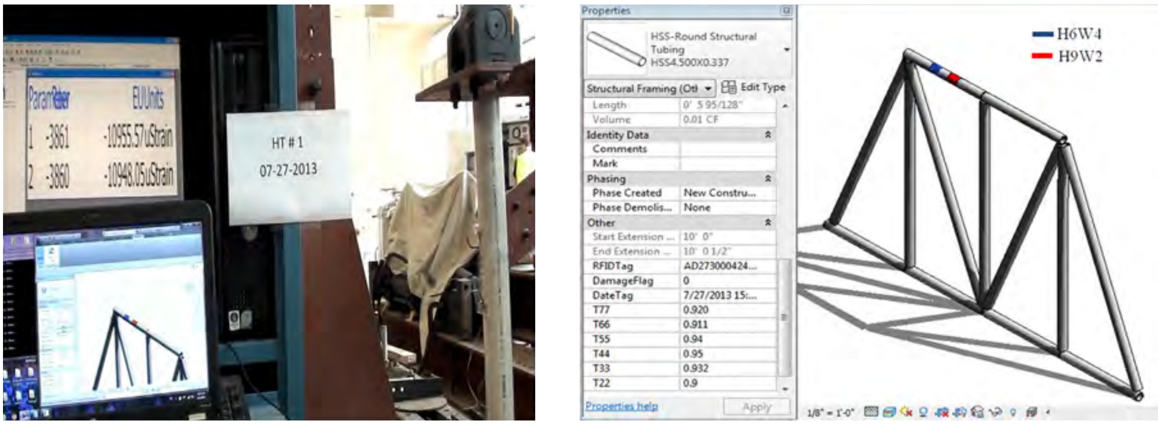


Figure 1.31: Test results of the first hybrid simulation test on truss structure: a picture of test setup at triggering of H9W2; and a screenshot of BIM user interface [33]

Other applications of BIM in structural engineering involve the use of special devices. For example, Setareh et al. [34] experienced the performance of structural analysis operations in a virtual environment. They presented a study in which they showed the development of virtual structural analysis program (VSAP). It consists in a virtual environment (VE) based on a structural analysis system developed by linking a visualization routine using the simple VE library and a structural analysis software. For this application, the PC-SAP4 was used, i.e. an open source already existing software. Using VSAP the user can create a three-dimensional computer model of the building. The model is rendered from the current viewpoint, which the user can control interactively. The user can create the building model using various elements such as beams, columns, beam–columns, slabs, partitions, and ceiling tiles from a database and also select a predefined loading condition.

The user has even the option of creating a PC-SAP4 data file and importing the entire file in order to generate the structural model. This method is very useful when creating a large building model interactively. At this point the program has created a PC-SAP4 input text file which the user can send to the structural software for execution. Upon completion of the analysis of the model, the results in the form of displacement response of structure are sent back to the visualization module for animation (Fig. 1.32). The user can make changes to the structural model and send it back for reanalysis. The cycle of creating a model, simulating, and animating can be repeated as many times as desired in order to test the various changes to the structure.

Four different user interfaces were developed, each intended for a specific situation: the immersive pen and tablet interface, the desktop interface, the portable immersive interface, and the cave automatic VE immersive interface. The main objective of this project was to develop a virtual environment such that practitioners can use it for better understanding of building structural behaviour. Usability studies of these interfaces were conducted so that it was observed that the Immersive UI performed better than the desktop interface in terms of ease of navigation, stylus control, and overall ease of use.

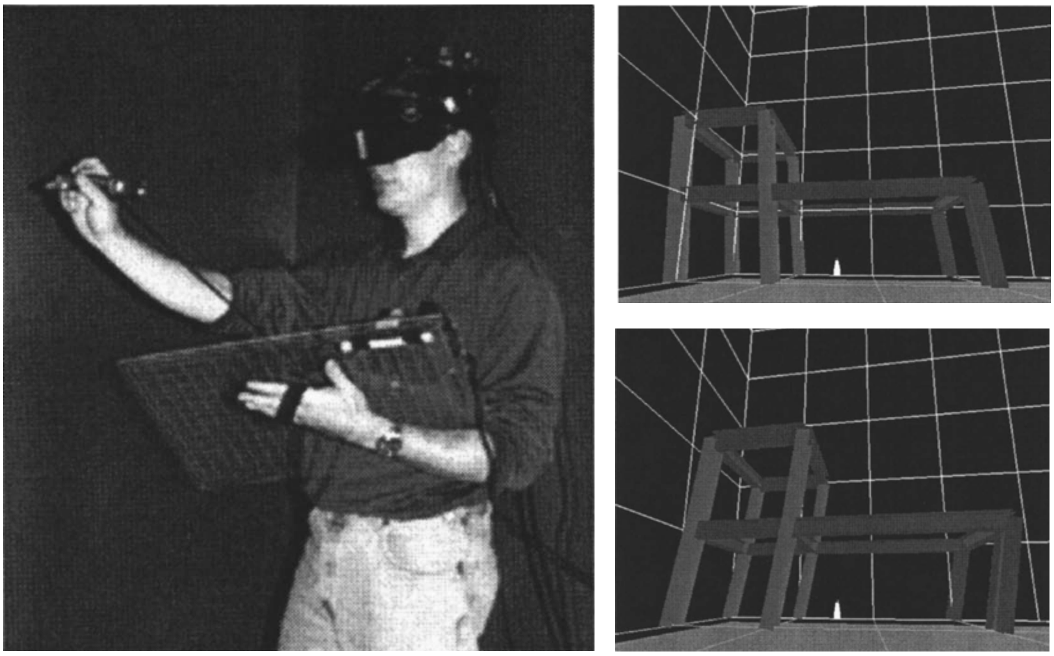


Figure 1.32: Test of the creation of a structural model and the visualization of the deformed shape in a virtual environment with the VSAP system [34]

An interesting application of the Augmented Reality (AR) has been presented by Huang et al. [35], who experienced a system able to assess the loads acting on a ladder and return the effects in terms of stresses almost in real time. Usually, load data acquisition and FEA simulations are carried out separately in practical applications due to the virtual and offline environment imposed by traditional FEA tools. With the use of AR, the coupling of these two processes becomes possible and promising. In the study is proposed a framework to integrate sensor measurement, FEA simulation and scientific visualization into an AR-based environment. Integrating scientific visualization into the AR-based environment allows superimposing of FEA results on physical objects, and facilitating result data post-processing and interpretation. The FEA simulator is able to acquire load data directly from the onsite environment. The load acquisition module plays the role of interface between the simulator and real-world loads. Utilizing an offline pre-computation, the simulator is able to update the results in real time. A case study was carried using a step ladder (Fig. 1.33), which is considered having moderate failure risks in usage. The ladder was equipped with four load sensors arranged on the various steps that measure the loads applied over time. Moreover, the loads in the case study are simplified to point loads and are allocated to the nearest quadrilateral vertices, which may impose unrealistic high stress gradients in the loaded areas especially when a fine mesh is applied. To improve this, the loads can be allocated to more nodes in the loaded areas during the sensor registration process. The relationships among the node numbers, accuracy of the result and frame rate were investigated, in order to find a compromise between the shell element dimensions and the accuracy of the elaboration. However, it is competent for addressing many practical situations. The research contributes a novel method to investigate full-field structural stresses onsite, which has the potential to be applied to monitor mechanical or civil structures in the actual operating environments.

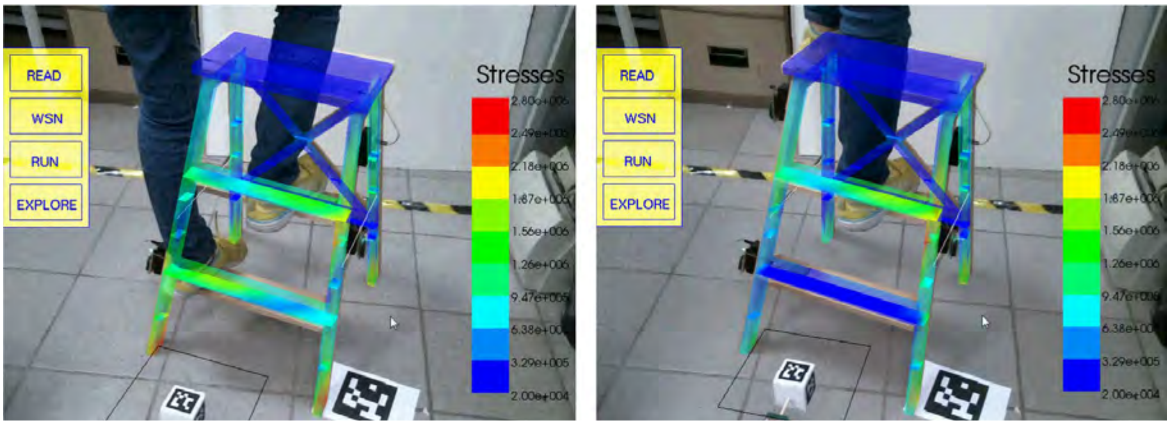


Figure 1.33: Visualization of the stresses acting on a ladder with an AR system [35]

Another research topic concerns the extension of the IFC scheme to structural processes not yet coded. An example is the one developed by Rio et al. [36], focused on the Structural Health Monitoring (SHM). The purpose of the instrumentation and monitoring of structures is to understand the building behavior in situ with accuracy and efficiency, to evaluate their performance over different loads in service, to detect damage or deterioration, i.e., to determine the health and condition of the structure. Despite there not being a single high level SHM system architecture, it can be usually organized in several mains components or modules, i) the sensors module, ii) the communication module, iii) the results data treatment and management module, and sometimes an iv) evaluation module. Some of the information concerning the SHM systems can be stored in a digital model such as a BIM, which seems to be suitable to represent the sensors, the data acquisition and transmission equipment and the actual building or infrastructure. Potentially, it could also include each sensor's data records. The existing IFC versions do not include the relevant kinematic sensors, neither do the proprietary model structures of the modeling software. In fact, the are usually inserted into the model as objects classified as proxy, that is the class included in the IFC schema specifically to be extended with objects not belonging to all other classes. In the study, for the addition of information pertaining the sensors's parameters, a new generic custom Property Set needed to be created, compatible with the existing entity IfcSensorType. For example, the generic Property Set of the Vibrating Wire Strain Gauge sensor was defined so as to handle the frequency of vibration, which this sensor measures. In addition to this parameter, the sensor records the temperature at the time of each vibration frequency measurement, since these sensors need a correction factor that is a function of such temperature. The extension is calculated based on the corrected vibration frequency with a known degree of accuracy. After the property sets creation, their interoperability and functionality were verified sequentially in a text editor, in a model viewer and again in the original modelling software. Data stored in IFC files can be accessed by external applications or by functions that may be included in the IFC data model itself. These external and IFC level functions can potentially be used to handle data, for example to calculate strain from vibration frequency in vibrating wires strain gauges. External applications, such as structural analysis programs may be supplied with SHM data to assess the impact of displacements, temperature variations or other events in real time. In such case, these functions could also be used to compare with externally obtained reference values. Such comparison can, in turn, lead to the triggering of automatic or human tasks. For example, a building can be evacuated if a displacement sensor detects large foundation displacements. However, the implementation of function processes was not carried out within the scope of the work.

To determine the feasibility of integrating sensor data, BIM and structural analysis, a case study with a prototype data transfer model was performed (Fig. 1.34). It was possible to model a building and the sensors in it, enabling the development of an integrated building and sensor data model with con textual data. Modeling, visualization and structural analysis tools were used, which served to cross-check the changes that were being introduced over time.

Figure 1.34: BIM model of a bridge provided with sensors [36]

At last, with reference to the existing structures, Bassier et al. [37] experienced a methodology for the safety assessment of wooden truss. The goal of the research is to provide the heritage industry with a workflow that will allow for more comprehensive documentation, the creation of more realistic geometric models and the improvement of interoperability between parties. Traditionally, hand measurements and visual inspections are employed to document cultural heritage. Such measurements, for instance, serve as a basis to create geometric models used in structural analysis. However, the sparsity and inaccuracy of hand measurements only allow for the creation of simplistic models. Denser and more accurate data is required to create more realistic geometric models. An increasingly popular data acquisition tool is Terrestrial Laser Scanning (TLS). The static scanning instrument is capable of capturing accurate 3D point measurements of an entire scene in a matter of minutes. The result is a geometric point cloud containing tens of millions of points with high accuracy. They propose an approach to create realistic BIM objects of structural elements based on point cloud data and apply these BIM objects as a base for structural analysis. Their approach consists of two phases. The Scan-to-BIM phase covers the data acquisition, modelling of the elements and their representation in a BIM environment. The structural analysis phase covers the exchange of the model to a Structural Analysis software and the evaluation of the model's behaviour. The wooden trusses used as case study are placed is a small castle in the city of Mechelen, Belgium. One section of the roof was modelled and 11 beams were isolated represented by 40 million points. The Poisson meshing in 3D Reshaper was performed using the two step meshing algorithm. A total of 1.2 million triangular surfaces were constructed, approximately 40 thousand triangles per meter. The meshes were manually segmented. For computational efficiency, the mesh complexity was reduced. A maximal deviation of 1 mm was allowed on the decimation, resulting in 50 thousand triangles. An average deviation of 0.35 mm was computed for the entire data set. The meshes were reverse engineered to solid models employing the ScanTo3D function in SolidWorks. Rectangular beams were employed to best approximate the structural elements. Also, the elements are linear and are located in the same plane. A structural analysis model is defined for the evaluation. The comparison between the two models is performed in two stages. First a metric comparison is made. Second, a structural analysis comparison is made. To compare both geometric models, a million sample points are generated on the surface of the models. The shortest Euclidean distance between the two geometries is calculated in the CloudCompare software. A mean distance of 20 mm with a standard deviation of 40 mm is calculated between both data sets. This results in a mean difference in profile area of 15 % and in volume of 12.5 %. The complex model has more weight because the modelling in the wire-frame model is based on the smallest section. The mass discrepancy both affects the load from self-weight and the structural behaviour of the beams. These differences are the result of the abstractions made by hand measurements. Moreover, the wire-frame model does not encompass geometries such as complex connections, non-rectangular and varying sections, non-linear beams and out of the plane elements. Both models are tested with the same material parameters and external loads. The discrepancy in deformation between the models is very noticeable. The complex model shows deformations up to three times larger than the maximum deformation in the wire-frame model. This is partially caused by a difference in weight and section profiles, as well as the difference in modelling between the two structural models. As stated in the geometry comparison, the complex model consists of non-rectangular beams that connect to the joints in varying angels at different locations. This causes forces to be transferred sub-optimal. Also, the location of the loads has a major impact. In the complex model, the loads are placed more accurately, causing a difference in stress concentration. As a result, the peak deformation is located elsewhere in both models (Fig. 1.35).

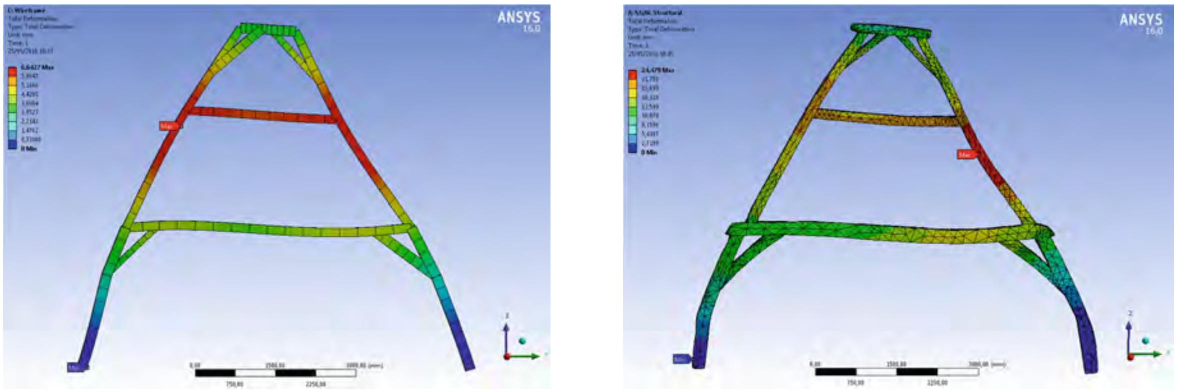


Figure 1.35: Structural analysis of the wooden trusses of the simplified model (on the left) and of the complex model (on the right) [37]

1.11. The Common Data Environment between national and international scenarios

Collaboration between the actors of a project can be greatly simplified thanks to the introduction of collaborative platforms, which allow the implementation of Common Data Environment. On the subject of CDE, national and international standards have defined characteristics that are in part discordant, and that have therefore been compared.

1.11.1. The Common Data Environment and digital processes for the construction industry

In the traditional approach to design, teams of professionals, taking into account the different needs defined by the client, develop a design solution that delivers to the client through paper-based graphics that are collected in an archive; this archive is called Ambiente di Condivisione dei Documenti (ACDoc according to UNI11337-1). With the introduction of digital methods and tools in the construction sector, paper documentation does not meet the new digital processes, as all interactions are centralized on BIM models, which are enriched with information as the design process progresses. In this new scenario, the traditional drawings do not disappear, but have a secondary function since they represent just a way to make the information contained within BIM models more explicit, in order to make them more easily readable by professionals. All the files, better known as containers of information according to ISO19650, are then collected in a digital repository, called Ambiente di Condivisione dei Dati (ACDat according to UNI11337) or also Common Data Environment (CDE according to ISO19650), which is an informatics infrastructure for the collection and management of data. The structure and function of the CDE changes according to the digital maturity of the processes: when BIM processes reach the so-called level 3, all information are integrated in the form of metadata within an informative model that become the only reference point for all the stakeholders. At present, however, digital processes have reached the level 2 and therefore BIM models are not yet able to centralize all types of data and information, so they are often still accompanied by survey datasheets, technical data sheets, maintenance datasheets, reports, photographic documentation etc. It is therefore essential to use environments that is able to take into account all the different sources of information. This issue has been well analyzed by many software companies that have created collaborative platforms that, if on the one hand comply with the need to provide cloud environments to collect information, on the other hand have drew up tools which allow its aggregation.

When a BIM model is uploaded within a platform, even if it will not be enriched with further information later on, it become a reference point on which all the documents placed on the platform can be referenced. For this reason, platforms are often equipped with tools, such as viewers, that allow to display together information belonging to different containers. In has to be noticed that even the federated model is obtained precisely by overlapping the BIM models relating to different disciplines or different portions of the within the same discipline. When the models belong to two different disciplines it may happen that they are also produced by different software, and therefore they would not be compatible with each other. For this reason, very often platforms are able to manage not only proprietary formats but also open ones, which greatly simplify the interoperability of models. The platforms are then often equipped with additional tools that aim to aggregate data on the models. In detail, any of the tools developed for the purpose are:

- Links: they allow to establish a direct connection between the model elements and documents on the platform. Each element can then be linked to the manufacturers' technical data sheets, Excel sheets on which are reported the maintenance operations carried out, photos that describe the actual state in which the real elements of the building, lists of beam and pillar reinforcement, reports on mechanical tests of materials, etc..
- Markers: they allow to place photos and documents at precise points on the model. When, for example, tests are carried out on site, it is possible to report on the BIM model the exact point where a given sample was carried out, etc.
- #tagBIM: they are alphanumeric metadata strings that allow highlighting certain information about documents or model elements and facilitating research operations.

The German standard DIN SPEC 91391-1:2019-04 accurately describes the level of aggregation of information provided by the CDE according to BIM maturity levels, as shown in tab. 1.4.

Table 1.4: The CDE in digital maturity processes level 2 and 3 [38]

	CDE Level 2 (container-based)		**CDE Level 3 (database-based)**		
Aggregation Level	**Packaged Model and documents**	**Single Model, Single Document**	**Element group, Model part**	**Building element**	**Element property**
Example	5D-Model, CADproject file with Model and Drawings	3D-digital model, contract document, CAD-drawing	Model of the Walls of a storey, Model of construction section, 3DMarkup	Model resp. Dataset of a construction element (e.g. column, space)	Dataset with properties of the construction element (e.g. material parameters of a concrete column)
Degree of Aggregation	high	medium	low		
Advantage/ Disadvantage	low resource consumption, low administration effort, no access to detail information	medium resource consumption, medium administration effort, access to some detail information	high resource consumption, high administration effort, direct access to detail information		
Common Data Management Systems	Common Data Share, document management system, internet-based Project platform	Common Data Share, document management system, internet-based Project platform, Product data management system	Product data management system, Product model server		

It can be observed how the CDE is easier to implement in level 2 processes that involve collaboration between several disciplines, since with a low consumption of resources maximum benefits can be reached, thanks to the simple creation og links between different containers. In any case, it has to be noted that since all the information is disseminated in different containers, there is a certain intrinsic difficulty in quickly finding the information needed. On the contrary, in level 3 processes a greater accuracy is needed in defining the structure of a CDE but with the result that a perfect integration of all data can be achieved.

1.11.2. Structuring the CDE: typical configurations, working areas and data security

The CDE can be imagined as a virtual working table shared between all the professionals but equipped with a separé, so that each team member elaborates the design solution pertaining his own discipline and, as soon as his proposal becomes mature, he shares it with the other team members. Then the interactions between the different designers begin and they modify the project until an optimal solution is reached and shared. In the traditional logic these operations do not take place exactly as previously described, mainly for logistical reasons; this poor interaction is precisely the cause of errors that inevitably occur and make the various order management processes inefficient. Collaborative platforms, on the other hand, make such interactions possible using virtual environments and thus make a significant contribution to reducing the possibility of errors. The working areas represent the cloud structure of a CDE and each of them corresponds to a specific function or processing status of each container, so as not to create ambiguity to the users. The Italian standard UNI11337-4 identifies four processing states for the informative containers:

- L0 – in fase di elaborazione/aggiornamento: the informative content is in the process of elaboration and, therefore, is still subject to changes or updates. The informative content may not be available to anyone other than the responsible party;
- L1 – in fase di condivisione: the information content is shared with one or more disciplines, but it is still subject to revision by other disciplines or other operators, including the client;
- L2 – in fase di pubblicazione: the information content is activeand all the processes concerning it are completed. No interested party other than the responsible one may make further changes;
- L3 – archiviato: the information content relates to a non-active version linked to a completed process and differs in L3.V (valido) for the version still in force and L3.S (superato), relating to previous versions replaced.

It is possible to organize the folder structure in the most appropriate way, provided that each processing state of a container corresponds to a single work area, and vice versa, each work area corresponds to a defined processing state of the container. It is in any case necessary that there is no overlap in the use between several working areas and that the chosen folder structure is carefully described within the BEP. In this regard, national and international codes are well harmonized and provide useful indications; according to British PAS1192-2 and European ISO19650-1, a hierarchy on four levels is identified (Fig. 1.36):

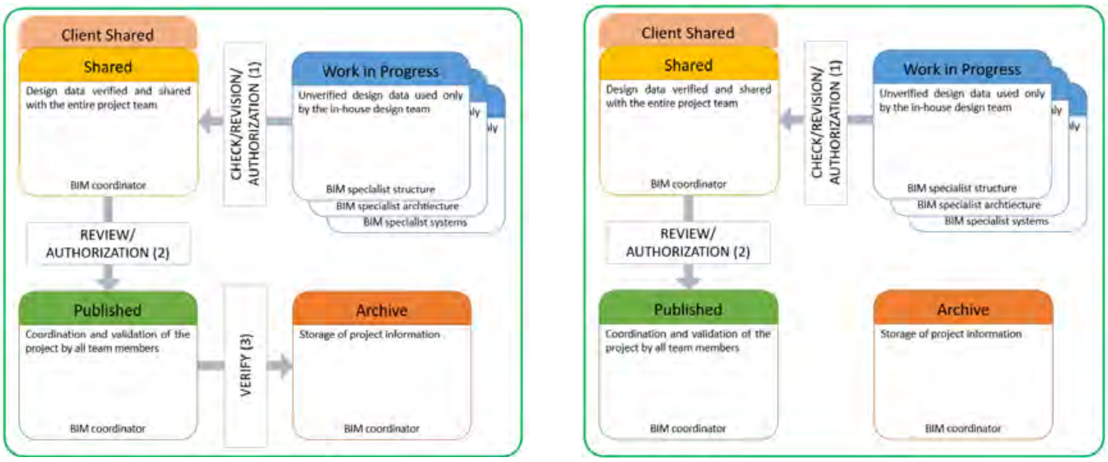


Figure 1.36: CDE working areas according to PAS1192-2 (left) and ISO19650 (right)

1. *work in progress* (WIP): it is generally divided in sub-folders, each one addressed to specific disciplines (e.g. WIP_architecture, WIP_structures, WIP_systems, WIP_costs and WIP_scheduling) and it is an area of relevance especially for BIM specialists. Within each WIP are uploaded the files that are produced by each working group; it is advisable in any case to make at least a weekly upload in order to prevent accidental loss of data. The informative content may not be complete and is subject to modification and updating. For this reason, it is not viewable by working groups but the responsible one. The Work in Progress area corresponds to the processing status L0;
2. *shared*: Information containers are shared with all the team members albeit of other disciplines so that they can view all the progresses, view different project ideas or coordinate disciplines. The sharing does not necessarily take place at the end of the modeling process but also at intermediate moments to have a greater interaction from the early stages of the design. In this working area, the files cannot be modified but only shared; if changes have to be made, it is necessary to return to the respective WIP areas. The information content is considered correct within each discipline, but any changes may occur. Access by the client can also be provided, in a special area defined as "Client shared". BIM coordinators mainly operate in this area. The Shared area corresponds to processing status L1;
3. *published*: it is the working area where the information containers are transferred at the end of all interactions. The information content is therefore completed and no changes may occur unless the client requests them. In Published are contained the documents ready for final delivery and to which the appointing party will have access when the deadline is set. The Published area corresponds to processing status L2;
4. *archive*: it is the working area in which the information containers are transferred when no changes and processes nedd to be carried out. The Archive area corresponds to the processing status L3. The function of this area has been declined a bit differently by the several standards: according to British PAS, the files are moved to the archive, for example after the final delivery of a design competition, and therefore it will contain only the final files; the ISO standards instead consider the archive as an area unconnected with the previous ones, where the historical record of all the information containers developed during the processes

is kept, thus containing both the final and intermediate files produced, accompanied by their respective attributes.

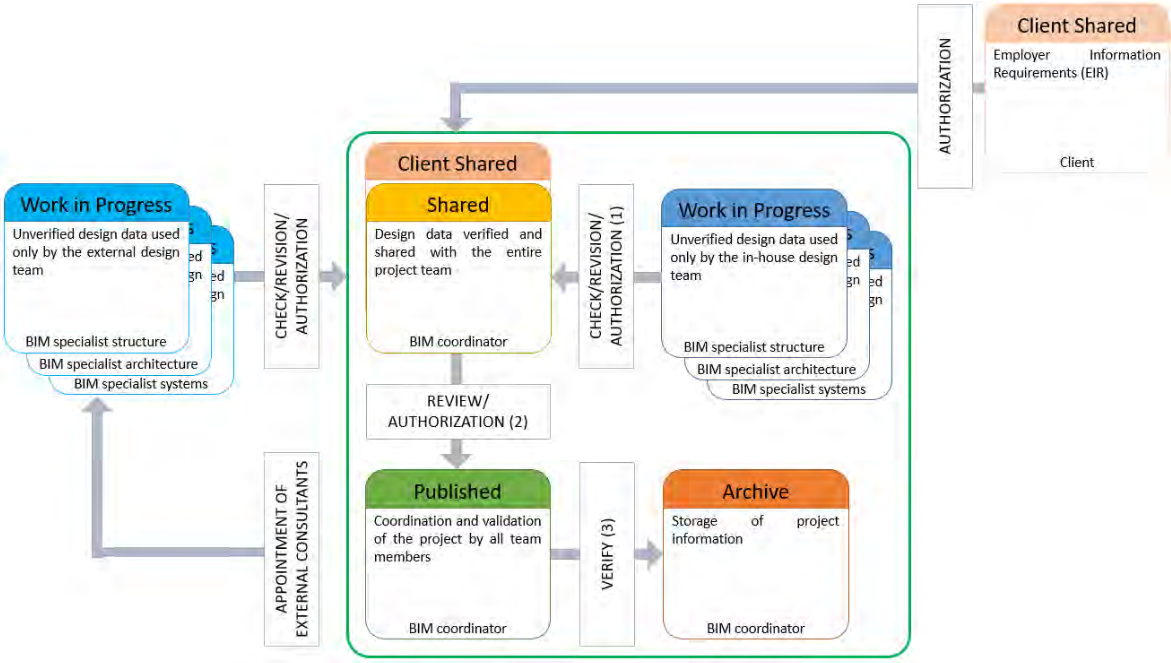


Figure 1.37: The interaction of the external consultants and the client with the CDE according to PAS1192-2

Then, other accessory areas can be added, with the access opened to all the stakeholders:

- *Incoming*: in which all the documents available before the design are uploaded, for example those produced in previous phases, site surveys, photographic documentation, legal documentation, etc.;
- *Resources*: where all documents that provide support during the design process, such as codes, urban planning regulations, libraries of BIM objects, etc., can be included.

Additional external Work in Progress areas can be added to this "closed circuit" if external designers or consultants such as surveyors and topographers, or even experts in the specialist design of prefabricated elements, are involved. n addition, another folder that can be considered is called "client shared", in which the client can upload the Employer Information Requirements (EIR), in which he formalizes his requests in terms of information modeling (Fig. 1.37).

The information flows of new construction projects originate from Work in Progress or a Client Shared as shown above. Projects that are part of a large real estate portfolio or that concern retrofit interventions on existing buildings that have already been previously developed in a digital way, are not new flows but represent the continuation of flows already originated in an existing Asset Information Model (AIM) that was previously developed within another CDE (Fig. 1.38).

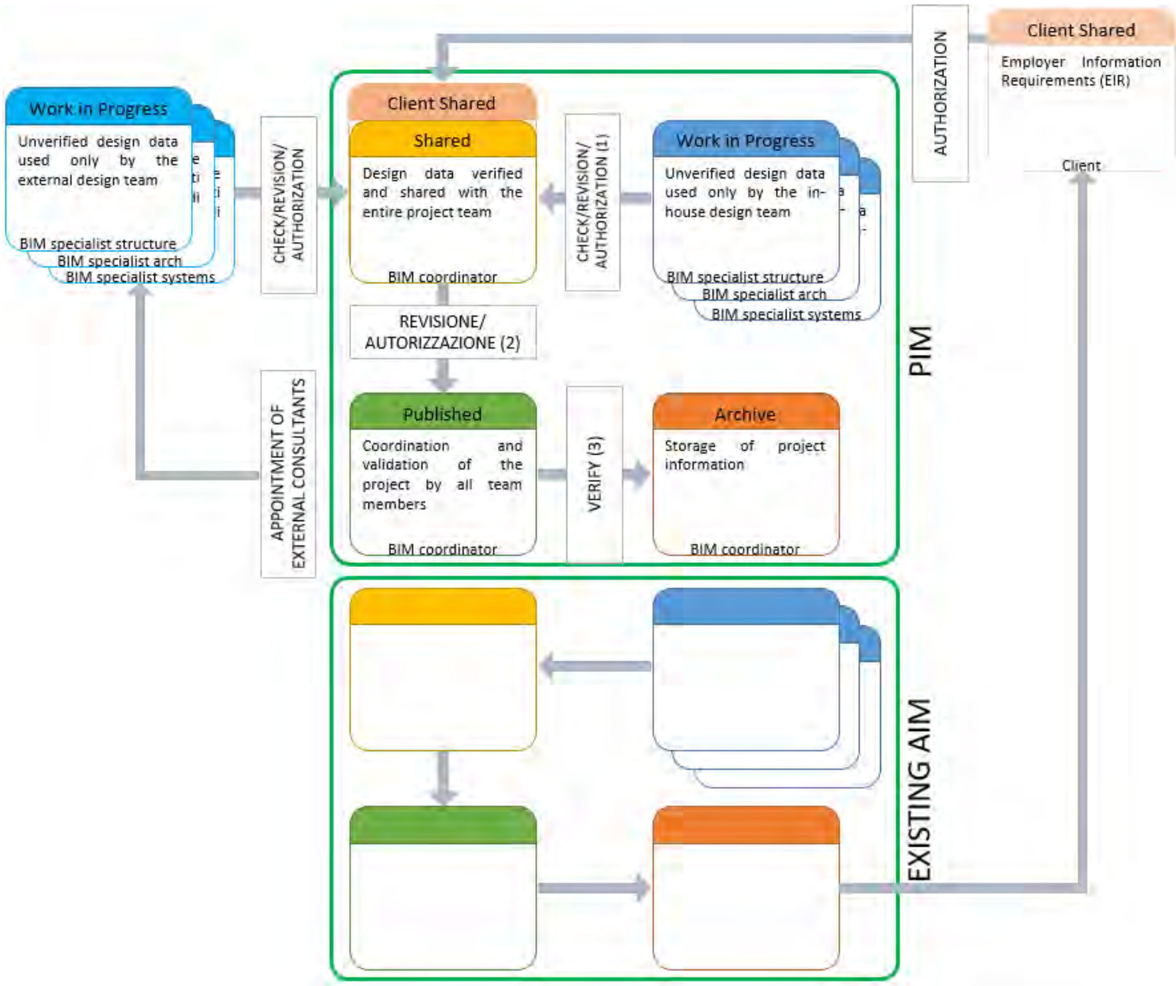


Figure 1.38: Information flows in the EDC linked to existing AIM

Access to each folder, as already mentioned, is differentiated according to the role and discipline of each team member. In detail, the following types of permissions can be distinguished:

- *Upload* (U): the user can upload documents to the folder but cannot view any content apart from those uploaded by himself. It is a permission granted for example to a consultant external to the design team, (such as a geologist who delivers the geological report) who for confidentiality reasons cannot view the other design documents;
- *View* (V): is a permission which can be assigned to users that can only view the contents of each folder, without being able to edit it. It is assigned, for example, to the client who may want to be updated on the progress of the design to give feedback;
- *Edit* (E): it is the permission assigned to those who need to modify the attributes of the documents, to promote or reject the progresses of the work, to perform links operations between the documents, etc.. However, it does not refer to the modification of the body of documents, which does not take place within a CDE but only to the modification of its status.

An example of assignment of the V, U and E permissions to the different users of the CDE are summarized in the permission matrix, i.e. a table schema in which in column is reported each folder of the CDE and in line the different professional figures. At their intersection the assigned permissions are pointed, as shown in tab. 1.5.

Table 1.5: Permission matrix to the folders of the CDE

	Incoming	Resources	WIP_Architettura	WIP_Strutture	WIP_Impianti	Shared	Published	Archive
BIM modeler architecture	V	V	E	-	-	V	V	V
BIM modeler structure	V	V	-	E	-	V	V	V
BIM modeler MEP	V	V	-	-	E	V	V	V
BIM coordinator architecture	V+U	V+U	V+U	-	-	E	E	V
BIM coordinator structure	V+U	V+U	-	V+U	-	E	E	V
BIM coordinator systems	V+U	V+U	-	-	V+U	E	E	V
Architect	V	V	E	-	-	V	V	V
Structural engineer	V	V	-	E	-	V	V	V
MEP engineer	V	V	-	-	E	V	V	V

1.11.3. Processes and gates

The working areas are "static entities" in which the information containers are placed during the project. The dynamic interactions between the various team members are managed through workflows, i.e. flowcharts listing the sequences of activities to carry out in order to achieve specific objectives. A workflow is then divided into tasks and each task corresponds to single activities that must be performed within a maximum duration of time by specific actors, who may be in charge of carrying them out or just checking them out. Within a workflow in progress, each task is characterized by a status, which can be in progress, expired, finished or canceled that changes as the process progresses and can include the exchange of some reports in which are described the results of the activities. Each workflow is focused on specific objectives and can concern both processes that take place within each working area (such as structural design, survey on-site, structural modeling) and processes for the verification and validation of the contents of each container necessary to promote each document to the next working area. In Fig. 1.39 there is an example of workflow for structural design.

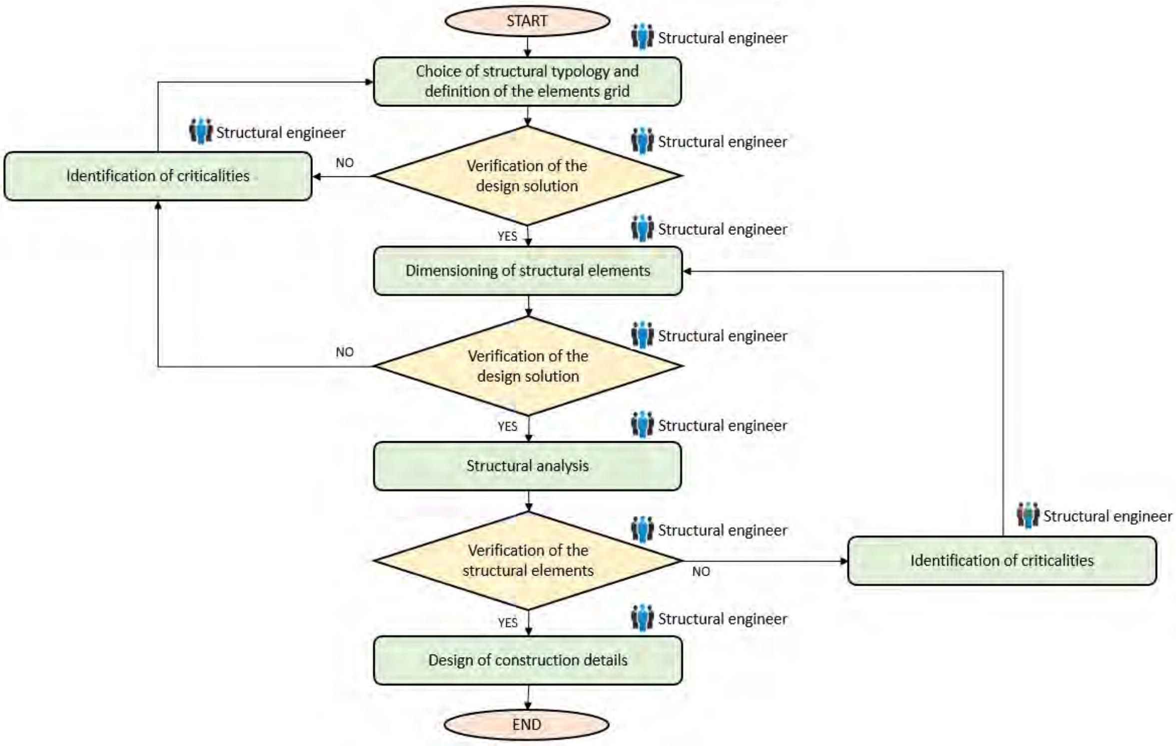


Figure 1.39: Example of workflow for the structural design

In detail, with a circular shape have been represented the start and end tasks, while with the rectangular shape, the activities to be performed. Finally, the decisional steps have been represented with the rhomboidal shape, which is followed by two alternatives depending on whether or not the verification are passed. Of course, in the example all a structural engineer carries out the activities as they are all proper of its own discipline but in different cases, other figures could be involved. These process maps are defined before the order itself begins, when the BEP is drawn up. In fact, by defining in advance all the tasks and persons in charge for them, overlaps and project downtime are avoided and the resources optimized. Thanks to careful process planning, some best practices can be defined, so that can be identified the working procedures that lead to the best results based on the experience gained over time and make them standard procedures. Within the CDE there are also areas where it is possible to check if the containers meet the requirements for the access to the next working area, which are called gates. The following gates can be identified:

- Check/revision/approval (Gate 1): regulates the transition from Work in Progress to Shared. It controls the overcoming of the coordination levels, the suitability of the model, the technical content, the completeness of the COBie, the consistency between the extracted tables and the models, the approval by the working group manager. The container is then checked with the information delivery plan and the agreed specifications, methods and procedures for the production of the information;
- Revision/authorization (Gate 2): regulates the transition between Shared and Published. It controls whether the containers have reached the coordination, completeness and accuracy requirements of the BEP;
- Verification (gate 3): regulates the transition between Published and Archive.

A slight discrepancy can be noted between the PAS and ISO standards since the latter do not provide for a Gate 3 due to the different function assigned to the archive. In fact, according to ISO standard, it is intended as an area for the historic record of the processes performed, so that the containers pass from each area directly to the archive without verification since it does not represent the end of a process.

At the end of the checks carried out at the gates, if they are successful then the containers can transit to the next working area, otherwise, they return to the Work in Progress for the necessary changes.

1.11.4. Verification levels, coordination levels and approval statuses

In order to ensure compliance with quality requirements for information management, BIM models and drawings should be periodically checked as the information content increases. The verification operations are carried out every time the container has reached the maturity necessary to get to the next working state. For this reason, the UNI 11337-5 standard identifies 3 Coordination Level (trad. Livelli di Coordinamento):

- Coordination Level 1 (LC1): it is performed on each BIM model to check whether or not that there are interferences or inconsistencies within the model itself;
- Coordination Level 2 (LC2): it is performed between BIM models from different disciplines to check whether or not there are interferences or inconsistencies between them;
- Coordination Level 3 (LC3): it is performed between each model and the drawing to check whether or not that there are interferences or inconsistency between them.

The Coordination Levels refer to interferences (clash detection) and inconsistencies checking operations, which are divided into model and code checking operations (Fig. 1.40).

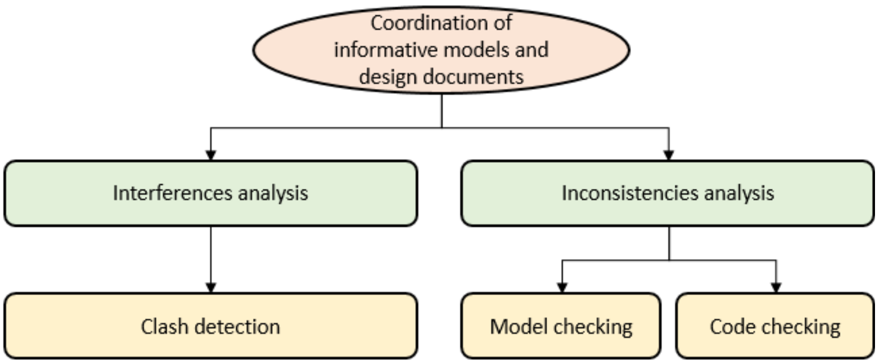


Figure 1.40: Coordination of informative models and design documents

In detail, clash detection consists in the verification of the intersections between the objects of the models and in the drawings; model checking consists in verifying the correctness of the model through diagnostic operations; code checking consists in verifying the correspondence of the information contained in the models with the requirements of the codes.

LC1 is generally performed before the disciplinary model is shared with team members from other disciplines, for the transition from the Work in Progress area to Shared. Taking advantage of automatic software, such as Navisworks or Solibri, it automatically verifies the intersection of objects in the models within the same discipline. With reference to the structural discipline, the clash detection may be superfluous. Since the BIM objects that make up the models are only beams, pillars, walls and foundations, the intersections are usually detected in the nodal zones; these intersections are unavoidable because in the analytical model the beam and column have necessarily to join in the nodes.

The LC3 consists in the coordination of the BIM models with the drawings. In some cases, it may be convenient that some of the drawings are not extracted directly from the model but produced in the traditional way, or that the drawings are extracted from the BIM models but are then modified adding information; for this reason, it may happen that the model and the elaborates have interferences. LC3 should not be understood, therefore, as an advancement of LC1 and LC2, but rather as a set of further controls to be carried out. These coordination operations can be carried out by a BIM coordinator or even by a BIM discipline leader, when they concern a single discipline. Fig. 1.41 shows the workflows corresponding to LC1 and LC2.

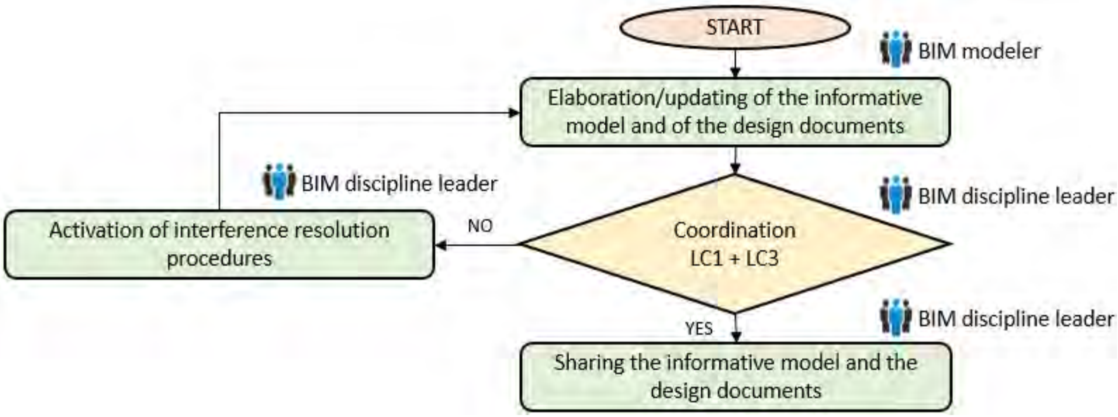


Figure 1.41: Workflow for LC1 and LC3

The LC2 is generally performed to verify coordination between several disciplines when the design process progresses, in order to avoid the occurrence inconsistencies. The detection of interference between the models of the different disciplines is not intended to assess the correctness of the model processing, as in the previous case, but to detect real design problems that require a revision of the design approach. Once all models are complete and all disciplines, as a result of the various interactions, have come to convergence around a single design idea, overcoming the LC2 becomes a requirement to be able to transfer the information models to the Published area, and is performed by the BIM coordinator. Also in this case, as in the previous one, LC3 does not constitute an advancement with respect to LC2, but is complementary to it since it is aimed at detecting any mistakes in the drawings.

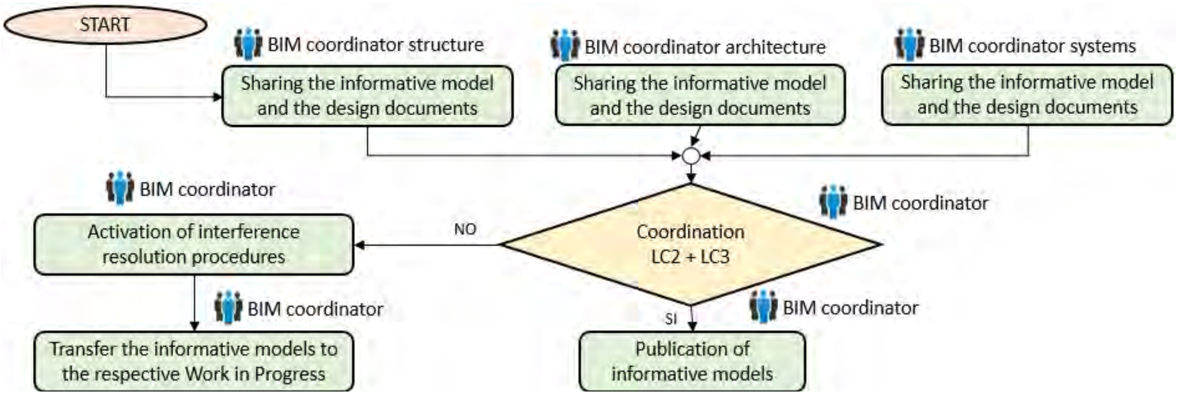


Figure 1.42: Workflow for LC2 and LC3

When coordination takes place, conflicts are resolved and the reliability of the information produced is increased. There are, however, additional checks to carry out which have been introduced by the UNI11337-5 standards as Verification Levels (trad. Livelli di Verifica):

- Formal internal verification (LV1): consists of verifying the correctness of the method of production, delivery and management of information. For example, it verifies that the file format, size (in MB) and nomenclature comply with what is declared within the BEP;
- Substantial Internal Verification (LV2): consists of checking that disciplinary models are readable and traceable and that data and information are consistent. These checks are carried out by making sure that the file is not corrupted) and that the object attributes, including the coordination level and LOD, are those necessary for the progress of the design process;
- Independent, formal and Substantial Verification (LV3): consists of verifications carried out by external bodies, which carry out all the checks they deem necessary. An example of LV3 corresponds to the acceptance of documents in a seismic authorization process.

Finally, the models and drawings are characterized by an additional coding, which is represented by the Approval Status (trad. stato di Approvazione) and concerns the status of the container within a process. In detail, four approval statuses are defined:

- To be approved (A0): identifies a container for which the process is still in progress, and therefore the information content may still be incomplete or incorrect;
- Approved (A1) identifies a container that has been the subject of a successful process;
- Approved with comment (A2) identifies a container that has been the subject of a process that has been partially successful, and for which indications are given of the changes that must necessarily be made in order to proceed with subsequent design developments and for the uses for which it is intended;
- Unapproved (A3): identifies a container that has been subject to a process but has ended with a negative outcome and is therefore rejected.

The Approval statuses can then be introduced at each stage of the information process. All the attributes analyzed so far are applied to each model or document in order to track all the operation performed.

Moreover, once the process is been completed, the operations carried out can be reconstructed a posteriori so that any final audits can be carried out.

For the sake of simplicity, all the concepts analyzed so far have been summarized in the diagram in fig. 1.43, which illustrates a typical process for requesting the seismic authorization.

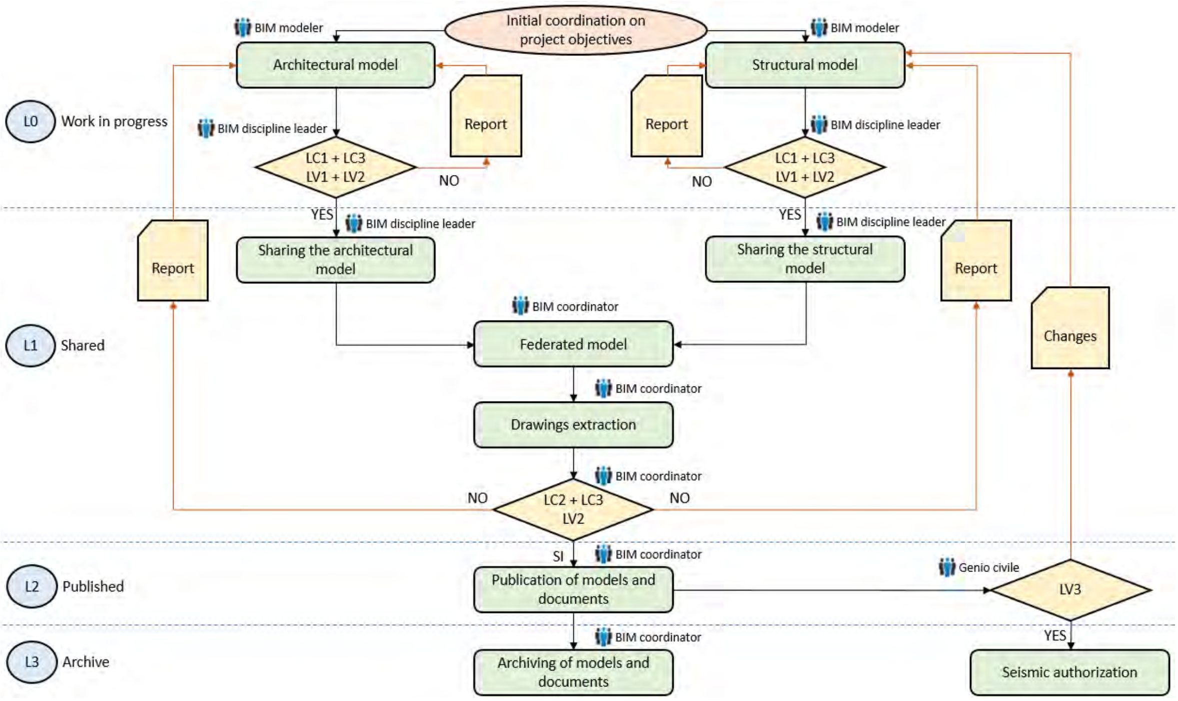


Figure 1.43: Workflow for requesting seismic authorization

1.12. An overview of the collaborative platforms currently on the market

The concept of collaboration during the management of the life-cycle phases of an asset has been declined in different ways by the different software providers, which have therefore made available solutions for collaborative platforms with very different features. In fact, some platforms understand collaboration only as process management and therefore allow to monitor in a smart way the progress of the project and to structure workflows to optimize and monitor all the operations that are carried out. Some other platforms, instead, have taken on board the collaboration in a more operational way and have therefore introduced the use of CDE to manage data and to link the different information containers together. With the aim of achieving maximum benefit from digitization, it should be therefore understood not only as a change of support (no longer paper-based) but also as speed of access to heterogeneous information. A description of some of the platforms available on the market is reported below.

usBIM.platform: is a BIM project management solution created to manage and coordinate the design, construction and management activities of the work in accordance with the D.Lgs. 50/2016 and the Technical Standard UNI 11337 for the digital management of construction information processes. The platform has been designed to achieve the maximum integration among BIM processes. It is based on a CDE that can host each kind of data, i.e. pdf files, BIM models, pointclouds, word file, etc.. Moreover, the BIM models constitute databases on which numerous specific tools are grafted in order to carry out operations that goes from the augmented reality visualization, to the pointcloud management and including even the bill of quantities, the health and safety plan, the rendering. It is integrated with new technologies like GIS and IoT and is provided even with tools specific for the management both of documents and processes thanks to workflow design. It is one of the most feature-rich solutions on the market (Fig. 1.44).

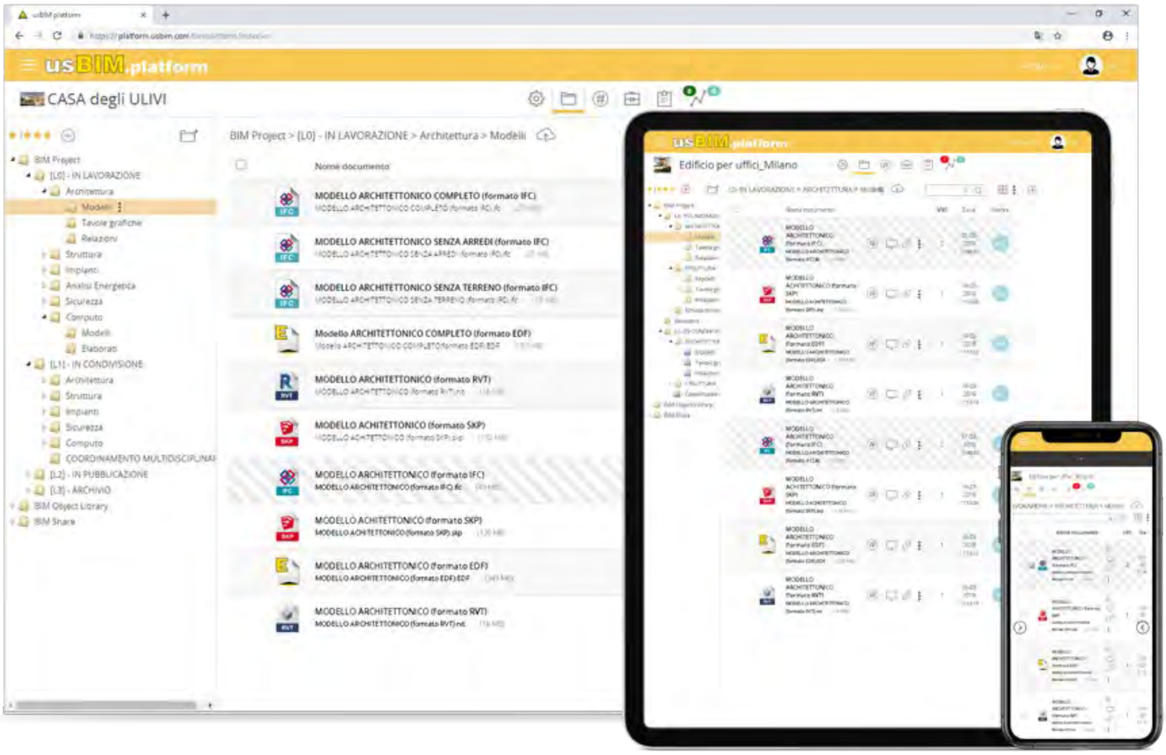


Figure 1.44: usBIM.platform by ACCA software

A360 by Autodesk: it is a platform based on a cloud where all the information pertaining a project is stored. Thanks to "A360 Teams", the information can be shared among all the team members, including architects, structural and mechanical engineers and all the party involved. Any participant can upload file in the platform, so that a perfect integration is realized among the different disciplines. Indeed, the collaboration is encouraged thanks to interactive chat, real-time revisions and the on-line viewer (available even for tablet and mobile) which does not require the installation of any software on the computer. All the team members can provide their feedback in real time and transform design files into opportunities for continuous collaboration. As the maturity of the design progresses, the file versions are managed directly on the platform so that the most updated file can always be displayed without misunderstanding, without losing at the same time the previous versions. Moreover, very different file formats are supported and viewable on-line, including the IFC format. The strong point of this platform is surely the implementation of advanced tools for work-sharing; any team members, working on a locally-cached version created on each workstation, can upload their progresses when the Revit model is stored within a project on A360. A360 is available in different tools, each of them covering different range of the project time frame, from the design phase to the operation phase, with features customized for the specific use (Fig. 1.45).

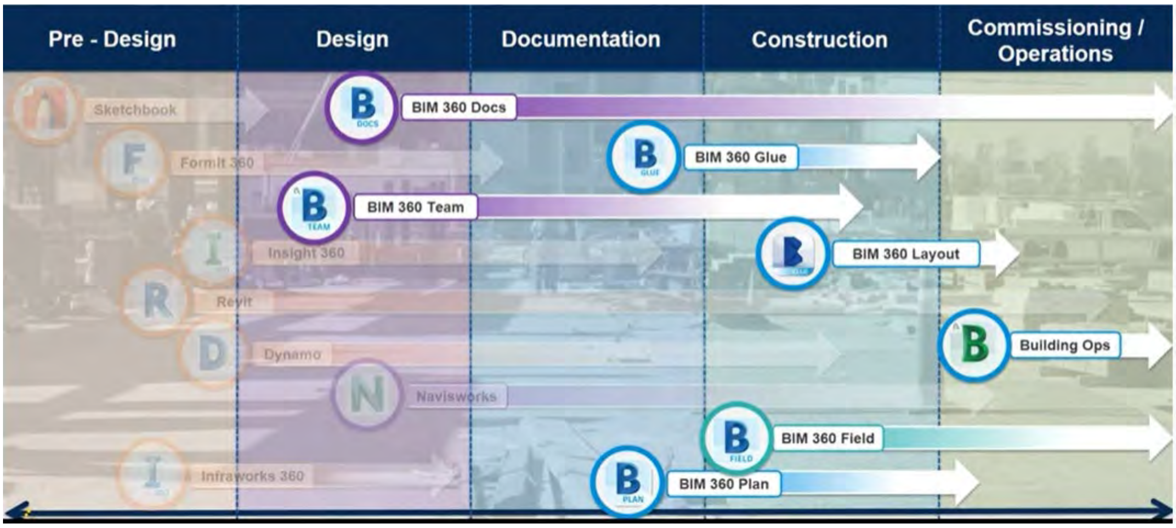


Figure 1.45: Autodesk A360 platform by Autodesk

Oracle Aconex: Oracle Aconex is a cloud-hosted operation management application that can be leveraged to manage processes and information between enterprises on complex engineering and construction projects. It has tools and features that enable construction firm owners, engineering, procurement and construction management companies (EPC/M), contractors, and project management consultants to collaborate in projects, manage data, documents, and costs with complete visibility across all stages of the project lifecycle. Key features include:

- Document Management, Project Controls, and Workflow Management – It provides all partners and organizations quick access to current documents that include drawings, BIM models, contracts, and more. It has tools for document distribution, transmittals, and drawing management and also has version control to ensure that everyone works on the current version. Project controls provide users an accurate view of how projects are performing across cost, schedule, design, and the effects of changes to all these. Workflow management helps reduce complexity, improves data capture, and increases control through process automation;
- RFIs, Mail & Forms, BIM Management, Quality & Safety – The platform improves project management by centralizing communications. It digitalizes RFIs and queries, provides users with a tool to easily manage and coordinate advice to RFIs, and allow them to issue site instructions and directions. It also has tools for requests and approvals, change management, and delays. BIM and model management tools provide a true CDE to simplify the process. It provides cross-discipline collaboration, with interoperability with other systems. It also has tools for design coordination, and review and approvals. For quality and safety, it automates and standardizes field-based processes, to speed up inspection times, drive accountability, and minimize delays. It has features for checklist and forms, health and safety, defects and punch lists, and more (Fig. 1.46).

Figure 1.46: Aconex platform by Oracle

Trimble Connect: it is a robust and reliable collaboration solution for AEC (Architecture, Engineering, and Construction) professionals such as project owners, general contracts, sub-contractors, engineers, and architects. It provides users with an environment ideal for collaboration and better building through a platform that is accessible, transparent, and can easily track information. Some of the main features are clash detection, model object filtering, file explorer, comment on to-dos, project creation, export reports, 3D markup, model alignment, and activity feeds. Trimble Connect ensures that every involved party of a construction project are able to see both the big picture and the finest details. Everyone from the ground level up to the top level, offsite or onsite, are kept updated about the project's progress and the next course of actions that would be taken. The platform is accessible through the web, mobile devices, and desktop which means that anytime and anywhere access to the project is possible. It easily integrates with other software, like Tekla, SketchUp, ProjectSight and many different Trimble products (Fig. 1.47).

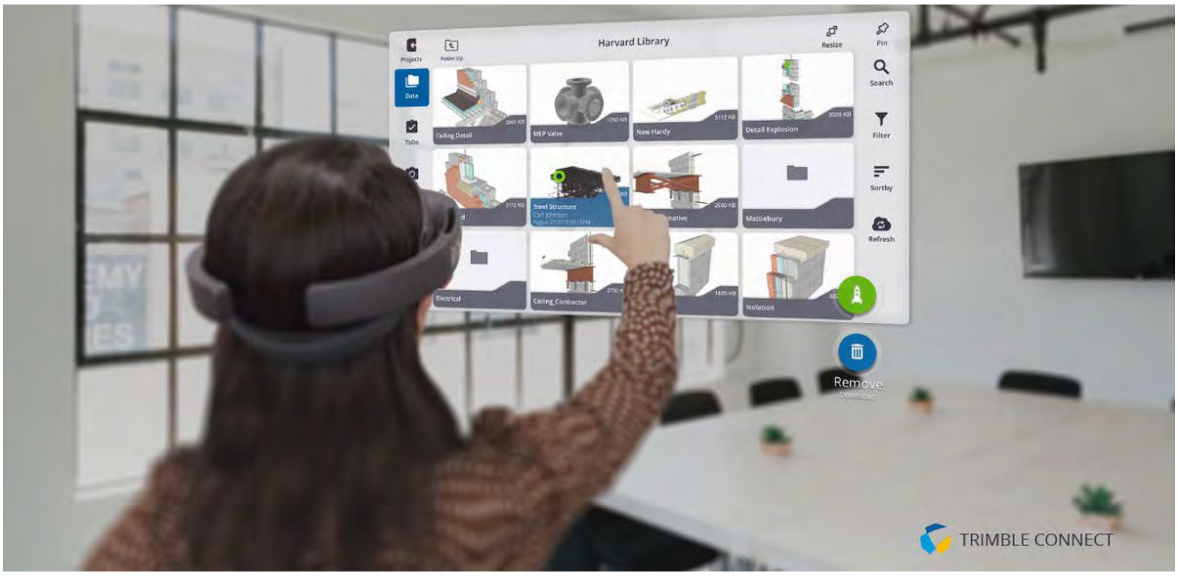


Figure 1.47: Connect platform by Trimble

Nemetschek dRofus: it is a tool for planning, data management and BIM collaboration. It enables to link metadata to BIM elements through simple Excel datasheets: it manages heterogeneous data sets and converts them into project information accessible to the professionals involved in the process. Developed according to the needs of large public and private clients, it enables to set up a database according to the client's requirements (EIR), to prescribe and verify compliance with the required regulations and standards, to plan the layout of equipment and to validate the design solutions in a BIM environment. In dRofus there is bi-directional synchronization between database and BIM model to keep them always updated, thanks to plug-in for Revit and Archicad and to the IFC with any BIM Authoring software. Thanks to the production of reports and their continuous updating, it allows to monitor facility management operations to promote collaboration between the various stakeholders involved (Fig. 1.48).

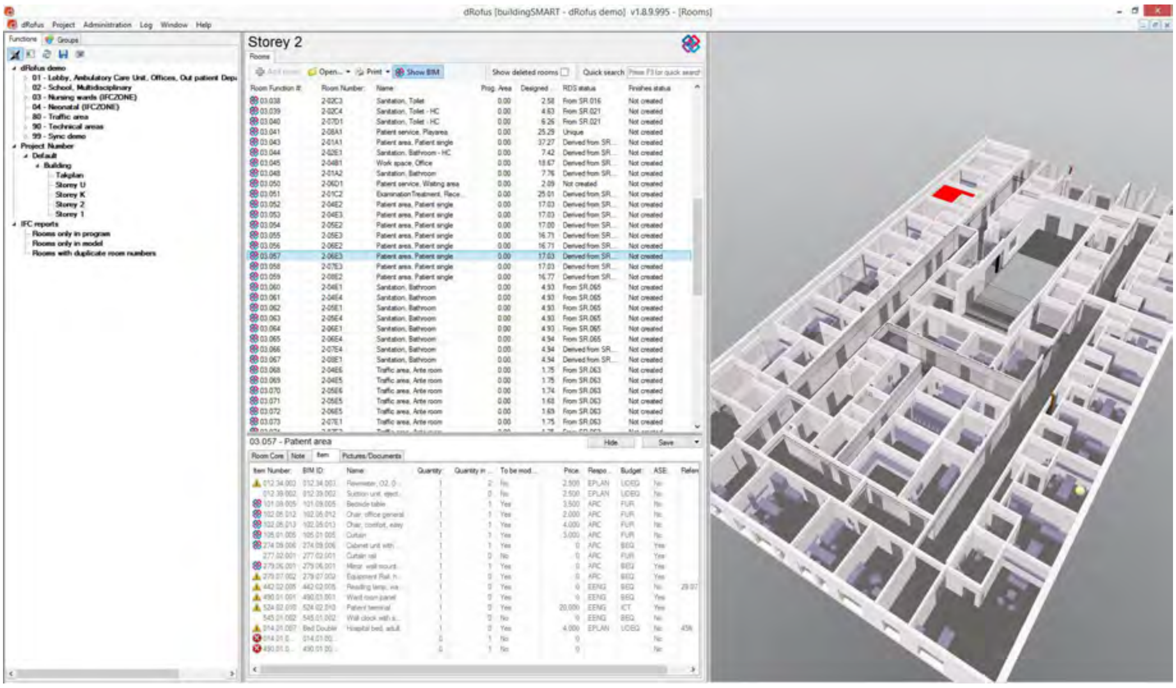


Figure 1.48: dRofus by Nemetschek

KUBUS BIMcollab: it is a platform based primarily on the collaboration among the team members, in which all the issues of the project are centralized exploiting the power of working in a completely openBIM environment. It was developed when the revolutionary BCF standard was first introduced. It is provided of a dashboard where statistics on the issues detected, resolved or in progresso of resolution are always readable turning out to be very useful for the management of modeling operations. BIMcollab is made out of 3 separate sets of tools: BIMcollab Zoom, BIMcollab BCF Managers and BIMcollab online. These applications fulfill separate functions, but still communicate together. More in detail:

- BCF Managers are add-ins for various authoring, clash detection, and model checking software programs developed for the issues management in BIMcollab. It has a BCF

Manager for most of the programs listed with a solid line below, and integrates through a normal BCF file-based exchange with the programs that show dotted lines.;

- BIMcollab Zoom is the desktop-based viewer, where IFC models can be imported. It is useful to raise and view issues retrieved from the BCF Managers.
- BIMcollab online: BIMcollab online is a web platform where all project issues are displayed. Issues

In addition to having numerous features specific for the BIM management, it also integrates with tools for the clash detection and the point cloud management (Fig. 1.49).

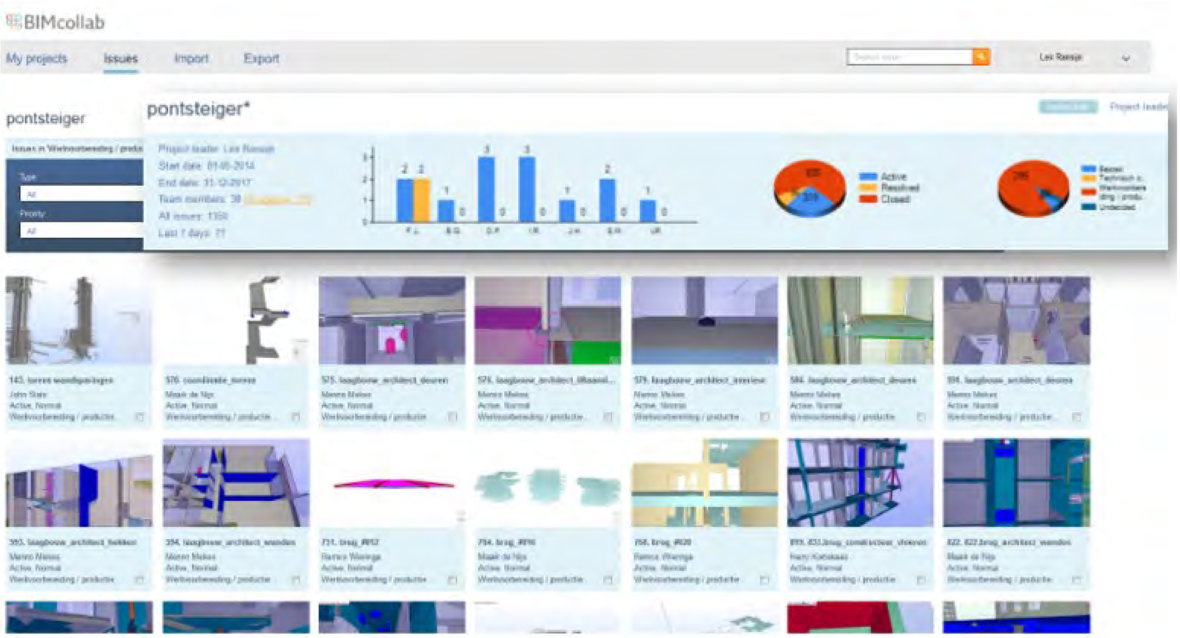


Figure 1.49: BIMcollab platform by KUBUS

Workflow Designer: it is a platform set up for drawing processes, procedures or even mind maps. Workflow Designer includes features such as template shapes, automated placement of shapes, and links to other maps documents or even business analysis information. All the information is developed in the right order required for the job that aligns itself with the workflow or procedure. With Workflow Designer, at each step corresponds procedural information. This ensures both accuracy and sense, up front, without rework or guessing sequences of information. Reference documents such as policies, standards or specifications (Fig. 1.50).

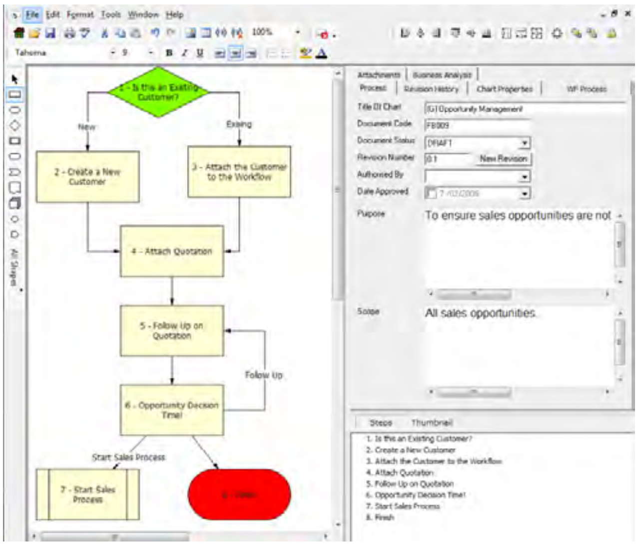


Figure 1.50: Workflow designer by FlowBiz

The platforms listed can concern only the operations management and basic activities, through the organization of workflows (e.g. dRofus, BIMcollab and Workflow Designer), or can also enable the structuring of an entire CDE and in this case they are enriched with multiple tools to manage more complex activities (e.g. usBIM.platform, A360, Aconex and Trimble Connect). Each one of them has different functions because they have been designed to integrate themselves in a different way within the processes. The main features that have been found exploring the platforms have been grouped into four categories; they correspond to:

- *basic functions*: structure of a CDE with folders according to the European standards, restrictive permissions for differentiated access to files, document management in smart modality, model federation and online viewer of BIM models in different file formats that does not require the installation of any software;
- tools that facilitate *collaboration* between the different team members: work on a single model from different workstations, organization of the activities through workflows that relate roles, activities, product and exchanged files, issues communication, e-mail notification and recording of the succession of events to carry out audits;
- *openBIM*: ability to interact with openBIM standards and obtainment of the buildingSMART certification;
- *tools* for different disciplines.

In tab. 1.6 are listed the features exhibited by each of the platforms analyzed.

Table 1.6: Collaborative platforms features

Platform		Basics					Collaboration					Tools					openBIM		
		Common Data Environment	Permissions	Document management	Model federation	Model viewer	Real-time model worksharing	Workflow	Issues and markups	Email notifications	Audit	Data sheets	Clash detection	Pointcloud	Field management	VR/AR	BuildingSMART certification	IFC	BCF
ACCA	**usBIM.platform**	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Autodesk	**BIM 360**	X	X	X	X	X	X	X	X	X	X		X		X			X	
Oracle	**Aconex**	X	X	X	X	X		X	X	X	X		X		X	X		X	X
Trimble	**Trimble connect**	X	X	X	X	X			X				X	X	X	X		X	X
Nemetschek	**dRofus**		X	X			X		X		X	X						X	
KUBUS	**BIMcollab**		X		X	X			X	X	X		X	X				X	X
FlowBiz	**Workflow Designer**		X					X			X								

Conclusions

The BIM methodology, although theorized over 30 years ago, is beginning to spread very rapidly only in recent years. In order to contribute to this diffusion, it is necessary to define information management processes of the structures that oriented as "big" and "open" processes, and that are independent from specific software applications. These processes must therefore follow the standards developed by buildingSMART, which guarantee information flows through all the phases of the life cycle of an asset.

The field of structural engineering is now actively facing with this new working methodology, thanks to the development of applications that allow the design and retrofit processes to be followed with significantly higher quality standards than traditional ones. These applications, some of which are experimental, are aimed at defining standardized workflows that save time and resources while ensuring more controlled processes.

In this way of thinking, collaborative platforms provide valid support for the implementation of the BIM methodology, and allow optimal exchanges of information between the various stakeholders, aimed at reducing errors and losses of time due to the repetition of the same processes.

The analysis of these principles forms the basis of all the applications which are explained in detail in the following chapters.

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Chapter 2:

THE OPEN BIM STANDARDS FOR MANAGING EXISTING STRUCTURES IN THE PRE- AND POST-EARTHQUAKE PHASES

* The research outcomes reported in this chapter were published in the following journal article:

Musella, C.; Serra, M.; Salzano, A.; Menna, C.; Asprone, D. - Open BIM Standards: A Review of the Processes for Managing Existing Structures in the Pre- and Post-Earthquake Phases. *CivilEng*, November 2020, 1, 291-309

Abstract

The problem of managing existing structures before and after seismic events has led to the development of many different strategies across the globe. These aim to mitigate the catastrophic effects of earthquakes on the occupants of a building, as well as improve the management of the emergency that inevitably ensues. In this chapter is explored the use of an openBIM approach to resolve the issues referred to above, with the implementation of two standards: Industry Foundation Classes and Information Delivery Manuals. A review of the most popular strategies adopted in both the pre- and post-earthquake phases is conducted using a process map. This organizes the relevant steps and processes into tasks, and additionally identifies the points at which information is produced and exchanged and the party responsible for doing so. Also described is how BIM models can be utilized in essential pre- and post-earthquake activities, as well as current benefits and ongoing developments intended to improve the processes themselves.

2.1. Introduction

The management of existing structures is a topic of great importance and the subject of much research. In the countries most affected by severe earthquakes, like the USA, New Zealand and Italy, studies aim to assist those involved in the processes of ensuring the safety of a structure for its occupants and optimizing resources before an earthquake occurs and subsequently. Although many methodologies have been developed thus far, their very similar features mean that they can be applied to only two categories:

1. Preventative activities: these are carried out in the pre-earthquake period, and aim to guarantee safety during a seismic event and reduce repair costs as much as possible thereafter. As they are conducted in the absence of an emergency and on individual buildings, they are supported by very detailed analytical assessments, which are used to define ad hoc solutions and strategically optimize the resources required;
2. Processes to manage damaged buildings: these are carried out in the post-earthquake period, and require very rapid evaluations of a building's viability, equally fast interventions in the initial emergency phase, and more accurate assessments in the subsequent reconstruction stage.

All these processes have traditionally been carried out without the use of digital tools, or where their use is limited to individual, unconnected, activities. Lately, however, by integrating relevant steps and encouraging collaboration between the different actors involved in a project, the digital revolution of recent years aims to identify both inefficiencies in these processes and alternative ways of working.

Latterly, new digital procedures have been used to explore the ways in which Building Information Modelling (BIM) might assist in the field of structural engineering, in particular in relation to the processes utilized in the assessment and/or mitigation of seismic risk [1,2]. Ma et al. [3], for example, proposed an information model to facilitate the flow of data for post-earthquake assessments of reinforced concrete (RC) structures, basing their approach on typical damage modes and the existing Industry Foundation Class (IFC) schema. Other research uses BIM in the visual detection and identification of sources of vulnerability in structures, taking advantage of procedures that are minimally (or not at all) invasive [4], while some studies examine the application of BIM-based techniques to automate the generation of cost estimates related to seismic damage [5,6]. Additionally, beyond the well-known uses of BIM in project management, applications are also available in quantity surveying, process visualization and scheduling (4D), and cost estimation (5D), enabling integrated project deliveries [7,8].

Taking advantage of new digital standards [9] and the increasing use of digital tools in the construction industry, this study aims to define optimized procedures for the management of existing structures. Also identified are features that it is hoped will be the subject of future research concerning the development of evermore mature digital processes. The paper has six sections: Section 2.2 describes the methodologies used to manage existing structures in the phases before and after the occurrence of a seismic emergency; Section 2.3 explains the role played by BIM models in enabling decisions to be made about any necessary interventions identified in all of the activities undertaken in the pre- and post-earthquake periods; Section 2.4 describes the elements comprising the Information Delivery Manual (IDM) standard. It also explains how a process map (PM) is developed to specify any necessary activities, as well as identify the points at which information is produced and the parties responsible for doing so. Section 2.5 contains our deliberations on the maturity of current digital methodologies and the aspects requiring further work in the years to come.

2.2. Processes for managing existing structures

2.2.1. Preventative activities

Until recently, the performance required of ordinary buildings (i.e., non-strategic work for the community) was mainly limited to: containing the damage caused to non-structural components due to earthquakes that may strike on several occasions during the lifetime of a construction; and ensuring the safety of occupants during rare-occurrence events [10]. The structural response to seismic actions has typically been evaluated using linear or non-linear analyses that produce information on structural capacity. These data are expressed in terms of strength or displacement, and are compared with demand to determine the requirements for newly-designed buildings. There are additional prerequisites for both strategic buildings like hospitals [11] and general infrastructure in order to ensure their functionality during seismic events.

In recent years, however, scientific progress in relation to buildings has led to a requirement that economic factors should also be taken into account, particularly with respect to repair costs, which are the costs of restoring a building to its pre-earthquake condition, or, in the case of total loss, replacing it with a new structure with similar features [12]. This is known as the expected annual loss (EAL), whereby losses are broken down annually and expressed as a percentage of the reconstruction costs. This new parameter is particularly effective for communications with expert technicians, as well as with all the other stakeholders in a project, including the client making the final decisions. This new, wholly probabilistic, methodology is described as Performance-based Earthquake Engineering (PBEE), and is known as the PEER approach because it was developed by the Pacific Earthquake Engineering Research (PEER) Center. The methodology has four stages:

1. Hazard analysis [13]—quantifying the intensity of potential seismic effects and the site-specific probability that those of a given intensity will occur;
2. Structural analysis—predicting a building's response to earthquake shaking, expressed in the form of response quantities (i.e., demands) that could be associated with structural and non-structural damage;
3. Damage analysis—described by probabilistic curves (known as fragility curves) [14]; these identify the probability of a specific level of damage as a function of an Engineering Demand Parameter (EDP) related to seismic actions;
4. Loss analysis—economic losses are estimated based on the performance of a structure.

Melani et al. [15] and Cardone et al. [16,17] have examined the EAL calculation for RC elements, while Kahre et al. adopted a similar approach to compare different types of RC walls. In these cases, the EAL values apply to each component investigated; when the same procedure is used for masonry structures, this value is applied to the building as a whole. Other relevant research includes a study by Bothara et al. [18], which focused on Unreinforced Masonry (URM), as well as work examining the application of the methodology to infrastructures like bridges [19]. The approach in these case studies produced rigorous results. However, because the methods are wholly probabilistic, they require considerable computational effort and a professional with significant expertise. As a consequence, this approach is now primarily used for research purposes, with very rare circumstances where it could be extended to more common applications. In some countries, however, this methodology is regarded as mature enough to be included in national codes and standards.

In Italy, the approach proposed by SismaBonus [20] takes into account both the vulnerability assessment and the EAL. In particular, the latter is determined using two different procedures: simplified, which is applicable to limited types of masonry buildings; and conventional, which can be used for any type of structure. Repair costs are fixed in advance and applied to an entire building. A seismic risk value from A+ (higher) to G (lower) is identified for each of the two procedures, with the lower value taken to be representative of a building's performance. Perrone et al. [21] and Sullivan [22] have described simplified methods within this range of uses, which attempt to strike a proper balance between the accuracy of the method and the time available for its application. This has led to some authors [23] proposing a simplified approach that even considers the advantages of utilizing a BIM model. The first simplification, which is not wholly probabilistic, concerns the characterization of site hazards, and is based on evaluations of the inverse of the return period (TR). The main difference to the PEER methodology is in the structural analysis phase, where a static non-linear assessment is preferred to a non-linear time-history version. This approach has also been proposed by other authors [24] as a way to reduce the complexity of the process. In addition, the cost estimation is related to each component of a building, both structural and non-structural, while the Damage State (DS) is linked to parameters like inter-story drift or the spectral acceleration on each floor. The real advantage, therefore, is the fact that the method makes it possible to conduct evaluations of different intervention strategies and adopt the approach that minimizes costs and, as a result, has the lowest EALs.

2.2.2. Post-seismic phase

The post-earthquake stage is very different to that analysed above. In particular, there is no time to perform detailed post-emergency analyses because of the vastness of the real-estate assets involved and the need to provide speedy responses to owners about the accessibility, or not, of their properties. Accurate evaluations are, however, possible in the medium to long term.

The procedure in most common use today was first launched in the USA, and is described in the Applied Technology Council's ATC-20 guidelines [25], which were published in 1989 and regularly updated until 2005. These recommend that assessments should initially cover all the buildings located in the area affected by an earthquake, before then identifying and focusing resources on those posing the most risk to occupants. These analyses are therefore performed in three stages:

1. Rapid evaluation;
2. Detailed evaluation;
3. Engineering analysis.

As is clear from their name, rapid assessments are brief, taking about 10–30 minutes per building. They are often cursory in nature, as their goal is to identify the presence or absence of hazardous conditions, particularly any earthquake-induced hazard that affects the safe occupancy of a structure. These hazards mainly involve structural or geotechnical (if recognizable) features that can be inspected with a rapid visual screening. In detail, this type of hazard can affect both an inspected building and neighbouring structures, and includes structural or foundation damage, damage to floors/roofs/walls, residual displacement, ground movement/settlement/slip, and overhead falling threats. The results of this inspection are communicated using a formal placard that employs a traffic-light type system that can be easily understood by even those with a non-technical background. The notice will state that a building:

1. Has been INSPECTED (green placard)—the damage does not pose any significant risk. This is only intended to notify people that the building is safe for occupation; it does not mean that any damage should be ignored or that repairs are unnecessary;
2. Is safe for RESTRICTED USE (yellow placard)—this addresses conditions where there are no clear safety concerns, but the damage identified precludes unrestricted occupancy. This notice is used if the evaluation reveals such damage that there should be no entry to part of a building, or where there is a restriction on the use or occupancy of the entire structure;
3. Is UNSAFE (red placard)—there is an immediate risk associated with entry, use or occupancy, denoting that going into a building is not permitted for any reason. This does not automatically mean that the property has been condemned or will require demolition.

These notices are generally placed at the entrance to a building or the part of it to which the sign refers. The placard also sets out any advice or possible action required to secure an area if it is thought to be unsafe. If assessors are unable to gain entry, the INSPECTED placard will state “Exterior Only.” Rapid evaluations are helpful for systematically identifying the condition of a large number of buildings immediately following an earthquake, as well as for understanding the scale of the impact in terms of the damage to built assets.

Detailed evaluations are typically carried out on buildings awarded yellow and red notices following earlier assessments. A team of two structural engineers familiar with seismic design are responsible for completing this more in-depth investigation, which should include both exterior and interior inspections of the structural systems. The aim of this evaluation is to define the health status of a structure in relation to both gravity and lateral loads, and it may take between one and four hours, depending on the building’s size and geometry. In most cases, this type of inspection does not need structural systems to be exposed, and structural drawings are likewise not required. The final stage, the engineering analysis, is mentioned in the ATC-20 guidelines, but no recommendations are made. In these circumstances, a building’s owner would be expected to hire a contractor to perform detailed investigations, including material tests and structural surveys, in order to determine the appropriate retrofit interventions.

Although developed for use in the USA, the guidelines have been adopted by a number of countries, albeit with modifications. In New Zealand, for example, there are also three progressive levels and three colour tags:

1. A level 1 rapid assessment involves a brief external visual inspection of a building to assess the type and extent of its structural damage;
2. A level 2 rapid assessment is still relatively brief but, importantly, requires access to both the interior of a building for more extensive observations, as well any available drawings. This type of evaluation is typically required for all critical facility, multi-story, and other buildings where the level 1 process identifies the need for further and detailed inspections [26];

3. Level 3 in-depth engineering evaluations are usually carried out regardless of the outcomes of any level 1 or level 2 rapid assessments.

The third stage in New Zealand has two parts (qualitative and quantitative), and involves a full structural survey and the completion of a standardized spreadsheet [27]. The methodology was particularly valuable after the 2010 earthquake in Christchurch, with 80% of the 7922 [28] structures inspected tagged with a green placard. As only 20% of buildings required further investigation, emergency management resources could therefore be focused on them.

In Italy, the approach to a post-earthquake emergency is fairly similar, as the first rapid inspection aims to determine whether the short-term use of a building is possible. An example is the 2009 L'Aquila earthquake, where evaluations were initially carried out in less-damaged areas in order to both rapidly identify usable buildings and reduce the risk to inspectors from strong aftershocks; it was only after approximately two months that investigations were extended to the "red zones", i.e., the inaccessible areas. The assessment after this 2009 seismic event was conducted using the AeDES form [29], which has nine sections and contains information on a building's identification, dimensions, age, use, construction type and the damage sustained. The severity of the damage is described using visible indicators of the loss of performance, such as cracks, deflections, changes of geometry, separations of components, concrete spalling and the buckling of RC bars. The damage classification is based on its severity and extent, according to the European Macroseismic Scale [30]. The final judgement on immediate occupancy is not provided using a placard, but with letters from A to F (A = usable; B = usable only after the implementation of short-term countermeasures; C = partially usable; D = requires reinspection; E = unusable; F = unusable, for external risk assessment only). A building can be used, even if it is slightly damaged, when it is given a category A classification. Categories B and C concern buildings with limited or no structural damage, but severe non-structural damage. If a building is in category B, inspectors have to set out the short-term countermeasures required to enable its use, such as the removal of false ceilings or the propping of a lintel. In category C, the possible partial or total collapse of a damaged part of a building is not an indication that any usable areas are unsafe [31].

This methodology was also used after the earthquake that struck central Italy in 2016. At the end of the seismic sequence in the historical centre of Norcia, 26% of 670 buildings under investigation were usable (A), 32% were unusable (E), and the remaining 42% were partially usable or required some short-term countermeasures. Sisti et al. [32] performed a number of calculations in their assessment of the inspected buildings, with their final report including their considerations on the impact of a building's position (isolated or aggregated), roof type, masonry quality and structural features.

2.3. The role of BIM models in pre- and post-earthquake investigations

Pre- and post-earthquake assessments have improved thanks to digital tools like BIM models [23, 33], which link all of the tasks that must be performed in any investigations. Due to their complexity, we have summarized the two operational phases in tables 2.1 and 2.2, respectively.

Table 2.1: List of pre-earthquake phases and activities

Phase	Activity	Description	Role
Knowledge of the construction	Document research	Researching documents, graphics and pictures	Structural engineer and architect
	Survey	Survey of a building's geometry	Surveying technician
	Geometrical BIM modelling	Geometrical BIM modelling using the information previously obtained	Architectural BIM modeller
	Structural, geological and geotechnical investigations	On-site and/or laboratory material testing for the mechanical evaluation of materials	Geologist, geotechnical engineer and material-testing technician
	Degradation and damage detection	Detection of the damage, if any, affecting the structural elements	Structural engineer and architect
BIM modelling	Architectural BIM modelling	Upgrading the architectural model	Architectural BIM modeller
	Structural BIM modelling	Structural modelling	Structural BIM modeller
	Clash detection	Checking the accuracy of the model	BIM coordinator
Structural analysis	Vulnerability and EAL assessment	Evaluation of the structural performance of a building's current state	Structural engineer
Retrofit intervention planning	Retrofit intervention	Definition of any intervention strategy required to improve the structural performance	Structural engineer and architect

Table 2.2: List of post-earthquake phases and activities

Phase	Activity	Description	Role
Emergency	Rapid evaluations	Rapid visual check of the structure, noting the damage extent and severity for an accessibility assessment of the building	Structural engineer
	Detailed evaluations	Detailed visual check of the structure, noting the damage extent and severity for an accessibility assessment of the building	Structural engineer
Engineering evaluations	Knowledge of the construction	Document research, on-site surveys and material testing	Structural engineer and architect
	Damage detection	Detection of collapsed elements and the extension and severity of the crack pattern	Structural engineer
	Architectural BIM modelling	Architectural BIM modelling of the building and its damage	Architectural BIM modeller
	Structural BIM modelling	Structural modelling	Structural BIM modeller
	Structural analysis and retrofit interventions	Definition of the intervention strategy needed to make the structure safe	Structural engineer and architect

The stages of the operations performed during the pre-seismic process can be classified in four ways:

1. Acquiring knowledge of a construction;
2. BIM modelling;
3. Structural analysis;
4. Retrofit intervention planning.

The starting point is acquiring the data that become the inputs in the definition of a BIM model. This is also known as "knowledge of the construction" [34] and has three phases:

1. A critical historical analysis to research documents, reports and available drawings;
2. A geometric structural survey to identify the load-bearing elements;
3. A mechanical characterization of materials, based on investigational assessments [35].

The expansion of the architectural BIM model begins in this phase, and is performed just after an in-situ survey to ensure that the precise geometry of a building is available for consideration. Any pathologies and degradations affecting the building's components are also identified in this phase, and are crucial for defining whether retrofit measures are required. This operation is often supported with specific datasheets created to store relevant information.

Depending on the quantity and detail of the investigations and tests carried out, a building is assigned a Level of Knowledge (LK, trad. *Livello di Conoscenza LC*): LK 1—limited investigations and tests have been performed; LK 2—these tests have been expanded; and LK 3—the tests have been exhaustive. The LK thus provides an indication of the reliability of the information available on a structure. Downstream, knowledge of the construction enables the architectural model to be upgraded to ensure the availability of all of the information needed to perform the operations that follow. In this regard, the specification in ISO19650, which concerns the data required on BIM objects for use in subsequent tasks, introduced the notion of a Level of Information Needed (LOIN) as the specification for the data that BIM objects must obtain for subsequent tasks.

A structural BIM model can be created after the production of an architectural BIM model. However, before any data processing occurs, a clash-detection analysis of each of the models is required to verify their coherence. It is not necessary to conduct a clash-detection assessment of the relationship between the structural and architectural models, which are already coordinated because they are the outcomes of the survey of an existing building. An analytical model is then incorporated in the structural software, which then completes the modelling operation by introducing the mechanical proprieties, boundaries and load cases, and combinations. The mechanical behaviour of the building is therefore simulated based on the steps identified in section 2.2.1. These processes aim to evaluate the performance of a building by calculating parameters like structural safety, displacements, or EALs. A determination is then made about whether retrofitting is required, before a plan is finally produced of the most effective intervention strategy.

Many of the considerations above are also valid in the post-earthquake stage (Table 2.2). One of the most relevant aspects in this phase involves the management of information relating to any damage affecting structural elements. The rapid and detailed evaluations conducted during an emergency produce information in either paper or digital form, because of the need for a quick response. As a result, BIM models are not used at the start of the process immediately after a seismic event. These rapid evaluations only take into account visible damage in the parts of a building that are accessible to inspectors, and relate solely to the damage's global severity and extent. Introducing BIM models during engineering evaluations enables the entire crack pattern to be digitalized when accurate inspections are carried out. It follows that the relevant properties are thoroughly defined and include accurate data on, for example, the width and direction of each crack and the phenomenon that caused the elements to fail. The process for completing the model in the post-earthquake phase is similar to that used in the pre-earthquake period, with the main difference being that the structural assessment of the DS is usually omitted in order to instead plan the retrofit interventions needed to make the building safe.

2.4. The IDM standard for encoding a structure's management processes

All of the processes analysed thus far are codified in an IDM, which is an additional open standard produced by buildingSMART [36]. ISO 29481-1:2016 details [37] the IDM's methodology for defining and specifying processes and information flows during a facility's lifecycle. As described in "IDM: Guide to Components and Development Methods" [38], the methodology enables the integration of the processes and data required by the BIM model. This is achieved by identifying the discrete steps undertaken during the building's construction, the information needed to execute them and the results of that activity. In particular, the methodology specifies:

1. Where a step fits into the process and why it is relevant;
2. The actors involved in creating, utilizing and benefitting from the information produced;
3. What the information created and consumed actually is;
4. How the information can be supported with software solutions.

The IDM is specifically designed to separate the schema of an Industry Foundation Classes (IFC [39] into smaller, useful, but still related, elements. It is normally used when it becomes necessary to expand the IFC for specific uncodified BIM uses. Generally, the IFC schema provide a comprehensive specification for Architecture, Engineering, Construction and Facilities Management (AEC/FM) projects, capturing data from all the stakeholders involved (architects, engineers, constructors, facility managers etc.) during all the stages of a building's lifecycle, including initial requirements, design, construction, maintenance and operations.

It is important to note when considering the relationship between the IFC and IDM standards that the complete IFC schema is developed in the form of a set of individual topic schematics, each of which typically represents a consistent overall idea (e.g., structural analysis, cost, materials). Upon completion, all of these topic schemas are combined in a single plan, which is the authorized working version. This contains hundreds of entities (classes), data types and property sets (the IFC components) [40], and means that the IFC can support all the business requirements in all the project stages; in contrast, the IDM only supports one business requirement in one project stage (Figure 2.1).

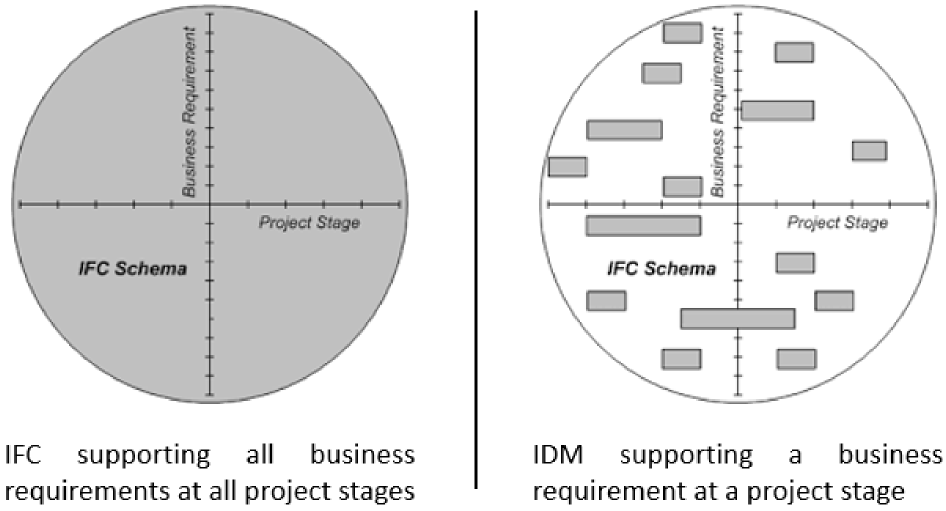

Figure 2.1: IDM support for business processes (IDM: Guide to Components and Development Methods)

The focus of the IDM on a particular topic enables it to define the data exchanged between the parties in each step and its level of detail, meaning that its involvement in the BIM stage is justified. In a Business Process (BP), deciding which IFC components should be used to satisfy the project's requirements is important for both BIM users (architect, engineer, constructor, etc.) and the creators of software solutions. This is crucial data for software users, who need to be sure that the IFC meets their requirements; meanwhile, solution providers have to be certain that the components meet the needs of their users (Figure 2.2).

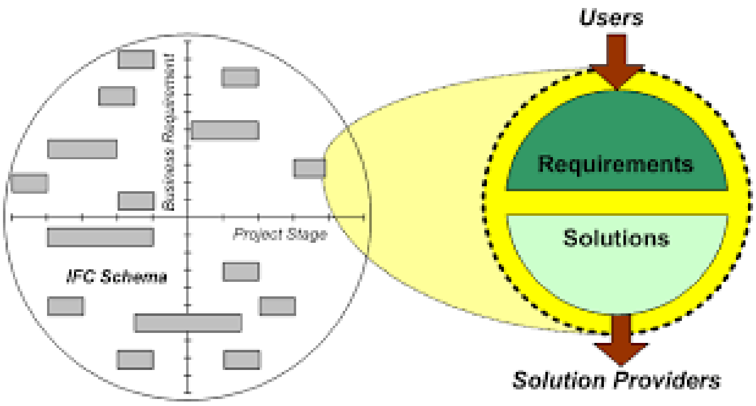

Figure 2.2: Business process requirements and solutions (IDM: Guide to Components and Development Methods)

The focus of the IDM on a particular topic enables it to define the data exchanged between the parties in each step and its level of detail, meaning that its involvement in the BIM stage is justified. In a business process (BP), deciding which IFC components should be used to meet the project's requirements is important for both BIM users (architect, engineer, constructor etc.) and the creators of software solutions. This is crucial data for software users, who need to be sure that the IFC meets their requirements, while solution providers have to be certain that the components meet the needs of their users (Fig. 2.2).

In more detail, an IDM has three parts: a PM [40], exchange requirements (ER) [24] and functional parts. The PM consists of a flow-chart containing all the steps that have to be taken throughout the process, as well as the connections between them. It also identifies the actors sending and receiving information within the process according to their role, and ensures that the definitions, specifications and descriptions are delivered in a suitable manner and are easy to understand by members of the project's team. The PM highlights the ERs, i.e., the information contained within the IFC that needs to be exchanged to support the process. This data is in different file formats, such as BIM models, graphics, point clouds, pictures and reports. The functional parts are the units of information used by solution providers to support an ER.

2.4.1. Process map

The PM is the first part of the IDM, and consists of a flow chart containing an accurate description of all the single steps that comprise the entire process [43]. It is a very useful tool for information management, especially for the very complex processes in the construction industry, and also offers support to both BIM users and BIM software developers. In particular, it provides BIM users with an easily understandable and plain language description of: the building construction processes; the details of what is required of the information needed to conduct the processes successfully; and the expected results of the processes themselves. This:

1. Makes information exchanges between a project's participants more reliable;
2. Improves the quality of information;
3. Improves decision making;
4. Enables a BIM project to be conducted much more effectively.

The PM is also valuable for BIM software developers, because it identifies and describes a detailed functional breakdown of the processes, as well as the IFC capabilities requiring support for each functional element. This:

1. Produces better responses to user needs;
2. Guarantees the quality of the information exchange;
3. Produces reusable software components.

As seen in tables 2.1 and 2.2, all the tasks have been organized by the author into project phases, meaning that they have been completely re-organized within a PM. The aim of the BP concerns the management of existing structures and is intended for use in the decision-making stage about a building. The graphical representation refers to the business process model and notation (BPMN) [37], which is a globally recognized methodology for specifying the BP in a BP model. Fig. 2.3 only includes the PM for the post-earthquake phase; the PM for the pre-earthquake period is a simplification of the version above and is obtained by excluding the tasks coloured in red in the figure. The steps in the PM are reported in the transverse direction to aid readability.

Many of the current methods analysed in par. 2.2 are implemented in the PM. The canvas for a map drawn with the BPMN consists of lanes and pools. The latter represent the organizations involved in a project, i.e., consultant, architectural, structural, and the common data environment (CDE) [42]. The lanes represent the individual participants, as well as their role within an organization when more than one professional from the same company is involved in the same process (e.g., BIM modeller, architect, structural engineer, geologist) [9]. The tasks that describe each operation performed by the respective skilled professional are placed inside the pool. The lines denote the connections between the tasks and are represented by a continuous line when both the preceding and succeeding tasks are contained within the same pool; a dotted line is used when the flow connects one organization to another. Each information exchange between the parties is represented with the envelope symbol.

An analysis of the PM in Fig. 2.4 highlights the clear definitions of the sequence of operations and the interchanging of the different professional profiles. The structural engineer starts the process, conducting rapid and detailed evaluations and providing occupancy advice in relation to the building. The architect and survey technician perform the engineering evaluations, managing the document research and on-site survey. The information they collect enables the BIM modeller to build an initial architectural BIM model. All of the BIM objects are modelled by only taking into account the geometrical information, ensuring that the model is even able to provide support in the knowledge phase (KP). The information about the damage detected and the investigations conducted by the architect and structural engineer is centralized in a database. In the intervening period, the geologist and geotechnical engineer define and perform their respective investigations. Then, at the end of the KP, the architectural model is upgraded with all the data collected for the LOIN. This can be used by the structural engineer to conduct the structural analysis required to assess the performance (P) of the structure in relation to the safety index, displacements and EALs. The complete process is finalized when a decision is made about any required action. The process comes to an end by comparing P with the threshold values P*, based on the engineering evaluations or code recommendations; if this is not done, it would be necessary to plan retrofit interventions.

As the core of the BP concerns the structural discipline, it should be noted that obtaining the necessary background information means that most of the tasks are located in the structural engineer lane, with the other professionals having only a supporting role. Some of the tasks, in particular the survey, BIM modelling and retrofit interventions, are articulated in the sub-process, but this is not set out in the PM for reasons of clarity and to maintain the focus on the BP. Moreover, as shown in Fig. 2.3, all the files exchanged during the process are located in the CDE pool. This has been subdivided into two lanes relating to the architectural data developed by the architect, as indicated by A_number (A_1, A_2, …, A_8), and by S_number (S_1, S_2, …, S8) for the structural data. The CDE is the virtual location where the information is stored and exchanged by the various team members. Each of the files in the CDE is an ER containing a precise set of data that must be explained in the IDM.

Figure 2.3: The process map for managing existing structures in the post-earthquake phase

2.5. The digital maturity of the processes for managing existing structures

The need to digitalize the management of existing structures is not new in the research field. Dong et al. [49], for instance, have described an extensive case history of the various techniques developed for pre- and post-event actions in relation to different types of data. In more detail, examples are studies that have led to: the creation of digital tools to support the rapid risk assessment of structures on a large scale [47]; and the use of multi-temporal satellite imagery techniques that enable the areas where the greatest damage has occurred to be detected in the post-earthquake period [48].

Intentionally highlighted in the passages above is the need for a strategy that involves all the activities and professionals participating in a project. To this end, the IFC and IDM standards provide relevant support, as they were developed to improve collaboration during ventures. However, it should be noted that the digital processes are not as effective as desired in relation to information exchanges, due to problems of software interoperability and the structure of the IFC schema, which have not yet achieved sufficient maturity. These issues concern both pre- and post-earthquake processes. One of the main reasons for such problems in the pre-seismic event stage is that the IFC standard, although a valid starting point for the integration of structural processes with other disciplines involved in building management, is not yet fully interoperable.

In this context, it has to be assumed that the structural analysis tool is capable of exchanging both incoming and outgoing information in the central database, i.e., the BIM model. The generation and transfer of the Finite Element Model (FEM) from the BIM model to the analysis software are delicate operations. They cannot, however, be conducted using open tools like IFCs, with reliance instead on ad hoc procedures or those that are only optimized to work within digital ecosystems created by individual software providers. This is partly because an analytical model cannot always be defined unambiguously, causing problems for coding operations. In addition, the structural performances are not actually coded at all within the IFC structure, which comprises objects, the relationships between them and properties. It may, therefore, be useful to expand the set of properties to include parameters that represent structural performance, including displacements or the work ratios of the elements. There is a further difficulty (still unresolved) regarding the inputting of parameters that characterize the behaviour of an entire structure, with examples being the safety index, EALs and the frequencies of vibration modes.

This is not an exhaustive review of the problems faced: post-earthquake processes have further critical issues in relation to the coding of seismic damage. Furthermore, the IFC standard covers neither properties relating to the DS of components, nor BIM objects specific to the virtualization of any damage, i.e., cracks and degradation phenomena. These properties are required to conduct the operations referred to in Section. 2.2, in particular assessments of the DS of these elements and an entire building. Moreover, the operations performed on damaged buildings often require the use of only paper-based forms to collect information on site. In this regard, digital archive management is one of the most promising aspects of BIM, given the high volume of forms that are commonly produced. The relevance of the matter is also emphasized by the fact that the IFC standard only enables the exchange of data, not documents, making it necessary to provide alternative solutions. The use of digital forms would facilitate the creation of central databases in which information is collected as easy-to-use data. At present, thanks to the integration of multiple types of data, a BIM model could be described as an informative model in which virtualization not only produces a 3D representation of a building, but is also a reference point for all the stakeholders involved in a project.

Conclusions

This chapter has analysed the processes usually performed in both research and common practice to manage existing structures. In particular, two process stages are outlined: pre-earthquake ones, in which the behaviour of structures during seismic events is evaluated using representative parameters (i.e., displacements, the safety index and EALs); and post-earthquake, which aims to define a risk scale for use when planning retrofit interventions. As the aim of the study was to define an effective procedure for managing these processes digitally, our investigation covered the roles played by BIM models and IDM standards. On the one hand, these encourage collaborative working and information exchanges between various professionals, reducing the likelihood of mistakes. On the other hand, activity planning facilitates reflections on opportunities to use digital tools to optimize current work practices. Our intention is to highlight that the expansion of digitization should be understood not only as the development of individual tools that support specific activities, but also as an overall strategy. It should be noted that the real benefit of digitization is the ability to connect all planned activities in a single business plan. The progress made in digitization is aimed at creating real digital ecosystems, within which stakeholders interact using information flows and exchanges based on effective and efficient platforms. As a result, because some of the applications developed in the field of structural engineering only cover single activities or have not yet achieved maturity, issues have been identified that require in-depth investigations if digitization is to advance further.

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Chapter 3:

THE PRE-EARTHQUAKE PHASE – THE SCAN-TO-FEM PROCESS FOR MASONRY EXISTING STRUCTURES

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Musella C., Weferling, U., Evers O. - SFM-based building geometry acquisition for BIM-purposes – a case study with different SFM-Software – *Proceedings of the conference 3D Modelling&BIM*, Roma, April 2019

Abstract

One of the most widely applied BIM processes for existing buildings is scan-to-BIM, a method that covers all the phases which go from the survey of the building using digital techniques to its restitution in a BIM environment. In this chapter the process has been extend to structural applications, and then has been optimized and aimed at restoring not only the model of structural systems but also the analytical model for calculating the vibration modes, stresses, deformations, etc, so that the scan-to-BIM paradigm has been modified in scan-to-FEM.

The digital survey techniques and technologies, both consolidated and emerging, the methods for creating the BIM model from the point cloud, and the interoperability between the authoring environment and the structural calculation environment are then analyzed in detail.

The methodology, developed by the author, was applied to both ordinary and historical buildings with the aim to define the applicability and the reproducibility on the two category of buildings.

3.1. State-of-art of BIM applications to existing buildings

From the study of bibliographical sources, it was found that the applications of BIM on existing structures are involving several digital techniques; they can be classified depending on their aim:

- Virtualization of the building in the as-built state, which includes geometric characterization and definition of the damage state;
- update the building's digital twin over time through continuous information exchange.

Indeed, a very similar classification is also used by the Italian standard UNI11337-4 that introduces a LOD scale just for existing buildings and which identifies models with objects developed at a LOD F in the first case and G in the second one. The first category includes methodologies such as scan-to-BIM, artificial intelligence (AI) and virtual and augmented reality (VR/AR), while the second category includes the COBie standard and RFID tags.

3.1.1 BIM methodologies for the virtualization of the as-built state

When working on existing buildings, very often there is no descriptive documentation available, or, when available, it may be incomplete or not fully corresponding to the actual state of affairs. The first operation to perform on the building consists in the complete definition of its geometry. The process for the elaboration of the geometrical model of a building in a digital way is known as scan-to-BIM and consists of a sequence of operations that goes from the data acquisition during the on-site survey to the elaboration of the BIM model. Indeed, digital techniques are not a novelty in the overview of the survey processes, but they are becoming more well-known in the last decade thanks to the affinity with the BIM methodology. In fact, while previously the surveying process was confined within its own discipline, thanks to the introduction of BIM, it represents the starting phase of a process that involves the entire residual life cycle of the building. In the survey phase the data are acquired through image-based or range-based techniques to extract mainly spatial, color and reflectivity information. The first category includes photogrammetry and videogrammetry, thanks to which from images or videos and metric information in terms of spatial coordinates (e.g. GPS), the three-dimensional building is obtainable while laser-scanning, with all its technological variants, belongs to the range-based techniques. Depending on the characteristics of site and building, the accessibility to the area and many other features, these techniques can be used separately or mixed in order to obtain a point cloud of the whole building. The first attempts to transform the point cloud into a BIM model first involved the extraction of 2D CAD data from the point cloud, and then the drawings were used for the 3D modelling. However, it has been experienced that eliminating the intermediate CAD modeling step and direct modeling in BIM environment would save many resources. Automatic as-built creation from point cloud is the ideal solution, which requires a shorter time for manual modeling [1]. For the purpose, different plug-in for Revit and ArchiCAD have been developed (such as PointCab, EdgeWise by Gexcel, scan-to-BIM by IMAGINiT, as-built and VirtuSurv by FARO) that speed up the operations for modelling walls, doors, windows, pipes and standard steel profiles. Many researchers have tested and compared several plug-in in order to verify their efficiency and found that the semi-automated 3D modeling process facilitate the facility management (FM) operations, even if a significant user intervention is still required to verify if the modeled elements correctly fits the point cloud [2]. Thomson et al. [3] experienced good results with the semi-automatic modelling on portions of ordinary existing buildings without elements of singularity, and assessed the plug-in performances through quality parameters, comparing the placement, size and angular discrepancies in relation to a reference model.

In historical buildings, many difficulties arise due to a considerable variation in the thickness of elements as wall and floor, as well as arbitrary deviations and inclinations [4] since it is more difficult for semi-automatic algorithms to recognize objects and evaluate these parameters. Moreover, the presence of numerous unique objects makes the modelling process with parametric objects more complex so that numerous studies have focused on the modelling of objects such as columns, etc. [5]. Indeed, it is desirable the creation of parametric families that can quickly adapt to real cases will positively contribute to the entire process. Moreover, it is important to understand that the components of the HBIM library can be used for both handling a virtual model of the historic buildings and illustrating the damage and declination of each architectural element [6].

There are also applications of the scan-to-BIM process in technical areas, and in particular in the structural discipline. Bassier et al. [7] experimented this approach to create realistic BIM objects of a wooden roof truss based on point cloud data in order to perform structural analysis.

Castellazzi et al. [8] proposed a new semi-automatic procedure, called CLOUD2FEM, aimed at generating finite elements (FE) models and is applicable to any building whose geometry is captured with a point cloud, regardless of its geometrical complexity, so it is well suited to be used even on building heritage. The procedure aims at solving the problems connected to the generation of FE models of these complex structures by constructing a fine discretized geometry with a reduced amount of time and ready to be used with structural analysis. The resulting discretized geometry contains all of the information to use with a FE analysis, including the mechanical properties associated with the material features, and guarantees the automatic generation of a reliable FE solid model. The technique has been validated through a study of a fortress damaged by the 2012 Emilia earthquake with a linear natural frequency analysis whose results, in terms of natural frequencies, showed very good agreement. An estimation of the global time spent to generate the FE model of a complex structure for both CAD-based and CLOUD2FEM-based procedures showed that there is a significant savings of user time.

In addition, more experimental applications aim to define fully automatic processes thanks to the point cloud auto-segmentation. It is the case of Poux et al. [9], who proposed an interoperable point cloud data clustering approach that account variability of domains for higher-end applications and a novel point cloud voxel-based featuring developed to characterize a point cloud accurately and robustly with local shape descriptors and topology pointers. The semantic segmentation framework can efficiently decompose large point clouds in related Connected Elements (unsupervised) that are specialized through a graph-based approach.

An important part that characterizes the as-is state of existing buildings is the damage assessment. As in traditional practices, the damage detection is time and resource consuming, in recent years' machine learning (ML) techniques have been introduced to simplify these operations, as they only need the photos taken in-situ as input information. In fact, specific Neural Networks (NNs) have been developed to detect damages on buildings in relation to their structural typology. With regard to reinforced concrete structures, many studies have focused on the detection of crack inspectable on structural elements [10]. More recent studies have taken into account further phenomena, such as the concrete spalling with or without exposure of steel bars, the reinforcement buckling or fracture, the holes and the efflorescence [11] with the aim of define the severity of the damage inspected and the repair costs associated [12]. With reference to steel structures, ML is applied for the maintenance of bridges more than for buildings, in which the target are rusted surfaces [13]. In wooden structures, the defects detected are usually knots [14] and hollow hearts, the latter detected by X-ray images [15]. Finally, in masonry structures, the crack detection [16] have some additional complexity, especially when brick blocks are exposed, as they could be confused with mortar joints. For this reason, for degradation phenomena such as efflorescence and spalling, often the detection is not performed on the single degradation but on the entire damaged block. Once the damage is detected automatically from the photos, the NNs also extract parameters related to them. Depending on the training suffered by each NN, the parameters that can be extracted can be both dimensional, such as surface area, center of gravity, length of the minor and major axis, and parameters of severity. Downstream of the use of NNs, the information extracted should then be introduced into BIM models to ensure a continuous information flow. The way in which this information can be introduced into BIM models is also currently being tested. For the purpose, Borin et al. [17] experienced the introduction of BIM objects related to degradation in the information model of a bridge.

Other applications of BIM on existing buildings concern not the way information is stored, but rather how it can be displayed. A first technique is Virtual Reality (VR), which eliminates the traditional separation between user and machine, providing more direct and intuitive interaction with information. By wearing a head-mounted audio/visual display (HMD), position and orientation sensors, and tactile interface devices, it is possible to actively inhabit an immersive computer-generated environment. The VR applied to the BIM allows to visualize the 3D geometry of buildings combined with all the information supported by the IFC format, as experienced by Barazzetti et al. [18] with an application for tablet for the cultural heritage documentation of an historical complex. Some applications of VR have focused on more technical aspects, such as those related to structural engineering so that specific API have been developed to visualize and quickly model irregular and complex structures [19]. Similarly, Setareh et al. [20] developed a system that enables the user to interact with building structures in total-immersive or semi-immersive virtual environments. With this system, the user is able to build a structure within a virtual environment and apply gravity loads, wind loads, earthquake loads, etc. After conducting the analysis in existing structural tools and observed the effects of the loads on the structure, the user can modify the structure and repeat the process, in order to find the best solution. A second technology is Augmented Reality (AR), which provides real time integration of digital content with the information available in real world. The virtual layer is overlapped to the reality thanks to markers or other systems. Marker-based AR Systems uses physical-world symbols as a reference point for computer graphics to be overlaid. For example, a 2-dimensional printed marker is placed in front of a webcam. The computer then interprets this symbol to overlay an on-screen graphic as if it were directly on top of the marker in the physical world. Lighting and focus related problems limit the performance of AR services using this system. Marker-less AR Systems uses a combination of an electronic devices' accelerometer, compass and location data (GPS) to determine the position in the physical world, which way it is pointing and on which axis the device is operating. This location data can then be compared to a database to determine what the device is looking at, and thus allows computer data/graphics to be displayed on-screen. Indeed, AR is proving to be more effective than VR for applications in AEC industry. Some applications have been experienced by Karadimas et al. [21], who used it for the cultural documentation of historical and cultural significant sites, and Chionna et al. [22], who used it to visualize technical information as thermography to the building, with the aid of a smartphone.

3.1.2 BIM methodologies for the virtualization of the updated state

Since the BIM methodology for existing buildings is still under development, many of the applications have focused mainly on as-built state virtualization, while there are still few applications for the updating information. Among these, one of the best known is the use of the Construction Operation Building Information Exchange (COBie) standard which can support FM operations for both new and existing buildings. It was proposed by PAS 1192-3: 2014 for the definition of Asset Information Models (AIMs) and consists in an open, vendor-neutral industry standard that describes product and process of collecting and validating building lifecycle data during design, construction and commissioning. It provides a template based on the composition of information about general building information, spaces/zones, and information on equipment such as their geometries, locations, certificates and warranties, performance data and testing results, preventive maintenance, safety and emergency plans or start-up/shut-down instructions [23]. This standard is complemented by a responsibility matrix that allots the kinds of required data to the responsible persons or roles. It can be used to define the owner/client’s requirements and provide support for the realization of FM tasks [24].

Silva et al. [25] contextualized the relevance of a linkage between BIM methodology and the COBie specification, identify the challenges and design guidelines for its implementation in structural rehabilitation projects.

Another technology that is emerging is the Radio Frequency Identification (RFID), a communication via radio waves. RFID systems, classified as active (battery powered), semi-passive (battery-assisted), or passive (without battery), are composed of a transponder and transceiver (reader) that gather and transmit information wirelessly to a RFID tag, often without the need of a direct line-of-sight to the tags. Each RFID tag can have its unique identification number. Active RFID technology can simultaneously and uniquely recognize facility items, store information regarding maintenance history of these items, and continuously update the information in real-time [26]. Passive RFID tags are most suitable for an indoor construction application because of various benefits: (a) reduced cost (less than $0.20 for a typical tag), (b) small in size (flat like a sticker), (c) extended operational life (no battery), and readable and writable data storage capacity of roughly 128 to 256 bytes (which can be hyperlinked to other information or a database) [27].

Actually, the RFID system is part of a larger set of technologies that exploit the potential of Internet of Things (IoT) for the exchange of information. The integration of Building Information Modeling (BIM) with real-time data from the IoT devices present a powerful paradigm for applications to improve construction and operational efficiencies. Connecting real-time data streams from the rapidly expanding set of IoT sensor networks to the high-fidelity BIM models provides numerous applications. However, BIM and IoT integration research are still in nascent stages, so that important developments are expected in the coming years.

Tang et al. [28] provided a comprehensive review with the intent to identify common emerging areas of application and common design patterns in the approach to tackling BIM-IoT device. Several prevalent domains of application can be identified, as Construction Operation and Monitoring [29], Health & Safety Management, Construction Logistic & Management, and Facility Management.

In Table 3.1 are summarized the applications of the BIM methodology for existing buildings previously reviewed.

Table 3.1: BIM uses for existing buildings

Objective	Techniques and technologies	Applications
As-built state virtualization	Scan-to-BIM	Ordinary buildings
		Historical buildings
		Structural applications
	Artificial Intelligence	Defects detection
	Virtual reality/ Augmented Reality	Visualization of historical complexes
		Structural applications
Updated state virtualization	COBie	Facility management
	Internet of Things	Construction Operation and Monitoring
		Health & Safety Management
		Construction Logistic & Management
		Facility Management

3.2. The complex combination of BIM and existing buildings

Existing buildings, especially when they are part of the historical heritage, may have many features of singularity, starting from the geometry and the distribution of the elements in plan. Conversely, the BIM methodology aims to reduce inefficiencies through the standardization of products and construction processes. In fact, its application for the management of existing buildings is neither simple nor obvious, but deserves deeper reflection. According to the current practices, the operations that are carried out for the management of existing buildings are often difficult to organize, monitor and carry out. More in detail, the first difficulties start to arise already during the knowledge phase of the construction, during which the main information is collected through the search for documents (such as reports or graphics) that are rarely available. In fact, even though it is available, may be incomplete or no longer corresponding to the actual state of the places. It follows that in order to assess the real condition of the construction, those data collected must be verified and then also increased through in-situ surveys with tests and. In addition, because of the disparate and irregular geometries of elements rather widespread in historical buildings, even the construction modelling can turn out to be difficult.

3.3. The scan-to-FEM process for scanning structural models of masonry buildings

The first of the processes here presented is the scan-to-FEM process, which includes all the steps to perform during the survey operations aimed at obtaining the stresses and strains acting on existing buildings, as well as all those parameters that characterize the global structural behavior (vibration modes, periods, etc.). Taking advantage of modern digital survey techniques and technologies, this practice is aimed at obtaining results with a high accuracy (higher than that which would be obtained with traditional techniques) in a relatively short time.

3.3.1. The innovative surveying techniques

The choice of survey method can be guided by considering the size of the object, its complexity and its accessibility, but constraints may arise from the budget and equipment available. In terms of size (scale) and complexity, Figure 3.1 well illustrates any of the differences between the available techniques to guide the user towards an appropriate decision. Hand measurements can provide dimensions and relative positions of small objects, but they can become uneconomic and impracticable for larger objects. Total station theodolites (TSTs) are used both for the collection of data and to survey a site control network for all the other methods. A global navigation satellite system (GNSS) is generally used for geographic information system (GIS) data collection and topographic work and is often used to measure control networks, especially when connecting to a national grid.

Photogrammetry and laser scanning are examples of mass data collection techniques (where millions of points can be collected quickly) and are suitable for more complex objects over a variety of scales, including aerial survey. For most projects mass methods still require control networks for overall data unification, and this highlights the fact that there is a strong interdependence between survey techniques. In the figure it is also noticeable how the techniques concerning the acquisition of a few points are contained in the lower zone of the graph (below 1000 pt.), while those aimed at the acquisition of the entire three-dimensional geometry of the building, which will be discussed in more detail in the following paragraphs, are located in the higher zone. Then, among these, it should be pointed out that those located in the left zone, being applied to buildings of small size, pertain photogrammetry or laser scanner from the ground, while for buildings of bigger size it is advisable to use the same techniques but they utilize the UAV in order to take advantage of the greater acquisition distances to optimize the amount of data to be processed.

Among these techniques, there are some that can be considered more consolidated, and therefore widespread such as laser scanning, which allows to obtain an accurate and detailed survey of the objects around the device at medium range. It allows to acquire with extreme speed and high precision (up to 2 mm within 25m), the survey of buildings (internal and external), historical architecture, and industrial plants, as well as the monitoring of structures such as viaducts and railway works. The high resolution of representation makes it suitable not only for the creation of traditional CAD 2d graphics, but especially for the creation of three-dimensional models for BIM.

Instead, photogrammetry is a survey technique that allows to acquire metric data of an object (shape and position) through the acquisition and analysis of multiple stereometric frames. Thanks to automatic algorithms, the frames are compared with each other to obtain the relative position in space, and from this to finally obtain the 3D geometry of the object to detect.

Among the most innovative techniques that are currently subject to continuous updates, are still the laserscanners, but with dynamic devices, which are associated with objects in motion such as SAPR, cars or transported directly by humans, which perform scans in motion.

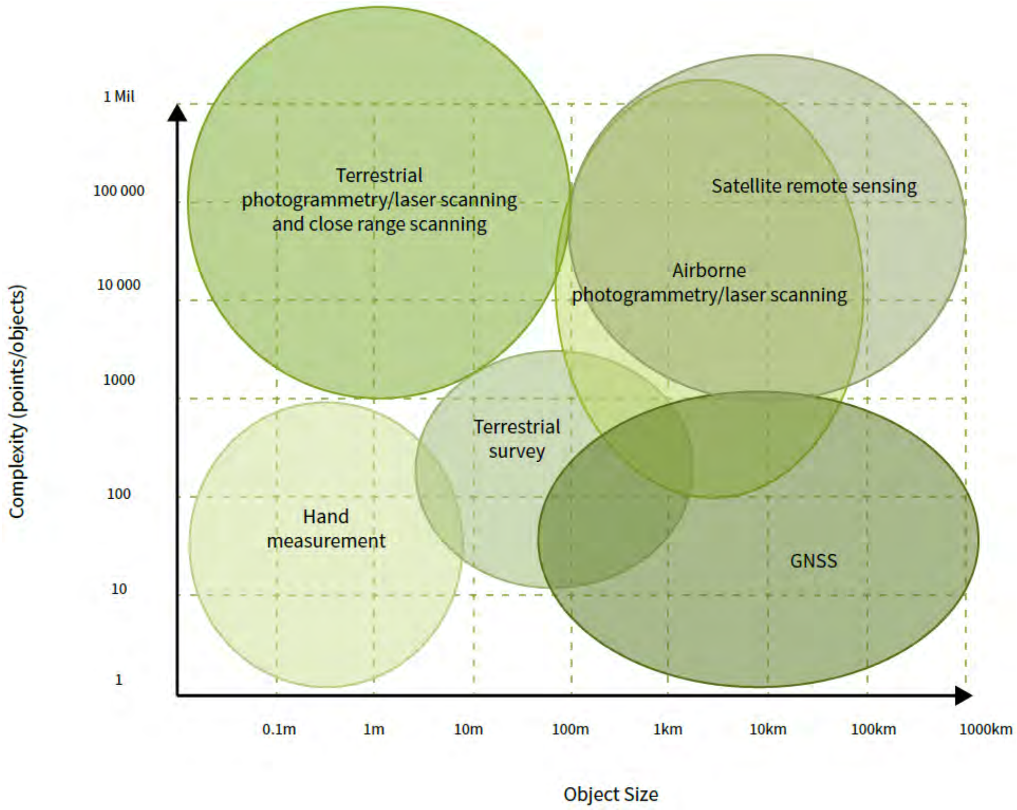


Figure 3.1: Survey techniques defined by object complexity (points captured) and size [30]

Another developing technology is the ToF camera. Instead of a light pulse being received by one sensor as scanners do, they use a matrix of sensors can act as an active camera measuring both range and intensity. Matrices are available at resolutions up to 640x480 pixels but their use has been confined mainly to machine vision and industrial applications. They can perform at up 60 frames per second, so a huge amount of data can be collected in a very short time. Because of the instantaneous capture, they are used for moving objects (perhaps in an assembly line) but equally the camera itself can be traversed around a subject similar to a handheld scanner. In order to collect 3D point clouds in real time, a miniaturised ToF camera is combined with its infrared projector and a wide-angle camera for tracking are combined. Although currently low resolution and the data collection is limited by the available battery and processor power, it will be interesting to see how the technology develops, but there appears to be serious potential for its use in the cultural heritage field.

3.3.2. The innovative surveying technologies

Laser scanner devices can be grouped into three categories, i.e. triangulation, time-of-flight and phase-comparison devices, depending on the system used to define the position of the points in the space.

Time-of-Flight laser scanner technology (Fig. 3.2) allows to generate the point cloud by calculating the time taken by the laser beam to travel the distance from the emitter to the affected subject and vice versa, knowing that the laser beam propagation speed is equal to that of light. Knowing the vertical and horizontal angle of the beam emission we can define the coordinates of the measured point. These laser scanners are characterized by the ability to detect data very far away, even reaching a radius of 6 km.

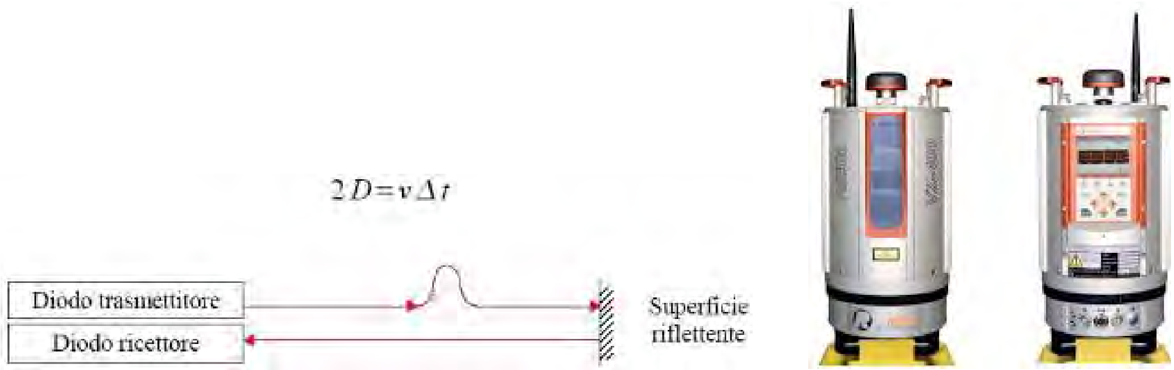


Figure 3.2: Time-of-flight laser scanner (Laser Scanner Riegl VZ-400i)

In phase-comparison laser scanners (Fig. 3.3) the distance is calculated by comparing the phase difference between the transmitted and received wave, this technique requires dedicated algorithms for general calculation of coordinate information in space. These laser scanners are characterized by a very fast acquisition speed and a high density of acquired data that can reach up to 0.6 mm between one point and another at a distance of 10 meters.

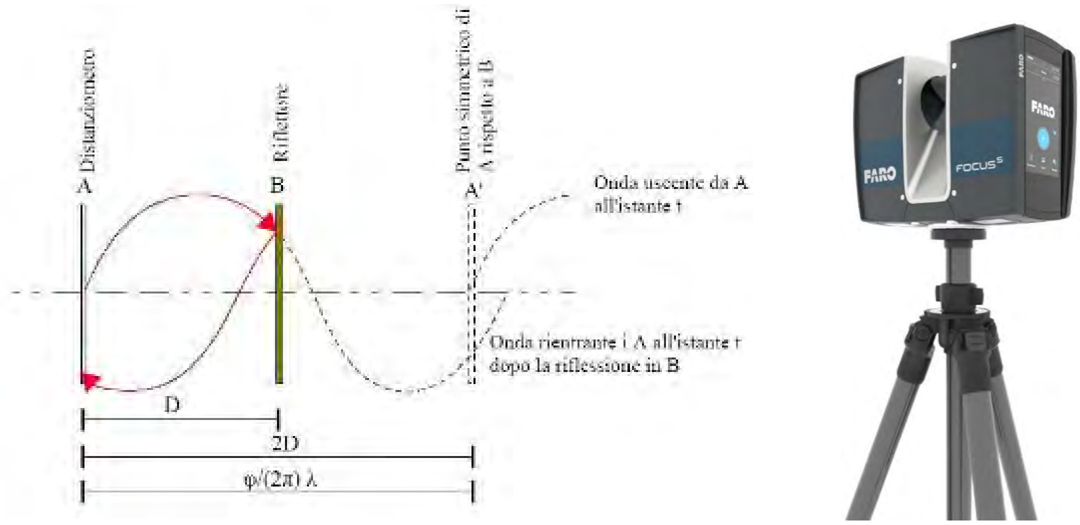


Figure 3.3: Phase-comparison laser scanner (FARO Focus S 350)

Triangulation laser scanners are more suitable for small to medium sized objects, having an acquisition range between 600 and 2000 mm (Fig. 3.4). The acquisition principle itself is different: in this case, the coordinates of the acquired points are calculated on the basis of triangulation; note the angle of emission from the laser source, the angle of reception in the CCD and the distance between source and detector (which is fixed), it is possible to trace the distance of a point from the center of the instrument. The coordinates are acquired with reference to the three-dimensional

Cartesian reference system inside the instrument, whose origin is located at the point where the laser beam is emitted.

Figure 3.4: Triangulation laser scanner (DotProduct DPI-8X)

These same principles are the basis of dynamic laser scanners (Fig. 3.5), which integrate the information pertaining the point's position with the motion information of the device. These are motion scanning systems that do not use GPS but use SLAM technology. SLAM (Simultaneous Localization And Mapping) is the process by which an instrument moves in an unknown environment, builds the map of that environment and is able to locate itself within that map. These scanners are very useful to detect large areas in a short time. The main applications can be:

- City Modelling;
- Survey of roads and tunnels;
- Survey of quarries;
- Environmental monitoring;
- Coastal and river survey;
- Suitable for underground environments such as tunnels, galleries, wooded areas and rooms architectural complexes.

As a way of example, the scanner ZEB Horizon has the following measurement performance:

- 300,000 points per second;
- accuracy <3 cm;
- distance 100 m;
- integration with spherical camera for cloud coloring and Bubble view management.

Figure 3.5: Dynamic laser scanner (GeoSLAM ZEB HORIZON)

These devices can then be associated with numerous motion means, such as backpacks, drones, cars or railway wagons, useful to significantly reduce acquisition times and access to areas impassable to humans (Fig. 3.6).

Figure 3.6: Dynamic laser scanners installed on as backpacks (left) and on railway wagons (right)

Besides, some of these technologies make it possible to upgrade static laser scanners into dynamic ones, allowing them to be used on the move without the need to purchase an additional device for this function, maximizing the advantages of these devices whose market prices are quite high. Some examples are FARO Swift, Beemobile and Stormbee (Fig. 3.7).

Figure 3.7: Stormbee, Beemobile and FARO Swift systems to upgrade static laser scanners in dynamic ones

A new technology that is spreading in recent years is the Time of Flight (ToF) camera (Fig. 3.8). The ease of use in this consumer-grade technology, also, make it possible for non-experts to map and model indoors. The most recent development in these devices is the mobile Structure Sensor, developed by Occipital Inc. in collaboration with Prime Sense in 2013. This small, lightweight, and wireless depth sensor collect and instantly register point cloud data, making the 3D reconstruction of indoor spaces more affordable. For this sensor to be useful in modeling indoors by volunteers, it is required to be user-friendly and for its output to meet or somewhat close to the standards set by industry. The Structure Sensor developed by Occipital is an open source platform that performs as a mobile Structure Light System (SLS) when connected to a tablet, mobile phone, or a computer. This SLS consists of a laser-emitting diode, infrared radiation range projector, and an infrared sensor and the iPad's RGB sensor that send data to a system on a chip (SOC) for processing.

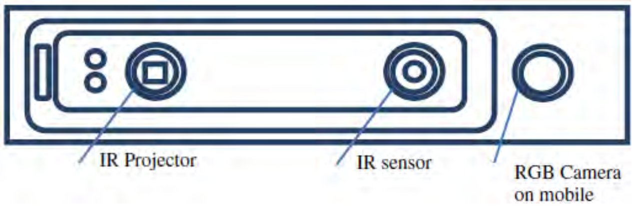


Figure 3.8: Structure Sensor schema

The output stream from the Structure Sensor alone consists of a point data-set, with a resolution of 640 × 480 pixels, where every pixel records the distance from sensor to the target. The infrared sensor records the reflectance intensity of the infrared (IR) light pattern projected by the IR projector onto the target while its SOC triangulates the 3D scene (Fig. 3.9) [31].

Figure 3.9: Time of Flight (ToF) camera (Structure Sensor by Occipital)

Many other devices can then be used as an aid for photogrammetric survey operations. Among the most used devices are certainly the UAVs, which is unmanned aircrafts on board, equipped with high-resolution cameras capable of capturing frames at greater distances compared to land surveys and to get to areas inaccessible to humans, such as mountain slopes, chimneys, etc (Fig. 3.10). These devices are then often associated with some software that make possible to optimize the number of frames to take while still ensuring compliance with the overlap and sidelap parameters between successive frames. Therefore, it is possible to achieve the best possible result in a short time, if the operation is correctly planned. For the purpose, many apps compatible with mobile devices used be UAV pilots have been developed: DJI Go, DJI GS Pro (available only on iPad), Pix4D Capture, and many other apps that can set the automatic flight on route and waypoint of UAV (Inflight, etc.). Some of these apps plan the flight, drawing on screen the portion of territory to be overflown for shooting, and then automatically calculate the lines of flight and the shooting frequency.

Figure 3.10: Use of UAVs for building inspections

Another support device for photogrammetric sureys is the 3DEYE photogrammetric system, consisting of a telescopic pole, high-resolution camera and a three-axis Gimbal that ensures good stability even in difficult conditions (Fig. 3.11). The stabilization system is installed on top of the carbon fiber telescopic pole, capable of reaching a maximum extension of 9m. The 3DEYE system is controlled by a high-performance Tablet in which is installed the ImagingEdgeMobile application for taking and vieweing photos of the camera. This system allows to acquire high altitude images of buildings up to two floors or not very high, replacing APR in such cases and simplifying considerably the planning of the survey operations.

Figure 3.11: Photogrammetric survey with telescopic rod

All the devices reviewed provide useful support for point clouds as a output of survey operations. They are essential to perform the scan-to-FEM process explained in the following paragraph.

3.3.3. Checking the performance and accuracy of SfM software

During the period spent in Germany, with the director of the photogrammetry laboratory Holger Evers, digital surveying techniques (photogrammetry and laser scanning) were analyzed in detail through field activities, with the aim of acquiring the methods, evaluating the potentialities and verifying the accuracy. It was an opportunity to test the maximum accuracy of the measurements achievable with the digital photogrammetry technique, and thus verify its compatibility for structural applications; in addition, the performance of different photogrammetry software was tested by setting different options to verify which of them is suitable for use.

3.3.3.1. Introduction and setting up to the survey on-site activities

The object for the case study is a gym in Leipzig-Connewitz, Teichstraße that was built in 1907 by the architect Arthur Werner for the 'Allgemeinen Connewitzer Turnverein' (Fig. 3.12).

Figure 3.12: Gym placed in Teichstraße, in 2019 (left) and 1907 (right) [33]

The building, declared a historic monument, is now used by the sports club 'Roter Stern' and has to be reconstructed in the next years. All inner and outer part of the building were scanned by Leica Scanner BLK 360, while for SFM evaluation the facade was photographed by Nikon D3300 with 20 mm objective (6000*4000 pix). The case study was concentrated on the south façade that is characterized by a variation of architectural element, such as a tree in front of the window that hides most of the façade. Due to a red fence in front of the façade the capture position of the images was difficult. A total of 184 images were taken in three lines, one in front of the fence (1.2 m height), one just behind the fence (2 m height) and one behind the parking area (2 m height) as shown in Fig. 3.13.

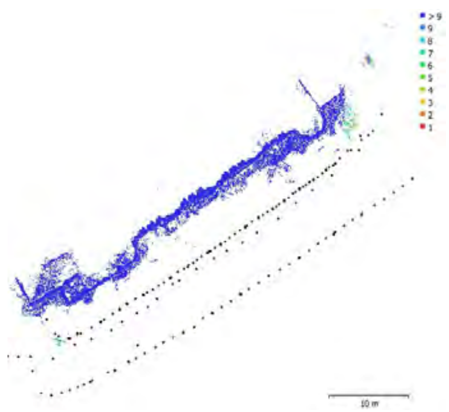


Figure 3.13: Camera positions and overlapping of images – screenshot of the Visual SfM software

For all the evaluations, three control points were used to define the coordinate system. The control points were measured with a total station with precision ± 3mm in all coordinates. The south façade was scanned additionally with BLK360 scanner in high resolution (5 mm) with precision ± 6mm / 10 m. This scan was used as reference model for the analysing of the SFM-models. Different evaluations were done with software VisualSFM, Agisoft PhotoScan and Pix4D mapper. All evaluations were processed in automatic mode to be able to compare the basic potential of the software for this study object. In the images provided to the software, the part with the fence and the tree in front of the façade were not masked to see the effects to the resulted model.

3.3.3.2. Processing with VisualSFM, Agisoft PhotoScan and Pix4D mapper

The evaluation with VisualSFM, Agisoft PhotoScan and Pix4Dmapper have done on a workstation with Intel® Xeon® Gold 5122 CPU, 3.60 GHz, 96 GB RAM and the graphic board NVIDIA Quadro P5000.

a) VisualSFM is an open source software developed by Changchang Wu largely used in the past, provided with different packages developed by several researchers from different parts of the world, which on many occasions have improved its tools. As can be noticed from Fig. 3.14 the final result shows very sensible differences compared with the real shape of the object. In fact, in presence of obstacles, such as the big tree covering the full height of the façade which change his position during the acquisition of the images, the software accuracy turned out to be not so precise. The software divided the entire façade in four parts that have been merged together with the merge-function of VisualSFM into one model. In the final assembly, a clear articulation resulted at the interface. Focusing the attention on each of that parts, it can be seen that all the details have been captured, especially in the tower which is the more struggling object. It fallows that VisualSFM can be used only if a great accuracy in the acquisition of the images is observed and there’s a lack of strong obstacles in the buildings target. Anyway, for practical uses more professional software are required. The result in resolution as well as in geometry was not sufficient so that the VisualSFM-model was not used for the evaluation. For the purpose two of the most popular software such as Agisoft PhotoScan and Pix4Dmapper have been investigated.

Figure 3.14: Dense point cloud of the Gym placed in Teichstraße, processed with VisualSFM

Table 3.2: Visual SfM elaboration

Accuracy	Aligned	Alignment time	Alignment	Alignment Control point error		Camera	Time dense cloud	Dense points
	Images	hh:mm:ss	tie points	cm	pix	param.	hh:mm:ss	
-	168/184	00:20:00	77816	-	-	8	01:42:25	10.948.432

b) Widely used by archaeologists and many UAV companies, Agisoft PhotoScan was developed by Agisoft LLC located in St. Petersburg in Russia. It is very popular with photogrammetry professionals in all kinds of industries and is commonly used to perform photogrammetric processing of digital images and generates 3D spatial data to be used in GIS applications, cultural heritage documentation, and visual effects production as well as for indirect measurements of objects of various scales (Fig. 3.15).

Table 3.3: Agisoft PhotoScan elaboration - image alignment

Accuracy	Aligned	Key point	Tie point	Alignment time	Tie points		Control point error	
	Images	limit	limit	hh:mm:ss	used	total	cm	Pix
lowest	183/184	40	4	00:01:21	21.045	29.332	1,90	4,64
low	184/184	40	4	00:02:45	95.934	113.008	0,62	1,07
medium	184/184	40	4	00:05:17	128.349	153.305	0,55	0,99
high	184/184	40	4	00:06:03	128.259	152.419	0,54	0,97

Table 3.4: Agisoft PhotoScan elaboration - adaptive camera modelling

Accuracy	Automatic adaptive	Time	Control point error	
	camera model fitting	hh:mm:ss	cm	pix
lowest	k1, p1,p2	00:00:05	1,00	0,01
low	f, b1, k1, k2, p1,p2	00:00:06	0,80	0,07
medium	f, b1,b2,cx,cy, k1-k3,p1,p2	00:00:07	0,57	0,25
high	f, b1,b2,cx,cy, k1-k3,p1,p2	00:00:05	0,57	0,42

Table 3.5: Agisoft PhotoScan elaboration - dense point cloud

Accuracy	Depth filtering	Time depth map	Time dense cloud	Total time	Dense points
		hh:mm:ss	hh:mm:ss	hh:mm:ss	
lowest	aggressive	00:00:47	00:00:31	00:01:18	1.219.225
low	aggressive	00:03:32	00:02:19	00:05:51	4.786.816
medium	aggressive	00:16:04	00:11:09	00:27:13	18.933.620
high	aggressive	01:01:00	01:20:00	02:21:00	71.155.427

Figure 3.15: Dense point cloud of the Gym placed in Teichstraße, processed with Agisoft Photoscan

c) Pix4D is a Swiss product that use photogrammetry and computer vision algorithms to transform RGB, thermal and multispectral images into 3D models. This software is developed and supplied by the company Pix4D SA, which started in 2011 as a spinoff of the École Polytechnique Fédérale de Lausanne (EPFL) Computer Vision Lab in Switzerland. With Pix4D the optimal evaluation was computed using a 15-days trial license. The high resolution which Pix4D provide was not used because of an excessive computation time and the extreme essential resolution that is not necessary for BIM-modelling (Fig. 3.16).

Table 3.6: Pix4D elaboration

Accuracy	Aligned	Alignment time	Alignment	Alignment controlpoint error		Camera	Time dense cloud	Dense points
	Images	hh:mm:ss	tie points	cm	pix	param.	hh:mm:ss	
optimal	182/184	00:11:56	1.073.986	0,16	0,82	F,px,py, R1,R2,R 3, T1,T2	00:25:15 (00:12:02 for texturing)	21.724.690

Figure 3.16: Dense point cloud of the Gym placed in Teichstraße, processed with Pix4D

d) Differences between Agisoft PhotoScan and Pix4Dmapper

The dense point clouds obtained with the Pix4D elaboration and the high resolution of PhotoScan have turned out to be different. In the Pix4D model the fence is modelled correct in position and details while in all PhotoScan evaluation the fence is not modelled at his correct position. Some elements of the fence are modelled as 3D-points below the façade. Moreover, on the façade are visible red lines that comes from the fence. Actually, that red lines are not 3D-points as in this part the façade gets just the color from the fence. The red lines are visible in all PhotoScan evaluations, stronger in the lowest resolution, smaller in the highest. Besides, in the Pix4D evaluation more details are visible than in the PhotoScan evaluation. Both the tree and the façade behind it are more detailed modelled. Moreover, the lightning conductor is visible only in Pix 4D model. In the Pix4D model small crack are visible on the façade, which means that the optical quality of the model is better than the PhotoScan model.

3.3.3.3. Comparison of VisualSFM, PhotoScan and Pix4D evaluation to the reference BLK360 scan

For the comparison, the BLK360 scan was used as the reference model, which can be considered the more accurate way of acquisition. It was scanned with high resolution (5 mm) and due to the short measurement distance the accuracy is better than ± 5mm. A total of 25 scans have been taken and merged together. In order to ensure the best result, the scans have taken places both in the front that behind the fence as well as at different heights. Many different prospective of acquisition have been taken into account to obtain a homogenous cloud of points. Although very precise, this technique is however not lacking in critical aspects. It's noticeable that a laser scanner is not comfortable enough for acquiring the entire external surface of the building as it is not bearable everywhere. All the scans inevitably could have been taken just from the ground as it is not so easy to bring it at high altitudes as well as on the roof. Consequently, not so many perspective views could have been investigated, so that possible shadow cones, due to the jutting parts of the building, turn into holes for the cloud of points, with a consequent lack of details. For this reason, a comparison has made just for a part common to all the outputs, consisting in the third segment of the façade that is influenced from the tree in the right part. This segment contains 25.124.893 points; the mesh was built by 34.397.201 triangles. Maximum mesh distance is 5 mm to avoid mistakes resulted of big meshes (especially at edges). The plot of the differences shows differences between -50 mm and +50 mm to the reference mesh. Differences < -50 mm are presented in deep blue, differences > +50 mm in red.

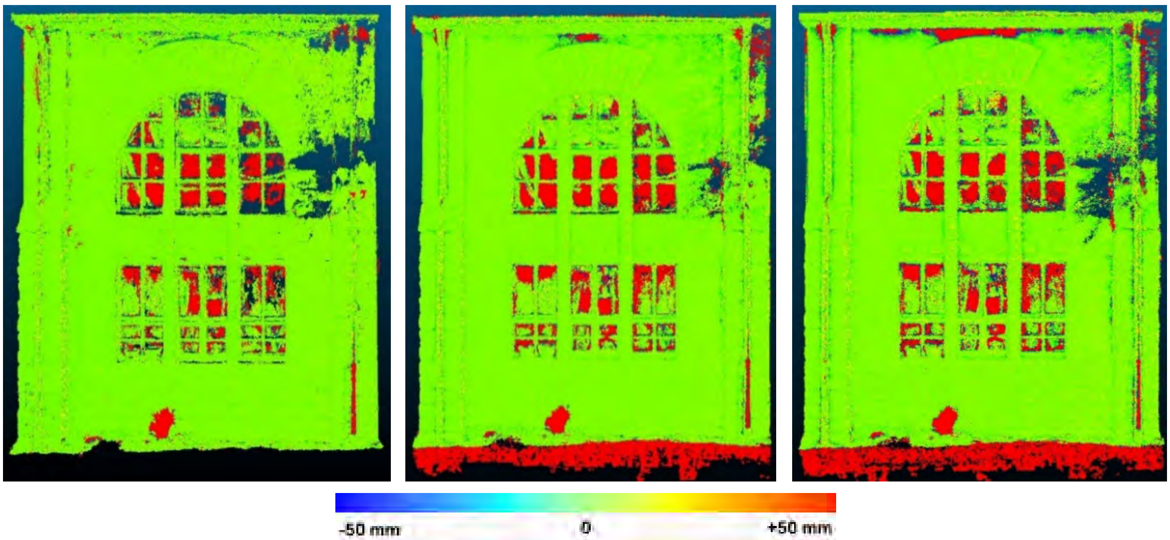


Figure 3.17: Differences between BLK360 scan and Pix4D optimal accuracy (left), PhotoScan high accuracy (middle) and PhotoScan medium accuracy (right)

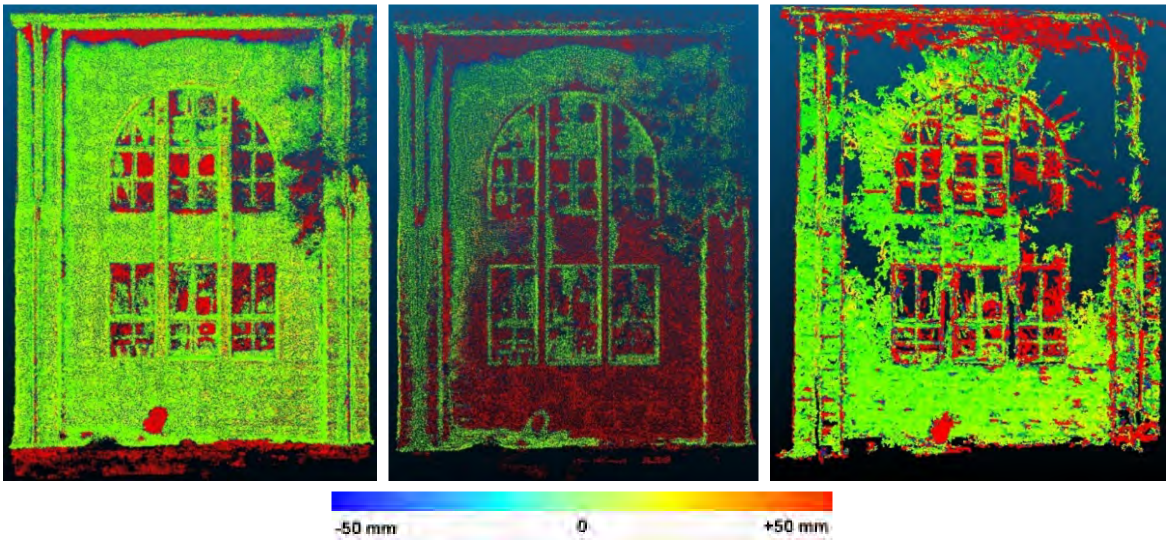


Figure 3.18: Differences between BLK360 scan and PhotoScan low accuracy (left) and PhotoScan lowest accuracy (middle) and VisualSfM (right)

From Fig. 3.17-3.18 can be observed the differences between the Pix4D evaluation and PhotoScan high and medium accuracy, that are in good quality and useable for 3D modelling. The low and lowest accuracy of PhotoScan evaluation obtains big differences compared with the BLK360 Scan. Lowest accuracy is surely not useable for 3D modelling. In VisualSFM evaluation is noticeable that the lower and left part with the column are modelled with small differences while the right part between the tree and the roof are modelled with big differences.

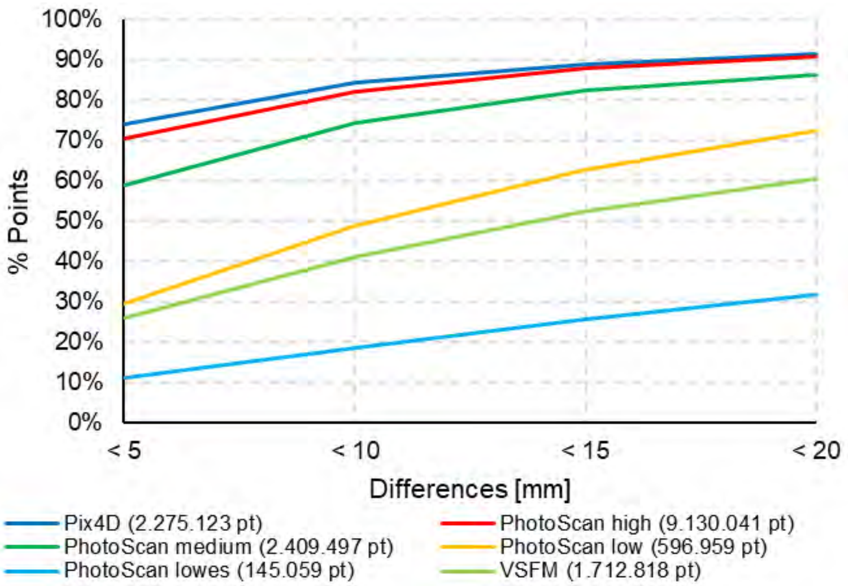


Figure 3.19: Statistics of the differences between BLK 360 scans and the different SFM-Models

In the graph above (Fig. 3.19) are plotted the statistics of the differences in terms of distances between the points of the clouds. In particular, it is reported the percentage of the total points of the SFM models which has differences less than ±5 mm, ±10 mm, ±15 mm and ±20 mm from BLK 360 model. It's clear that very big differences have turned out. PhotoScan medium and high accuracy and Pix4d's curves become almost flat up to 20 mm distance, which means that almost all the points are included in that gap (above 90%), while all the others demonstrate to grow with higher distances, that are not reported because a higher difference is considered not acceptable for the modelling purpose. Moreover, VisualSFM elaboration is quite similar to PhotoScan low accuracy, as Pix4D and PhotoScan high accuracy.

Figure 3.20: Detail of the column and window in segment three: Pix4D (left), then PhotoScan from high to lowest accuracy (right)

The tendency is reflected even focusing the attention on some details. In Fig. 3.20 are shown the particulars of the pipe and the column in the left part of the third window. In PhotoScan lowest and low accuracy is hard to distinguish the contour and the dimension of the pipe while the column is just pronounced with the low accuracy. Only from the medium accuracy on the real shape is reproduced with such precision to be suitable for modeling.

3.3.4. The scan-to-FEM process

The process here illustratedwas developed by the author, and pertains all the operation to perform in order to obtain a FEM model suitable for structural analysis and assessment of masonry buildings, whose geometry is acquired with a laser scanner. Usually known as "*scan-to-BIM*", the paradigm has been here modified in "*scan-to-FEM*" because of an additional step added. In fact, the method is customized and aimed at obtaining an FEM model that can be correctly used to perform structural analysis. In Fig. 3.21 is shown the workflow proposed with its steps and the software proposed.

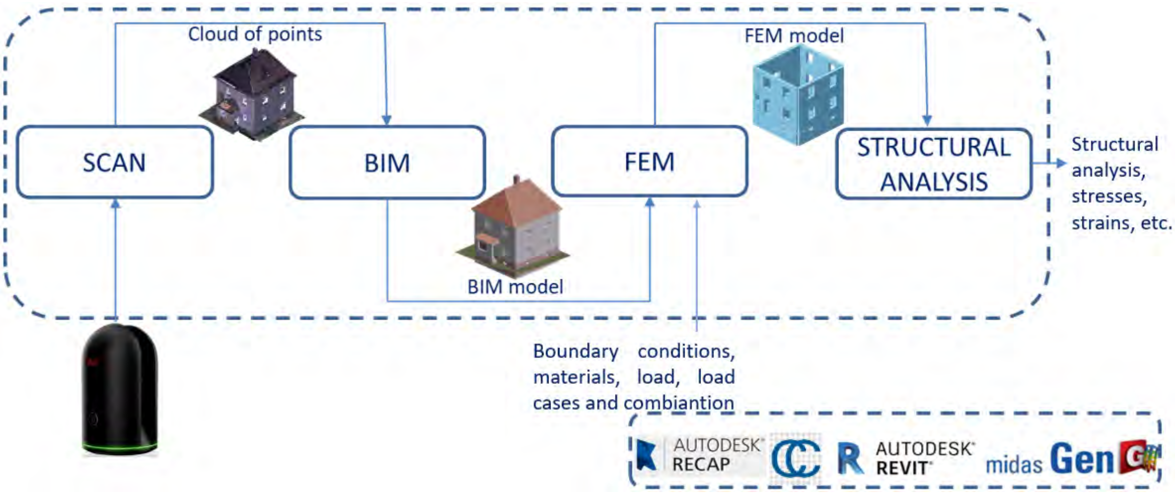


Figure 3.21: Scan-to-FEM process

The details of the operations of each step can be summarized as follows:

- I Step: SCAN

The first step of the process pertains the acquisition of the geometry of the target building and its restitution as a point cloud of the whole building. As stated before, there are different ways to perform this operation, that has to be executed by whom have the technical skills and knowledge. In addition, the peculiarities of the techniques are particularly indicated for the masonry building. The first thing that has to be noticed, is that the geometry of the masonry walls coincides almost perfectly with the geometry of the load bearing elements of the structure, and usually not so many in-depth investigations are needed. In presence of covering layers, such as plaster or other materials, any adjustments are to be done as they alter the thickness of the wall, but the BIM software are capable to take into account the matter.

Very often the laser scanning technique is used for the internal environments because it is more suitable for the purpose, and the photogrammetry for the outer envelope, because it is of a more rapid execution.

With reference to laser scanner acquisition, scans must be registered by identifying common points between them, so that they can be merged into a single point cloud.

With reference to the photogrammetry, using Structure from Motion algorithm the shape of the three-dimensional building can be obtained directly from 2D images. The images are processed with automatic algorithms that, by comparing them two by two, derive their orientation and relative position. After that, a scattered point cloud is reconstructed recognizing some key points (such as door and window frames) that are common between the various frames, and then a dense point cloud is obtained significantly increasing the number of points of the cloud. Then, the metrical information can be added by assigning some known measurements, or with GPS coordinates or with ground control points (GCP). Moreover, the photogrammetry outcome is strongly influenced by the features of surfaces to be acquired. The quality of the output increases considerably when the surfaces are textured. In this regard, the presence of mortar joints provides a very useful guidance to the software in the matching and alignment of the frames.

Once the global point cloud of the building is obtained, the coordinates of the target points can be added to ensure the accuracy of the survey and georeference the cloud. In addition, the cloud must be cleaned of the background noise to eliminate excess points and thus ensure that the cloud is sufficiently precise and not too large to require excessive computational power for further processing. Finally, it must be noticed that a millimetric accuracy of the final point cloud is not necessary for the definition of a structural model. A threshold of approximation in the measurements can be set at 2 cm, so that it follows that for buildings of ordinary dimensions these techniques are valid. Likewise, it should be noticed that it is not necessary to obtain a point cloud excessively dense, since even with low-density it is quite simple to obtain the shapes of walls and openings, i.e. the elements of interest for structural analysis and that, on the contrary, excessive density involves only computational burdens.

- II step: BIM

The cloud of point elaborated in the previous step is suitable for the elaboration of BIM model of buildings, as it is a 3D representation of the building. A first method consists in recreating the model setting each element in the correct position and with the correct dimensions having the point cloud as reference.. Currently, since these operations turned out to be time consuming, many software houses are introducing plug-in for BIM authoring software for defining the position of the surfaces of some elements, such as walls, windows, doors, floor directly from cloud of points. Therefore, the metrical parameters can be extracted directly from the cloud and the elements created taking advantage of this accelerators. This semi-automated methodology seems to be more suitable to the BIM logic because the chance of making mistakes is reduced and the speed of work significantly increases. Some promising developments on the topic are aimed at introducing Artificial Intelligence methodologies to perform that operations in a completely automated way, thanks to the segmentation and classification procedures. This methodology consists in automatically segmenting the point cloud into its elements, to extract metrical parameters from that and to create BIM objects with such information

- III Step: FEM

The BIM model defined above is consists in a three-dimensional representation of all the structural elements, that are beams, columns, walls and foundations, useful to produce drawings, quantity take-off, clash detection and so on. In order to perform structural analysis, one more step is necessary. The definition of a correct analytical model enables the transition from a BIM authoring environment to a BIM tool, thanks to interoperability methodologies. The transition of information via IFC format is not always consistent, so that very often are used closed solutions within a single software house (e.g. Revit - Robot by Autodesk) or ad hoc plug-ins developed between two specific software. In order to ensure the interoperability, it is necessary to set modelling rules that ensure the full transfer of information required to perform structural analysis. In this phase is very important the execution of model checking operations, that consists in:

1. Definition of the elements that constitute the structure to be analysed, marking all the others as not intended for analysis;
2. Correct generation of the openings, with a visual inspection;
3. Congruence at the joints of the elements. For the aim, many software provides shrinks object options that facilitate the check. Moreover, the visualization of the stress distribution under gravity loads helps to detect any defects;
4. Checking of the local axes;
5. Absence of elements overlapped, that can alter the stiffness and strength distribution in the structure. Many software has commands useful for the purpose;
6. Absence of shell elements with too high distortion ratio.

Once the model geometry has been imported into the structural analysis tool, the modelling continues with the introduction of constraints, loads, materials, cases and load combinations. Once the FEM model is checked, it is suitable to perform structural analyses, which allow to obtain some synthetic parameters that characterize the seismic behaviour of the structure. These parameters are the site seismicity, dynamic characterization of the structure (modal analysis) thorough the periods of the vibration mode and the global bearing capacity about seismic loads.

3.4. Application of the scan-to-FEM process to ordinary masonry buildings

The scan-to-FEM process has then been applied to a three-dimensional masonry building, with the aim of defining the operational procedures, the applicability and the reproducibility of the method to all the ordinary masonry building.

3.4.1. Description of the case study

The building has a load-bearing masonry structure, consisting of the assembly of solid bricks and lime mortar. It is located in the German city of Leipzig, and it has a hight equal to 12 m, of which 1,76 m underground and 10,24 m above ground and consists of two levels above ground, a basement and an attic. In detail, each level is characterized as follows:

- basement, 2,30 m high with walls 55 cm thick;
- level 1, 3 m high with a wall thickness of 45 cm;
- level 2, 2,70 m high with walls 45 cm thick;
- four-pitched roof with a height of 4 m.

The plan of the building has a rectangular shape with sides of 8,08 and 8,45 m measured externally and a surface area approximately equal to 54 m^2 for each level. The South and East façades are regular, i.e. the openings are aligned horizontally and vertically; the North and West façades are irregular because the openings are not aligned. The roof consists of a four-pitch wooden structure, inclined at 60° and 42°.

3.4.2. Building laser scanner survey

The geometry of both the indoor and outdoor environments of the building was surveyed with a BLK360 laser scanner. During the initial preparation of the scene, all fixtures (both doors and windows) were removed so that the scans had as many points in common with each other as possible. In addition, since the windows are made of reflective materials, they alter the direction of the laser by providing incorrect information to the laser scanner. As a first step, target points have been set both outside and inside the building for a total of 24 points. For the external targets, a coordinate system was set using the tacheometer, while for the internal targets it was not considered necessary because their function consisted only in the optimization of the match between scans. Then we proceeded with the acquisition of the scans first of the outdoor environment and then of the indoor, for a total of 58 scans with high accuracy. During this operation, care was taken to detect as many target points as possible in each scan. The greatest difficulties were found in the area of the attic, whose only access was guaranteed by very narrow stairs, which therefore does not fit the necessary manoeuvring space for the laser scanner.

After the survey on site, the second phase was performed in the laboratory for the recording of the point cloud. After downloaded the scans, a point cloud was processed by Autodesk ReCap software to superimpose the scans automatically. However, the result was that not all scans were well aligned, as alignment errors were found especially between building parts that were quite similar to each other such as facades and wooden roof beams. Therefore, we proceeded to manual recording by identifying 3 common points between each pair of scans. In terms of time, for each floor and for the exteriors 1 h were used, for a total of 5 h (Fig. 3.22).

Figure 3.22: Point cloud obtained with a laser scanner survey (left) and axonometric split (right)

3.4.3. As-built BIM model creation and checking

The point cloud was imported into BIM authoring Revit software to start the modelling phase. For the purpose, As-Built™ for Autodesk Revit was used, a plug-in produced by FARO Technologies, Inc. to generate BIM models of buildings from point clouds. Among the functions that this add-on module provides, the following were used:

- Quick and precise creation of walls directly from the point cloud, with no need to generate plants and sections first. The software automatically selects the most appropriate wall types according to the wall thickness detected. If an appropriate type is not found, As-Built automatically creates a new adapted wall type;
- automatic wall alignment for creating rectangular plans (with orthogonal walls) and axis alignments, even in multiple planes, with appropriate tolerances;
- insertion of instances such as windows, doors, beams, columns, etc. directly from the point cloud.

The point cloud was exported in..rcp format from ReCap and imported into Revit, setting the automatic positioning from "origin to origin", for which the origin point of the point cloud reference system coincides with the origin of the Revit project's coordinate system. A single BIM model including both structural and architectural information has been created. Before starting to position the BIM objects, levels were created at each floor (Fig. 3.23).

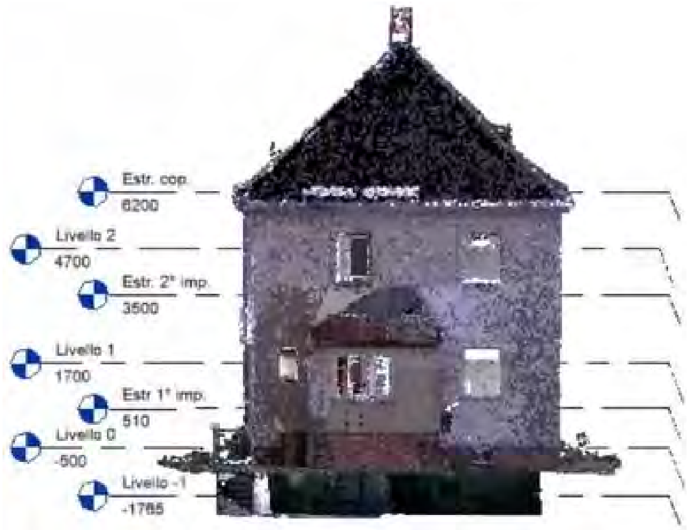


Figure 3.23: Creating levels on the point cloud

The point cloud was then prepared for the objects modeling. In this phase the point cloud of the active plane view is converted into a dense point image. This image was then inserted into the plan view for a better view of the wall edges (Fig. 3.24).

Figure 3.24:"Preparing point cloud" from As-Built - Preparation of level 0

The walls have been modeled in a semi-automatic way in the plan view once the constraints at the upper and lower levels of the walls were assigned; in detail, the upper constraint of each wall corresponds to the upper surface of the floors of the several decks.
Once the “skeleton” of the structure has been obtained, the door and window openings are inserted in the elevation views, taking advantage of the semi-automatic procedure as for the wall modeling.

For the BIM objects that the As-Built module did not provide specific tools for modeling, the traditional Revit software procedures were used. Such elements are:

- reinforced concrete slabs;
- wooden roofs;
- any doors and windows, for which the cloud could not be used as a reference;
- internal and external stairs;
- topographic surface.

The slabs have been modeled as structural floors with a thickness of 30 cm according to the point cloud, which were bonded with the upper surface of the slab to the correspondent level. The floor is made of reinforced concrete, and has a good connection with the masonry, favoring a box-like behavior of the structure.

Then the wooden roof was modeled with a detail corresponding to LOD C. The primary and secondary beams were then modelled consistently with the point cloud with the "Beam system" command, setting a spacing of 50 cm between one beam and another (Fig. 3.25).

Figure 3.25: Roof modelling detailsAs next step, the doors and windows were inserted using the standard Revit procedure

Then the external staircase tower for the access to the building has been realized, for which the 28 cm thick walls have been defined through the command "Fit Wall" of the additional module As-Built. The internal staircases were then built with the monolithic staircase type. Then the walking surface was created as a "Topographic Surface" (Fig. 3.26).

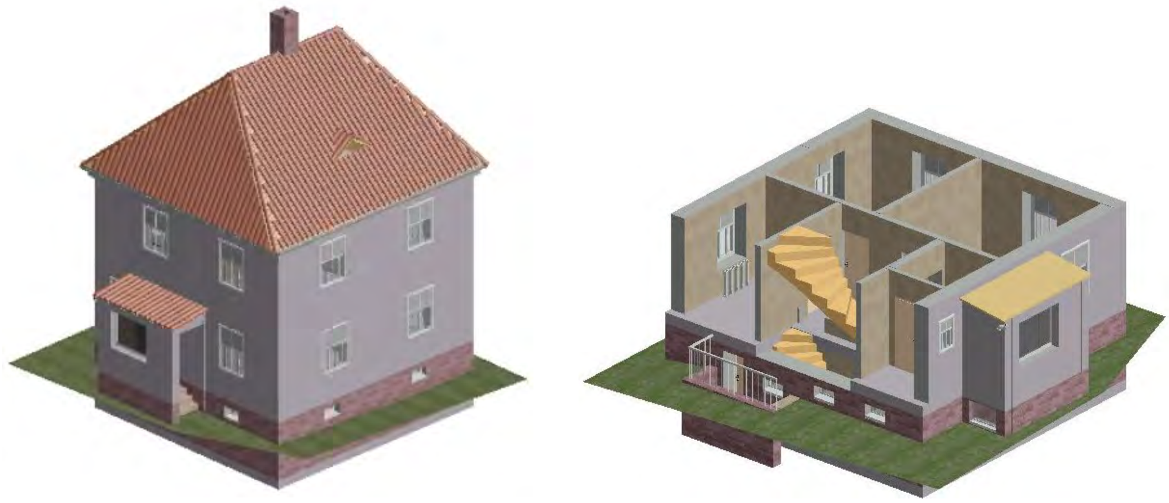


Figure 3.26: As-built BIM model of the building (left) and axonometric split (right)

The BIM model thus obtained, as it was partially created automatically, was checked to make sure that the measurements of the elements are not too much far from those detected on site and collected in the point cloud. The coordination procedure carried out between the point cloud and the BIM model is the LC2 level, and was carried out through the "Calculate" tool of the plug-in As-Built; thanks to this command, the deviation of the points of the cloud (grouped in cells) from the surface of the BIM model is evaluated. The results obtained can be visualized directly on the model through colored surfaces with a gradation scale that varies from blue, to green and red: the green areas are those that have a distance from the cloud almost nil, while the red and blue areas are those that have a distance detected inside or outside of the model surfaces.

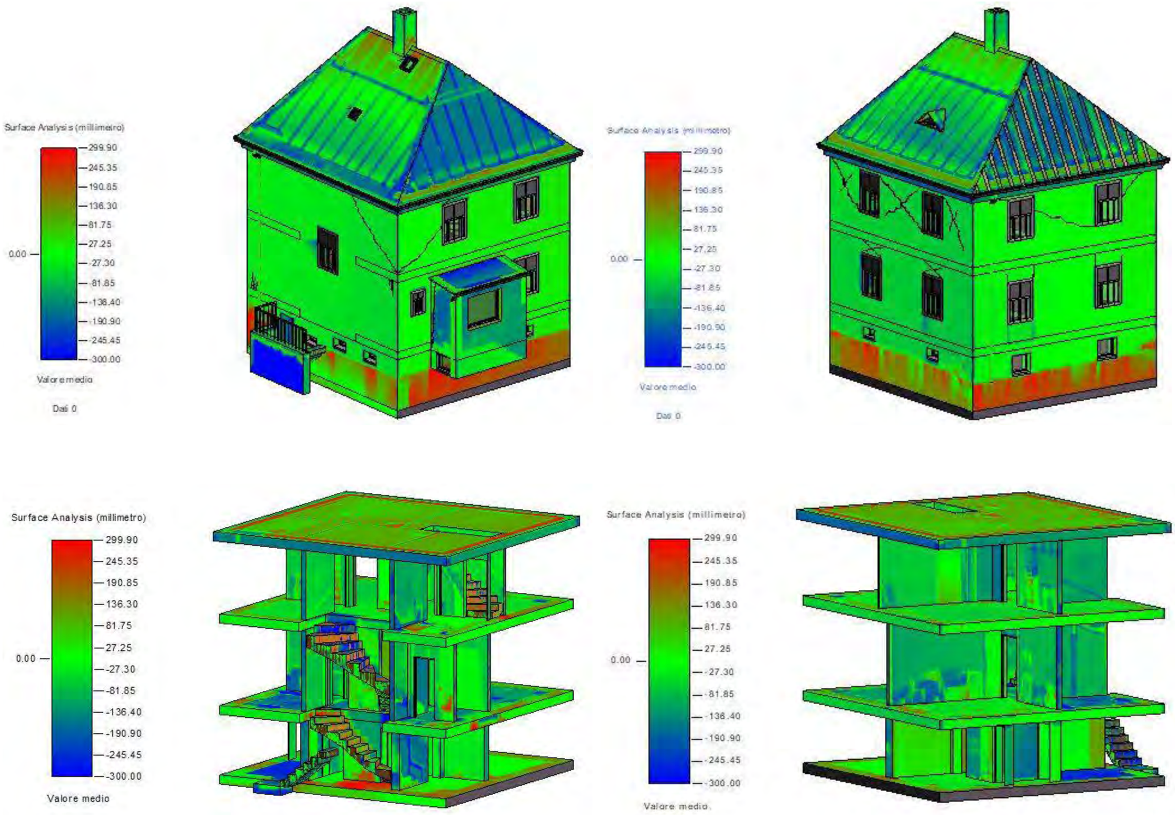


Figure 3.27: Average values of the distances of the point cloud cells from the BIM model of outside (up) and inside (down)

As can be noticed in Fig. 3.27, the analysis showed almost total compatibility in terms of tolerances for the elements built with the As-Built add-on module (perimeter walls and internal partitions). Some traces of inconsistencies are only observed on the walls due to the presence of furniture during the survey, which can therefore be neglected. As far as the other elements realized through traditional procedures are concerned, there are small inconsistencies between the two models. However, the elements that present a greater divergence between the models are the perimeter walls of the basement, the stairs and the wooden roof: for the perimeter walls the deviation is due to the fact that the data provided by the cloud of points are limited to the internal surface due to the surrounding presence of the ground; for the stairs and the roof, given the complexity of the elements, the divergence is accepted because, for the purposes of the subsequent structural calculation, they are evaluated as "carried elements". In fact, it should be noted that these elements are not included in the calculation model for structural analysis, but have only architectural purposes, so these intolerances can be neglected. Once the reliability of the model was verified, all the graphic representations of plans, sections and elevations of the building were automatically exported, some of which are shown in Fig. 3.28.

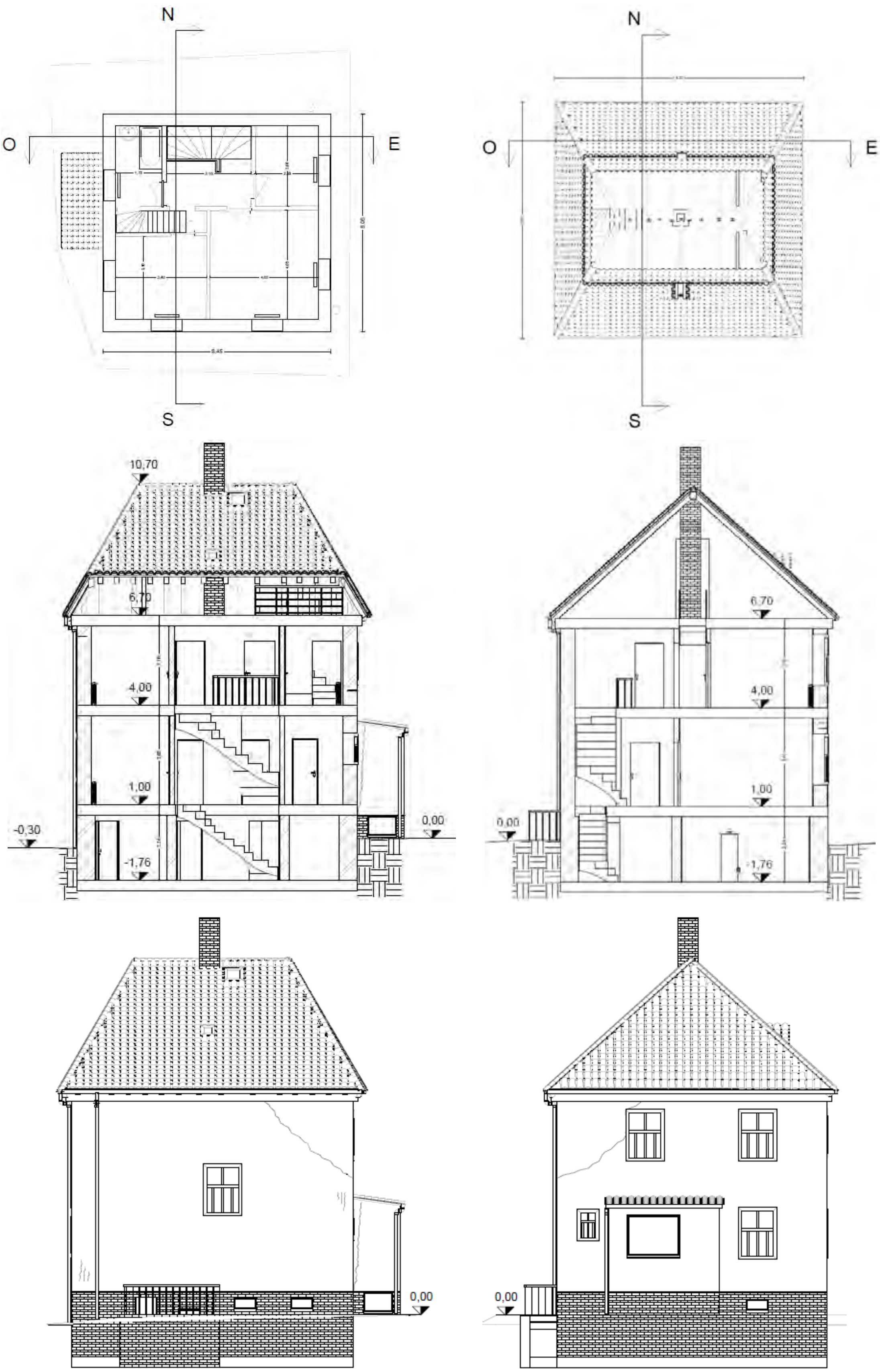


Figure 3.28: Plans (up), sections (middle) and prospects (down) of the building exported by the software Revit

3.4.4. Structural analysis

The structural model of the building was obtained from the BIM model thanks to the add-in module "Midas Link for Revit Structure", taking advantage of a level II interoperability between the two software belonging to two different software houses. Specifically, thanks to the link a .mgt model file format was generated (different from the native Midas .mgb format) whose objective is precisely to allow the transfer of information between the two software. For structural calculation purposes, a model consisting only of walls with a thickness greater than 0.20 m was exported. Neither the walls with a thickness below the threshold value, nor the decks, nor the stairs, nor the pitched roof were imported. The dimensions of the mesh elements (Fig. 3.29) was qualitatively defined (varying from end to coarse), so we proceeded by attempts to thicken the mesh in such a way as to be sufficiently dense and regular, also avoiding too high distortion ratios among the sides of the elements.

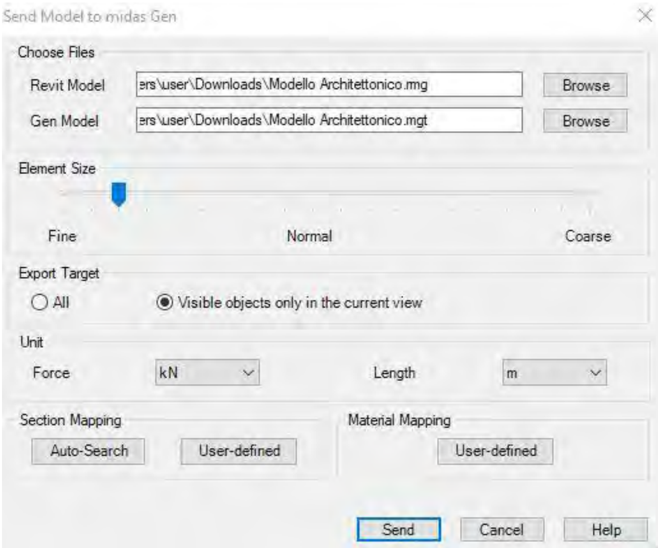


Figure 3.29: Transfer the model from Revit to MIDAS/Gen via the "Midas Link for Revit Structure" plug-in.

Geometric model

The walls have been imported as "Plate" elements, i.e. elements with in-plane stiffness, rotational stiffness and out-of-plane stiffness. In detail, there are "Plate" elements of four different thicknesses: 0.55 m, 0.45 m, 0.40 m, 0.30 m. After importing the model into MIDAS/Gen, the curbs were input as "Beam" elements (Fig. 3.30). These curbs all have the same height, equal to 0.30 m, and a width equal to the thickness of the wall on which they rest. In detail, four sections with the following dimensions have been defined:

- 0,55x0,30 m;
- 0,45x0,30 m;
- 0,40x0,30 m;
- 0,30x0,30 m.

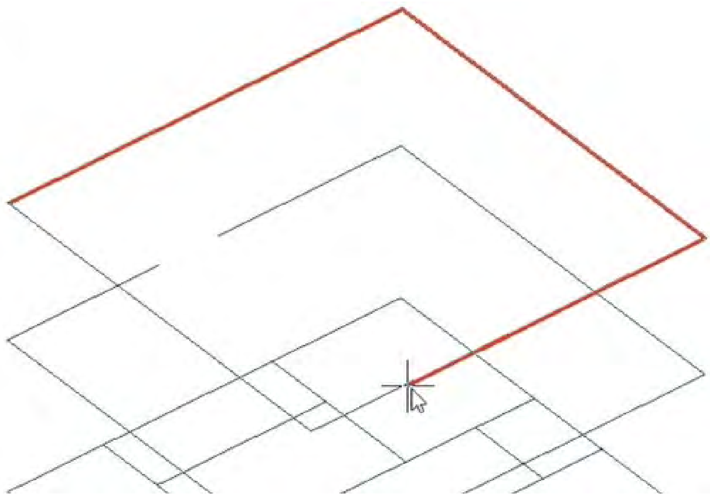


Figure 3.30: Curbs modelling in Midas Gen

In total, the structural model is composed of (Fig. 3.31):

- 5915 nodes;
- 5465 “Plate” elements;
- 609 “Beam” elements.

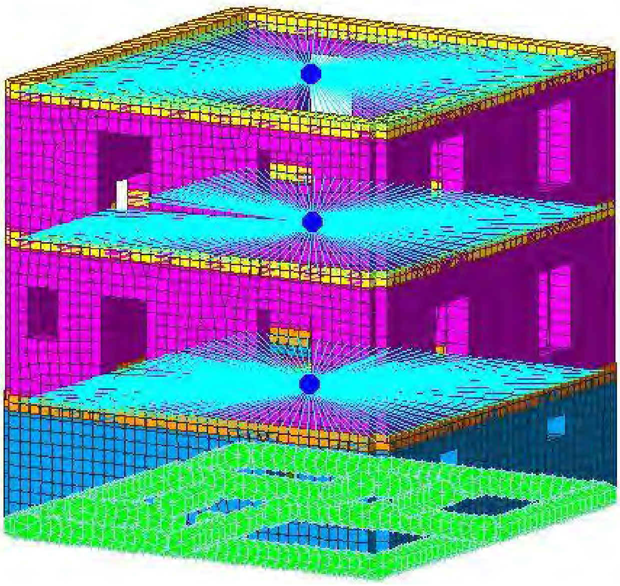


Figure 3.31: Boundary conditions and diaphragm

After defined geometrically and mechanically the elements that make up the structural model, we proceeded to define the constraints of the structure. All the slabs, with the exception of the first one, have been modeled as rigid plane through the assignment of the "Diaphragm" constraint. This assumption was made because of the presence of a 5 cm thick reinforced concrete slab. The interlocking boundaries were then assigned to all the nodes at the base of the structure, which prevent both translations and rotations.

Mechanical model

Then we moved on to the definition of the materials to be assigned to the elements. The material considered for the walls consists of a solid brick masonry and lime mortar, whose mechanical properties were obtained from Table C8.5.1 of the NTC2018 Circular (Tab. 3.7).

Table 3.7: Table C8.5.1 of Circular No. 7 of 21.01.2019

Tipologia di muratura	f_m (N/cm²) Min-max	τ_0 (N/cm²) min-max	E (N/mm²) min-max	G (N/mm²) min-max	w (kN/m³)
Muratura in pietrarse disordinata (ciottoli, pietre erratiche e irregolari)	100 180	2,0 3,2	690 1050	230 350	19
Muratura a conci sbozzati, con paramento di limitato spessore e nucleo interno	200 300	3,5 5,1	1020 1440	340 480	20
Muratura in pietre a spacco con buona tessitura	260 380	5,6 7,4	1500 1980	500 660	21
Muratura a conci di pietra tenera (tufo, calcarenite, ecc.)	140 240	2,8 4,2	900 1260	300 420	16
Muratura a blocchi lapidei squadrati	600 800	9,0 12,0	2400 3200	780 940	22
Muratura in mattoni pieni e malta di calce	240 400	6,0 9,2	1200 1800	400 600	18
Muratura in mattoni semipieni con malta cementizia (es.: doppio UNI foratura ≤ 40%)	500 800	24 32	3500 5600	875 1400	15
Muratura in blocchi laterizi semipieni (perc. foratura < 45%)	400 600	30,0 40,0	3600 5400	1080 1620	12
Muratura in blocchi laterizi semipieni, con giunti verticali a secco (perc. foratura < 45%)	300 400	10,0 13,0	2700 3600	810 1080	11
Muratura in blocchi di calcestruzzo o argilla espansa (perc. foratura tra 45% e 65%)	150 200	9,5 12,5	1200 1600	300 400	12

As an LC1 level of knowledge was obtained from the survey and knowledge phase, the minimum value of these ranges has been assumed for the resistance values, while the average value has been assumed for the elastic modules. Then, the mechanical properties of the masonry are:

- $\mathbf{f_m}$=2400 kN/m²;
- $\mathbf{f_t}$ = 60 kN/m²;
- **E** = 1500000 kN/m²;
- **γ** = 18 kN/m³;
- **ν** = 0,25.

The behavior of the material has been assumed elasto-plastic. The constituent law adopted for the masonry is the Strumas Model, which is an equivalent homogeneous material obtained from the homogenization of the three constituents (blocks, horizontal and vertical mortar joints). With the Strumas material implemented in MIDAS/Gen only the tensile strength, while the compressive strenght is considered infinite. The analysis remains linear in each step, but if the main tensile stress exceeds its strength, the contribution of the same elements to the updated stiffness matrix is reduced or cancelled. The reduction depends on the "Stifness Reduction Factor" parameter (coefficient that scales the value of E once the yield point of the material is exceeded), to which a value close to zero has been assigned. In this case the same values of resistance and stiffness have been assumed for both the stone blocks and the mortar, equal to the values in Fig. 3.32; the "Stifness Reduction Factor" has been assumed equal to 1e-009.

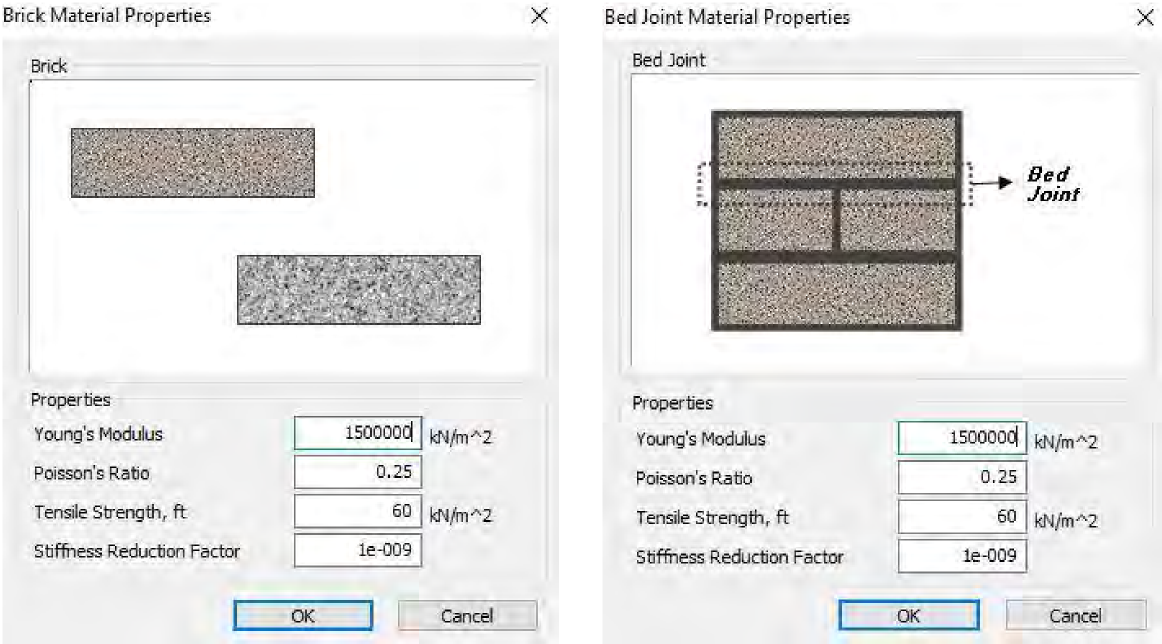


Figure 3.32: Mechanical parameters of masonry material according to Strumas Model.

A C20/25 concrete was used for the curbs, molded as an elastic material.

Load model

Before proceeding with the structural analysis of the building, the loads were assigned to the structure. Various "Static Load Houses" were then defined:

- Self-weight of all elements modeleded in MIDAS/Gen;
- G_{1k}, i.e. the fixed structural loads beared;
- G_{2k}, i.e. the fixed non-structural loads beared;
- Q_k, i.e. service loads;
- Q_n, that is the snow load;
- Static Earthquake X;
- Static Earthquake Y.

In order to apply the self-weight of all the elements, a "Self-Weight" has been defined, multiplicated for a -1 factor along Z, to take into account the different direction of the reference system. For the loads of the elements not modeled in the software, two types of "Floor Load" have been defined for the floor type and for the roof, which was applied directly to the "Beam" elements. For each of them, the values per square meter of the above mentioned loads have been defined, which have been calculated with the analysis of the loads of the structure and using normative pricelists for the calculation of the weight per square meter of the pitched roof. Below is the analysis of the loads carried out separately for floor plan (first and second level), and Roof.

- **Floor plan**

Concrete layer: $\frac{\gamma_{ca} \times \mathrm{h}_{soletta} \times 1m}{1\,m} = \frac{25\,\frac{kN}{m3} \times 0{,}05\,m \times 1\,m}{1\,m}$ = 1,25 kN/m²

Joysts: $\frac{2 \times \gamma_{ca} \times \mathrm{b}_{joysts} \times \mathrm{h}_{joysts}}{1\,m} = \frac{2 \times 25\,\frac{kN}{m3} \times 0{,}10\,m \times 0{,}22\,m}{1\,m}$ = 1,1 kN/m²

Pignatte: $\frac{2 \times \gamma_{brick} \times \mathrm{b}_{pignatta} \times \mathrm{h}_{pignatta}}{1\,m} = \frac{2 \times 8\,\frac{kN}{m3} \times 0{,}40\,m \times 0{,}22\,m}{1\,m}$ = 1,41 kN/m²

Screed: $\frac{\gamma_{screed} \times \mathrm{h}_{screed} \times 1m}{1\,m} = \frac{15\,\frac{kN}{m3} \times 0{,}03\,m \times 1\,m}{1\,m}$ = 0,45 kN/m²

Plaster: $\frac{\gamma_{plaster} \times \mathrm{h}_{plaster} \times 1m}{1\,m} = \frac{18\,\frac{kN}{m3} \times 0{,}015\,m \times 1\,m}{1\,m}$ = 0,27 kN/m²

Floor: $\frac{\gamma_{gloor} \times \mathrm{h}_{floor} \times 1m}{1\,m} = \frac{20\frac{kN}{m3} \times 0{,}015\,m \times 1m}{1\,m}$ = 0,30 kN/m²

Partition walls: 1,2 kN/m²

Variable load: 2 kN/m²

Table 3.8: Load analysis for intermediate floors

G_{1k} – Fixed structural loads [kN/m²]	
Concrete layer	1,25
Joysts	1,1
Pignatte	1,41
TOTAL	**3,76**
G_{2k} - Fixed non-structural loads [kN/m²]	
Screed	0,45
Plaster	0,27
Floor	0,30
Partition walls	1,2
TOTAL	**2,22**
Q_k – Variable load [kN/m²]	
Variable load	**2**

- **Roof**

The weight of the pitched roof is assumed to be 0.78 kN/m², based on a Portuguese tiled roof regulation booklet. Even if the roofing is not practicable, a possible maintenance overload of 0.5 kN/m² was taken into account. In addition, in roofing, the snow load calculated with the following ratio has also been taken into account:

$$Q_n = \mu_i \times q_{sk} \times C_E \times C_t$$

Where

μ_i is the shape coefficient of the cover, equal to 0.48 for pitched with a slope of α=42° and α=60°;

q_{sk} is the reference value of the snow load on the ground, equal to 0,60 kN/m²;

C_e is the exposure coefficient, equal to 1;

C_t is the thermal coefficient, equal to 1.

Concrete layer: $\frac{\gamma_{ca} \times h_{soletta} \times 1m}{1\,m} = \frac{25\,\frac{kN}{m3} \times 0{,}05\,m \times 1\,m}{1\,m}$ = 1,25 kN/m^2

Joysts: $\frac{2 \times \gamma_{legno} \times b_{travetto} \times h_{travetto}}{1\,m} = \frac{2 \times 5\,\frac{kN}{m3} \times 0{,}10\,m \times 0{,}20\,m}{1\,m}$ = 0,1 kN/m^2

Wooden decking: $\frac{\gamma_{wood} \times h_{decking} \times 1\,m}{1\,m} = \frac{5\,\frac{kN}{m3} \times 0{,}02\,m \times 1\,m}{1\,m}$ = 0,1 kN/m^2

Screed: $\frac{\gamma_{screed} \times h_{screed} \times 1m}{1\,m} = \frac{15\,\frac{kN}{m3} \times 0{,}03\,m \times 1\,m}{1\,m}$ = 0,45 kN/m^2

Plaster: $\frac{\gamma_{plaster} \times h_{plaster} \times 1m}{1\,m} = \frac{18\,\frac{kN}{m3} \times 0{,}015\,m \times 1\,m}{1\,m}$ = 0,27 kN/m^2

Portuguese roof tiles: 0,78 kN/m^2

Waterproofing: 0,1 kN/m^2

Maintenance load: 0,50 kN/m^2

Table 3.9: Load analysis for the roofing slab

G_{1k} – Fixed structural loads [kN/m^2]	
Concrete layer	1,25
Joysts	1,1
Wooden decking	0,1
TOTAL	**3,45**
G_{2k} - Fixed non-structural loads [kN/m^2]	
Screed	0,45
Plaster	0,27
Portuguese roof tiles	0,78
Waterproofing	0,1
TOTAL	**1,6**
Q_k – Variable load [kN/m^2]	
Maintenance load	0,5
Snow load	0,288

The loads have been input in the model as "Floor load", with a negative value to take into account that the direction of application is discordant with the Z axis of the global reference system, directed upwards. For the application of the loads, a single warp in the X direction was used for all floor fields, so that the loaded walls are only those in the Y direction. Once the loads were applied, they were transformed into seismic masses. First, the self-weight of the elements is converted to mass in the X, Y direction via the "Structure Type" command. Then, the same thing is done for the applied loads: the conversion is done through the "Load to Masses" command, transforming the "Floor Loads" into nodal masses. The two seismic load cases, Static Earthquake X and Static Earthquake

Y, were then defined as "Seismic Load", whose values were automatically calculated by the software, based on the masses and parameters of the SLV elastic spectrum of the site. Finally, the seismic hazard parameters of the site and the fundamental periods of the spectrum at the SLV were calculated.

Table 3.10: SLV Seismic Hazard Parameters

SLV Seismic Hazard Parameters	
$\mathbf{a_g}$	0,158
$\mathbf{F_O}$	2,276
$\mathbf{T^*_C}$	0,322
$\mathbf{S_S}$	3,45
$\mathbf{S_T}$	0,45
S	0,27
$\mathbf{C_C}$	0,78

Modal analysis

A first check on the correct elaboration of the structural model was performed through the modal analysis of the structure, i.e. of the periods of the structure and the vibration modes. Since the structure is composed of 3 decks, 9 vibration modes were considered (Tab. 3.11).

Table 3.11: Period, frequencies and modal participation masses for the vibration modes of the structure

Node	Mode	UX	UY	UZ
EIGENVALUE ANALYSIS				
	Mode	Frequency		Period
	No	(rad/sec)	(cycle/sec)	(sec)
	1	41.4422	6.5957	0.1516
	2	45.3586	7.219	0.1385
	3	59.7778	9.5139	0.1051
	4	125.4528	19.9664	0.0501
	5	132.5208	21.0913	0.0474
	6	170.1751	27.0842	0.0369
	7	178.9282	28.4773	0.0351
	8	191.8998	30.5418	0.0327
	9	198.8505	31.648	0.0316

MODAL PARTICIPATION MASSES PRINTOUT													
	Mode	TRAN-X		TRAN-Y		TRAN-Z		ROTN-X		ROTN-Y		ROTN-Z	
	No	MASS(%)	SUM(%)	MASS(%)	SUM(%)	MASS(%)	SUM(%)	MASS(%)	SUM(%)	MASS(%)	SUM(%)	MASS(%)	SUM(%)
	1	0.0002	0.0002	62.0775	62.0775	0	0	14.0081	14.0081	0	0	0.0213	0.0213
	2	64.7705	64.7707	0.002	62.0795	0	0	0	14.0082	12.2249	12.2249	1.5277	1.549
	3	2.3631	67.1338	0.0386	62.1181	0	0	0.0001	14.0083	0.2982	12.5231	72.2312	73.7802
	4	0.0209	67.1547	14.245	76.3631	0	0	1.4069	15.4151	0.0026	12.5257	0.0016	73.7817
	5	17.4398	84.5945	0.0469	76.41	0	0	0.012	15.4271	4.7682	17.2939	0.4328	74.2146
	6	1.6297	86.2242	0.0058	76.4158	0	0	0.0149	15.442	3.0732	20.3671	8.5919	82.8065
	7	0.0003	86.2245	8.0206	84.4364	0	0	12.413	27.855	0.0053	20.3725	0.0537	82.8602
	8	0.0082	86.2328	1.3325	85.7689	0	0	0.722	28.577	0.0183	20.3907	0.0002	82.8604
	9	0.0201	86.2529	0.0549	85.8239	0	0	0.0151	28.5921	0.0465	20.4372	0.0106	82.871
	Mode	TRAN-X		TRAN-Y		TRAN-Z		ROTN-X		ROTN-Y		ROTN-Z	
	No	MASS	SUM	MASS	SUM	MASS	SUM	MASS	SUM	MASS	SUM	MASS	SUM
	1	0.0007	0.0007	237.995	237.995	0	0	155.7723	155.7723	0	0	1.4681	1.4681
	2	248.3195	248.3202	0.0077	238.0028	0	0	0.0004	155.7727	135.9422	135.9422	105.5237	106.9917
	3	9.0597	257.3799	0.148	238.1508	0	0	0.0009	155.7736	3.3157	139.2579	4989.1437	5096.1355
	4	0.0802	257.4601	54.6129	292.7637	0	0	15.6445	171.4181	0.0293	139.2873	0.1075	5096.243
	5	66.8614	324.3215	0.1797	292.9434	0	0	0.1335	171.5516	53.0231	192.3104	29.8968	5126.1398
	6	6.248	330.5695	0.0223	292.9657	0	0	0.1657	171.7173	34.1745	226.4848	593.4589	5719.5987
	7	0.0012	330.5707	30.7497	323.7154	0	0	138.0342	309.7514	0.0595	226.5443	3.7113	5723.31
	8	0.0316	330.6023	5.1087	328.8241	0	0	8.0289	317.7804	0.203	226.7474	0.0165	5723.3265
	9	0.0772	330.6795	0.2106	329.0347	0	0	0.1679	317.9483	0.5166	227.264	0.7321	5724.0586

The period of the first vibration mode of the structure is T = 0.15 s. It is mainly translational in the Y direction and mobilizes about 62% of the building mass; the second mode is mainly translational in the X direction and mobilizes about 65% of the building mass; the third mode is rotational around Z and mobilizes about 73% of the entire building mass. Below are the modal shapes of the first two modes.

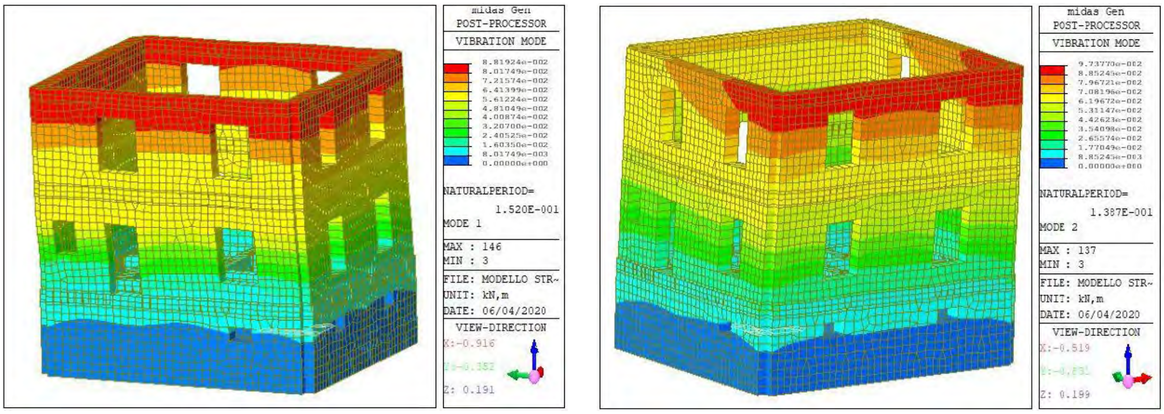


Figure 3.33: Modal shapes of the first (left) and the second (right) vibration mode

From the observation of the modal shapes in Fig. 3.33 it is possible to observe how the congruence to the nodes is always guaranteed, since there are never evident discontinuities in the displacements.

Static linear analysis

The verification for vertical actions is carried out through a linear elastic analysis. The verification is performed in terms of stresses, comparing the active stresses with the resistance of the material, both tensile and compressive. In the case of gravitational loads only, we refer to the fundamental combination, generally used for the SLU:

$$\gamma_{G1}G_1 + \gamma_{G2}G_2 + \gamma_Q Q_k + \sum_{j=2}^{n} \gamma_{Qj}\psi_{0j}Q_{kj}$$

According to the MIDAS/Gen convention the tensile stresses are positive, while the compression stresses are negative. Fig. 3.34 shows the distribution of the main operating stresses on the structure for the SLU load combination. The maximum values of the compressive stresses are instead on the East and West walls, orthogonal to the ceiling warp.

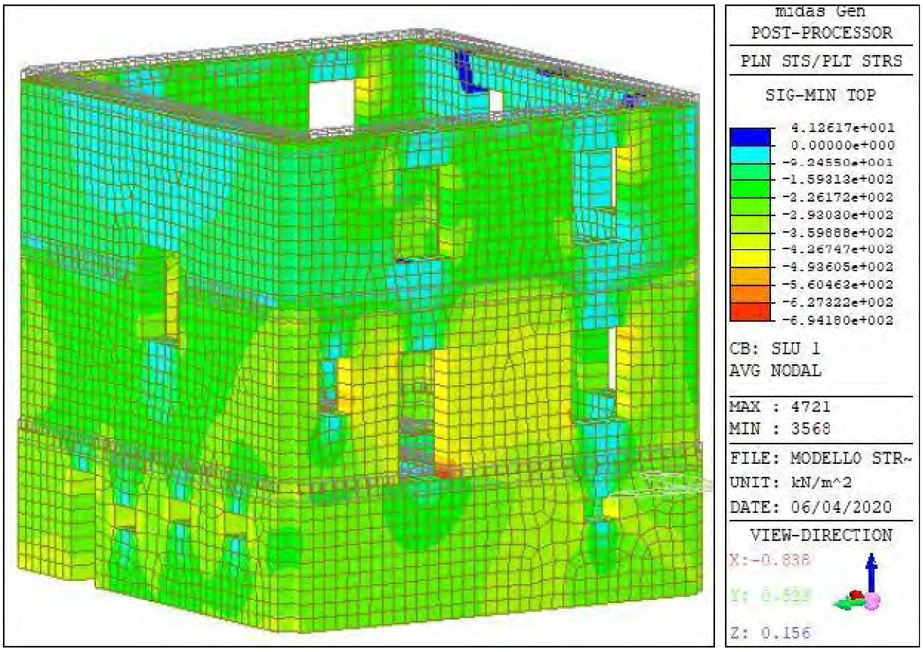


Figure 3.34: Minimum principal stress distribution for SLU load combination.

The maximum value of tensile stress is 41 kN/m^2; the maximum value of compression stress is 694 kN/m^2. In both cases, these values are lower than the resistance of the material so that the verification is satisfied.

Non-linear static analysis

It was performed a non-linear static analysis for the vulnerability assessment of the building, in order to take into account the non-linearity of the "Masonry" material and obtain results more reliable than those that would provide a linear analysis. The SLV verification was carried out with two non-linear (Push-Over) analyses, one in the X direction and the other in the Y direction, with a distribution of forces proportional to the masses. The analyses were performed in displacement control, assuming the center of gravity of the masses of the deck as the control point.

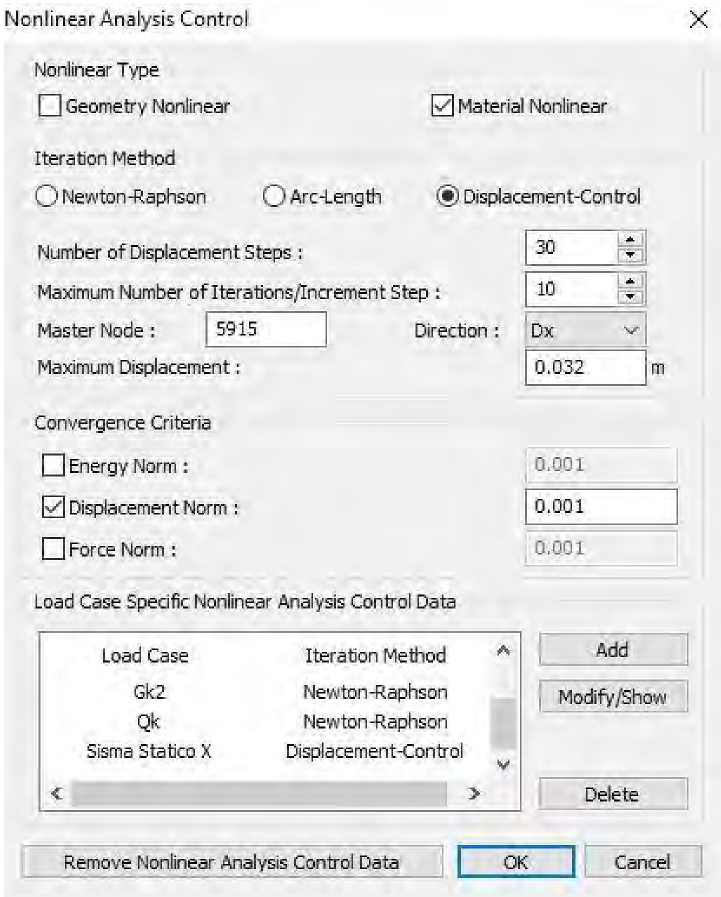


Figure 3.35: Parameters set for non-linear static analysis in X direction

Once the loading sequence and the number of iterations/step of increment were defined, the analysis was performed and the results in terms of displacements and forces relative to the control point were exported. The constitutive model of the masonry implemented, provides that the capacity curve does not present a downward segment, since the non-linear behavior is obtained by lowering the value of the elastic modulus for those parts of masonry that have reached the tension values established when the elastic limit is reached; Therefore, the push-over curve obtained was cut when reaching a limit in terms of displacement equal to 0.4% of the height of the whole building; this displacement was assumed to be 0,032 m. Starting from the capacity curve of the building (MDOF), the verification has been carried out by transforming it into a curve referred to an equivalent degree of freedom (SDOF), dividing the abscissae and the ordinates by the modal participation factor associated to the considered mode.

Table 3.12: X-direction pushover

X Direction						
MDOF capacity curve		**SDOF capacity curve**		**Bilatera**		
Dx max	**Fx max**	**Dx* max**	**Fx* max**	**D* yielding**	**F* yielding**	**D* max**
m	**kN**	**m**	**kN**	**m**	**kN**	**kN**
0.032	1229.39	0.0244	935.25	0.0054	838.6	0.024

Table 3.13: Y-direction pushover

Y Direction						
MDOF capacity curve		SDOF capacity curve		Bilatera		
Dx max	Fx max	Dx* max	Fx* max	D*yielding	F*yielding	D* max
m	kN	m	kN	m	kN	kN
0.032	1088.570	0.0241	785.000	0.0035	785	0.024

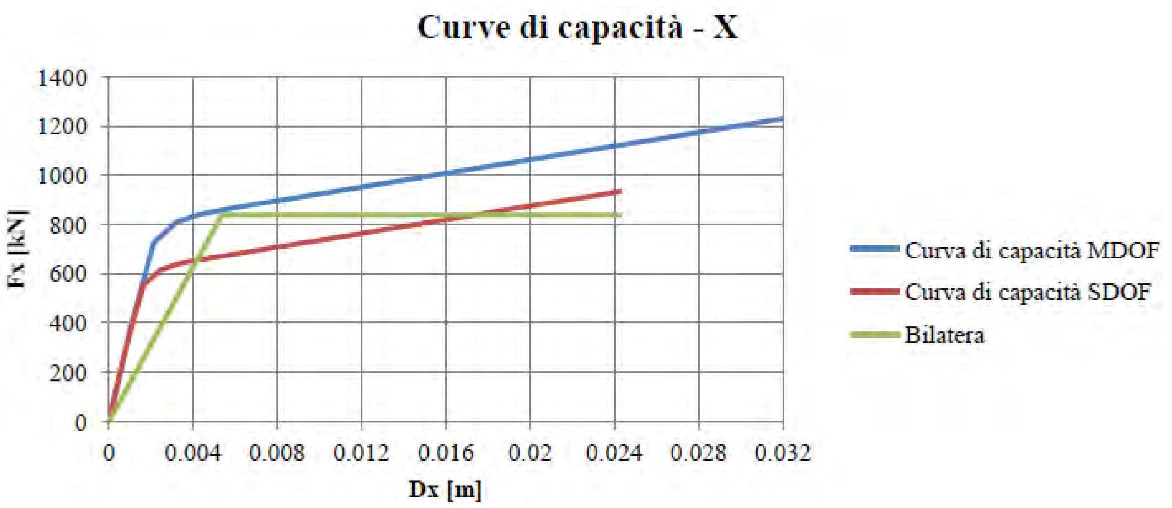


Figure 3.36: Pushover for the seismic combination in X direction

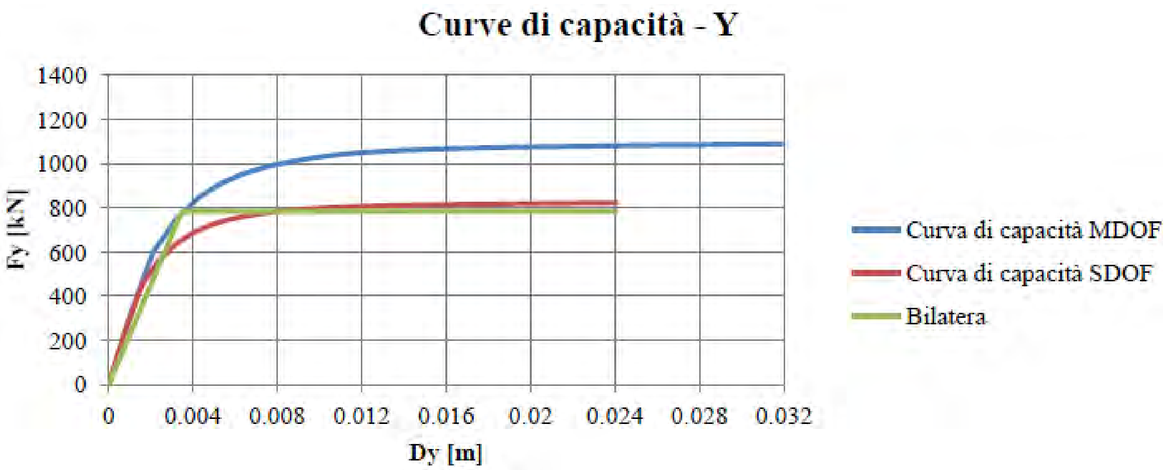


Figure 3.37: Pushover for the seismic combination in Y direction

The Push-Over (Fig. 3.36-3.37) verification has been carried out in terms of displacement, comparing the capable displacement with the one required during a seismic event at the SLV. The displacement capacity is equal to the final point of the bilatera; the requested displacement was obtained from the intersection of the line relative to the indefinite linear elastic behaviour and the ADSR spectrum. Therefore, in order to perform the verification, the ordinates of the capacity curves were transformed from forces to accelerations, while the abscissae of the SLV spectrum from periods to spectral displacement. Fig. 3.38-3.39 show the straight line representing the undefined linear elastic behaviour and the overlapping of the capacity curves with the ADSR spectrum in the X and Y directions.

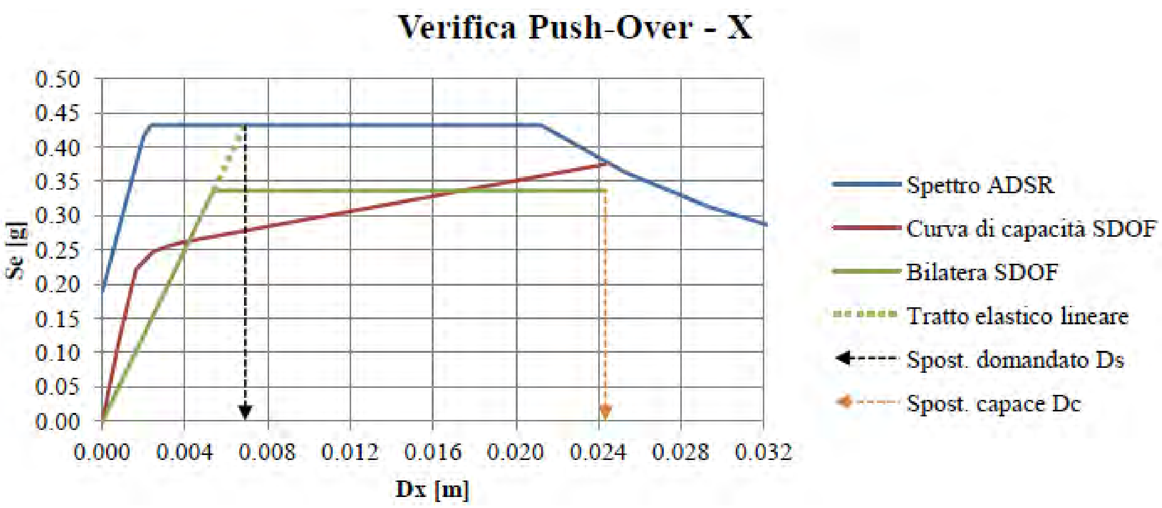


Figure 3.38: Pushover verification in X direction

Figure 3.39: Pushover verification in Y direction

From the above graphs it is possible to observe that in both directions the verification is satisfied, since the displacement capacity of the structure is always greater than the SLV displacement demand.

Table 3.14: Pushover verification in X direction

Push-Over – X verification		
D_s	**D_c**	**$D_s < D_c$**
m	**m**	**-**
0.0069	0.0244	Verified

Table 3.15: Pushover verification in Y direction

Push-Over – Y verification		
D_s	**D_c**	**$D_s < D_c$**
m	**m**	**-**
0.0048	0.0241	Verified

In addition to the global seismic analysis, the Push-Over analysis also allows to identify the points where the tensile strength of the material is exceeded, which in MIDAS/Gen are indicated as "Yield Point". Fig. 3.42-3.43 shows the distribution of the "Yield Points" at Load Steps No. 1, 15, 30 for earthquake X and earthquake Y load cases.

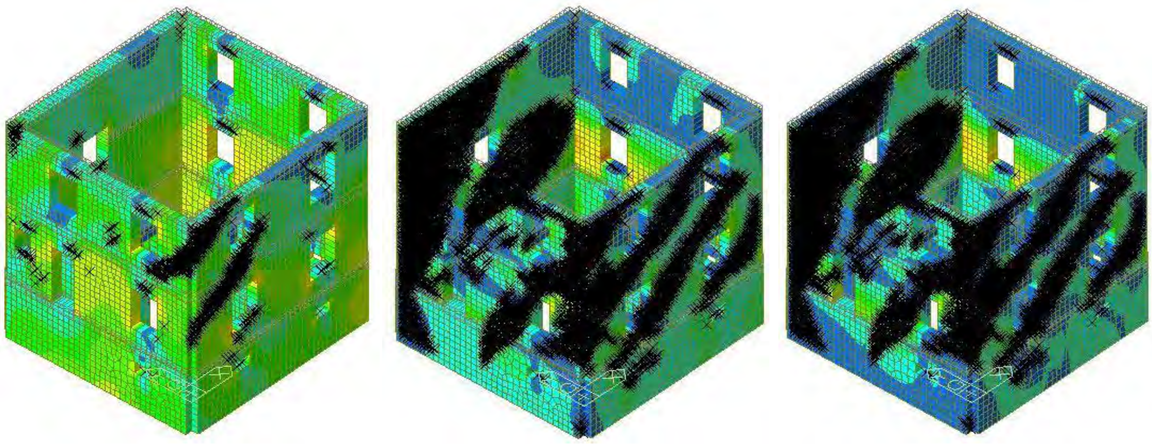


Figure 3.40: Load step n° 1, 15 and 30 for the seismic load in X direction

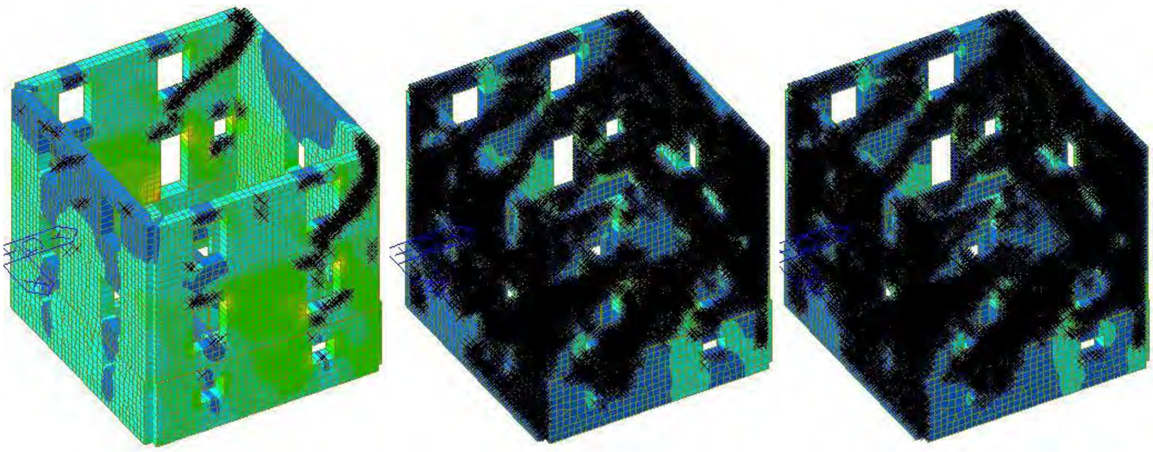


Figure 3.41: Load step n° 1, 15 and 30 for the seismic load in Y direction

For the safety assessment of the building, the NTC introduce an indicative parameter, ζ_E, defined as the ratio between the maximum seismic action that can be beared by the structure and the maximum seismic action that would be used in the design of a new construction on the same soil and with the same features (own period, behaviour factor, etc.). This parameter provides a quantitative indication of any deficit of the structure, in terms of seismic resistance.

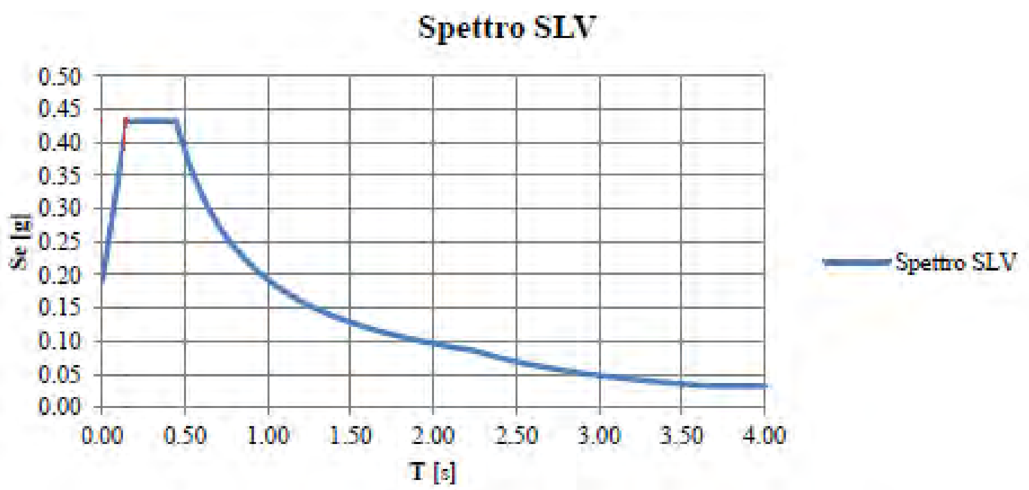


Figure 3.42: SLV spectrum for the considered site

From the comparison of the pushover curves with the response spectra related to the site of the construction it was obtained:

$$\zeta_E = 1{,}01$$

The safety verification for the seismic condition is satisfied, so no restoration, improvement or adjustment is required to increase the safety level of the structure.

3.5. Application of the scan-to-FEM process to the historical façades of the Santa Chiara monastery

The application of the scan-to-FEM method was then tested on some façades of the Santa Chiara Monastery, with the aim of verifying its extensibility to historical buildings. It is one of the biggest historical basilica of the city of Naples, built between 1310 and 1330, and it is part of a bigger complex, which includes four monumental cloisters, archaeological excavations in the surrounding area and several other rooms in which the homonymous Opera Museum is housed (Fig.3.43).

Figure 3.43: Santa Chiara monastery's façades

The whole process has been carried out with the aid of the following suite of software (Fig. 3.44):

Photogrammetry | Cloud of point | BIM modeling | Structural analysis

Figure 3.44: Software suite for the implementation of the scan-to-FEM process to the Santa Chiara monastery's façades

A 15-days trial version have been used for Pix4D, while educational licenses for Revit and Midas Gen. Of the whole structure, only two facades have been investigated, that are the frontal and a lateral one, as they were the only accessible for the survey and with no obstacles for the photos. The target facades were lacking in plaster and other cover layer, that made the surface textured and suitable for the acquisition, and have dimensions of 56 m and 26 m in plant, and 31 m in height, till the bottom of the pitched roof. A set of 464 photos have been taken with an Apple iPadPro with condition of partly cloudy sky, respecting a constant overlap of 70-80% that ensured a high percentage of correctly matched photos (about 99%). In fact, 460 photos have been correctly matched and the cloud of points elaborated in a processing time of 9h 50min 55s. In the resultant cloud some holes are present as in the perspective of acquisition some elements covered others (Fig. 3.45).

Figure 3.45: Pointcloud of the Santa Chiara monastery's façades elaborated with pix4D software

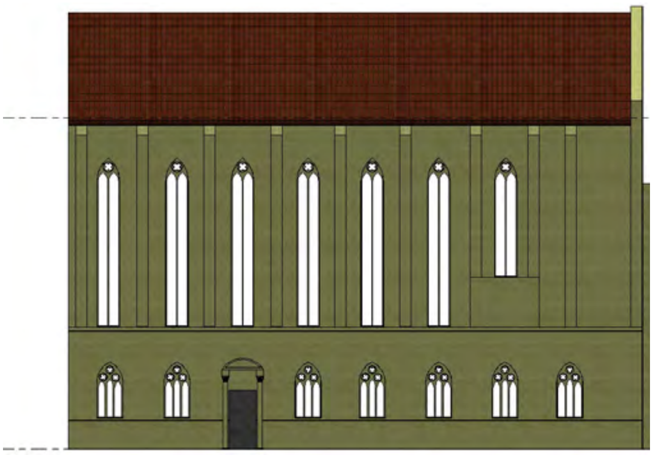
The cloud, exported in .las format, has been imported in CloudCompare, cleaned and scaled setting 3 measurements in the 3 x,y and z directions as measurement constraints in order to adapt to the effective dimensions measured on site. The resultant cloud, composed by 12˙404˙217 points, have been indexed in Revit in an .rcp format (Fig. 3.46).

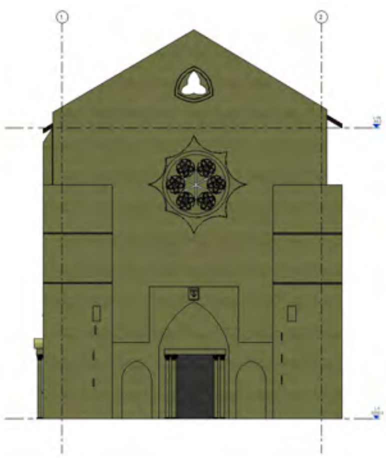
Figure 3.46: Dimensioning the pointcloud of the Santa Chiara monastery's façades

In Revit the operation performed have been the following:

- Cloud of points imported in a new project;
- Input of grids at the bottom of the walls;
- Input of levels at the ground floor and in at the bottom of the pitched roof;
- Editing structural walls;
- Editing architectonical walls;
- Creation of the openings into the wall.

With the aim of reproducing a geometry suitable for structural analysis without renouncing modelling of some architectural details, a good compromise has been found: a structural wall with the actual thickness have been modelled simplifying the geometry at the rose windows, while another architectonical wall has been set in the front with a very small thickness, in order to reproduce the geometry of the decorations, fitting the geometry acquired in the cloud of points with arch and circular shapes (Fig. 3.47-3.48).





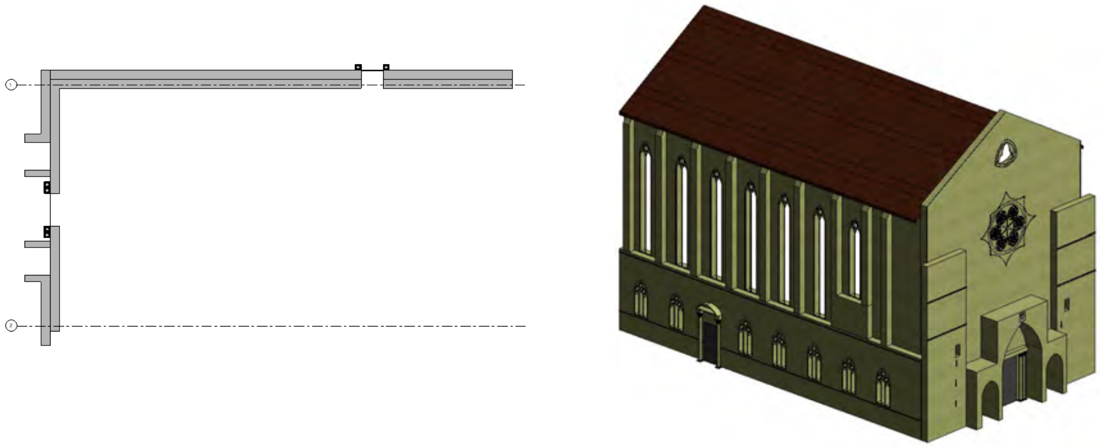


Figure 3.47: Views of the H-BIM model of the Santa Chiara monastery's façades

Figure 3.48: Discretization of the wall in structural and architectural layers

What has been experienced is that the most linear way to reconstruct the analytical model is to export from the BIM model only the geometry of the elements, which are transferred as crossing sections in Midas. The other information, which are boundary conditions, materials, loads and combinations have been added directly in Midas, which is an environment specialized in hosting this information. The geometry of the load-bearing elements has been transferred directly to Midas to perform the structural analysis. For information exchange an external plug-in "Midas Link for Revit Structure" has been used, which ensured the lower loss of information by writing a special exchange format (.mgt). After the importation, the FEM model has been completed assigning the bounding condition, as hinges at the base, defining and assigning the material properties and the self-weight loads. In absence of on-site tests, the tab. C8.5.1 of the *Circolare 21 gennaio 2019, n. 7 C.S.LL.PP.2019* has been taken as reference for the definition of the mechanical parameters as indicated below:

- Material: tuff masonry;
- $E = 5,5 \cdot 10^6$ kN/m^2;
- $G = 1,83 \cdot 10^6$ kN/m^2;
- $\gamma = 20$ kN/m^3.

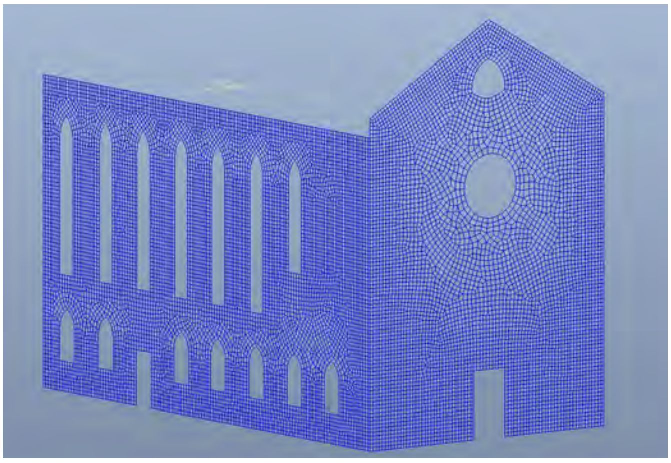


Figure 3.49: FEM model of the Santa Chiara monastery’s façades

The presence of the roof has been taken into account applying nodal forces directly to the node of the mesh elements at the height of the roof.

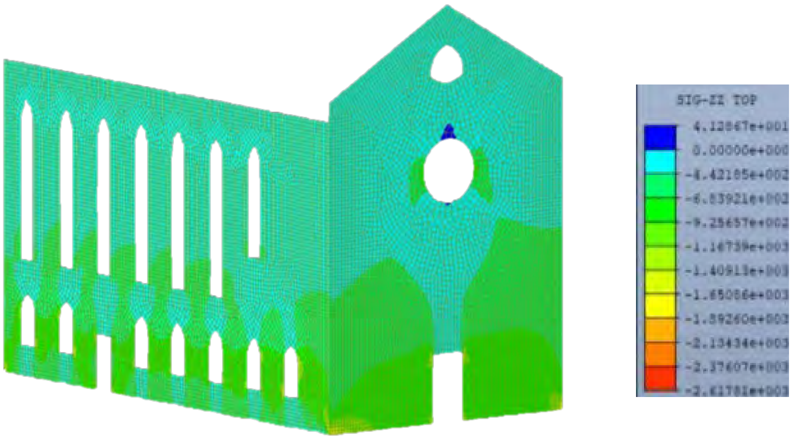


Figure 3.50: Distribution of the vertical normal stresses acting on the Santa Chiara monastery’s façades

The distribution of the vertical normal stresses has been reported above. Although the distribution of the stresses is not very realistic as the model of the building is not provided with all the walls, what has to be noticed is that it correctly works basing on the input data.

Conclusions

Survey techniques using digital methods currently offer numerous possible solutions that refer to a vast panorama of more or less sophisticated technologies, which must be appropriately combined according to the expected degree of precision, the accessibility to the area and the conformation of the building.

The scan-to-FEM methodology developed by the author, which covers all the operations that go from the survey on site to the structural analysis of masonry buildings, , was tested on an a three-dimensional ordinary masonry building, taking advantage of a laser-scanner to speed up all the process with the elaboration of a very precise pointcloud of the entire building. Thanks to the interoperability of the software, starting from the pointcloud, the BIM model and then the FEM model have been obtained, which has been used to perform modal analysis, static linear analysis and static non-linear analysis. The entire process resulted more controllable, more accurate and more time-saving if compared to traditional ones, and can be replicated on any masonry building with no limitations.

The scan-to-FEM method was then tested on some facades of the monastery of the Santa Chiara monastery, to assess its extensibility to historic buildings. In detail, it was proved that the use of photogrammetry instead of the laser-scanning technique is preferable for applications on external facades of buildings if all the "rules of good practice" are taken into account. In fact, it was found that comparing the photogrammetric point cloud processed with several SfM software with the pointcloud of reference acquired with a laser scanner, more than 80% of the points had an error of less than 2 cm. It has been observed that given the very articulated geometric conformation of historic buildings, characterized by the presence of numerous decorative elements (such as rosettes, capitals, etc.) and by the irregoular shae oh the cross-section of the walls, the method is much less effective, especially with regard to BIM modeling, which cannot be done in a semi-automatic manner, and thus losing the advantages in terms of time savings. In addition, the geometry of structural systems can be significantly different from the architectural one, so ultimately it can be said that the application of the scan-to-FEM method cannot therefore be replicable to all historical buildings, resulting therefore much less convenient than for ordinary ones.

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Chapter 4:

THE POST-EARTHQUAKE PHASE - BIM&AI: ADVANCED TECHNOLOGIES FOR THE DIGITALISATION OF SEISMIC DAMAGE IN MASONRY BUILDINGS

* The research outcomes reported in this chapter were published in the following journal article:

Musella, C, Serra, M, Menna, C, Asprone, D. - Building information modeling and artificial intelligence: Advanced technologies for the digitalization of seismic damage in existing buildings - *Structural Concrete*. 2021; 1– 14.

Abstract

This research, based on the digital technologies of building information modelling (BIM) and artificial intelligence (AI), reports on the achievements made in the field of detecting, assessing and digitalising the damage in existing buildings. The purpose of the study is to explore how the structural assessment methods can be combined with the automatic digitisation of hazard-induced damages. For the purpose, the afore-mentioned technologies are used in the form of an image-based recognition-BIM classification technique applied to on-site visual damage data. By extending the proposed methodology to existing masonry buildings, is the results obtained open new possibilities to speed up the process of assessing, designing and managing seismic repair/retrofit intervention starting from the acquisition of image data.

4.1. AI studies for defects detection

Italian territory is characterised by the presence of numerous buildings of both historical and architectural value. Most of them are aged and have been affected by important seismic events. Consequently, there is now an urgent need for monitoring the degradation and damage caused to these structures with the aim of planning maintenance and/or restoration interventions. In this regard, use of the BIM methodology to manage existing buildings is attracting growing interest. This approach plays a major role in the digital transfer of data concerning the properties associated with such structures, as well in the scheduling of restoration and renovation activities. Deep learning (DL) [1], meanwhile, enables experts to obtain information more automatically from the process of drafting damage/crack patterns and analysing images from a building location.

In this regard, many research groups have proposed DL-based structural health monitoring (SHM) techniques as a way to support the progress made with the use of machine-learning for monitoring both masonry and concrete existing buildings.

With reference to the masonry buildings, many applications have been proposed by several authors.

Oses N. & Dornaika F. (2013) [2] in turn described the algorithms required to implement a built-heritage analysis, as well as a classification ICT tool.

Wang et al. (2018) [3], meanwhile, proposed a deep architecture of CNN damage classification techniques based on a sliding-window CNN method with an accuracy of 94.3% in identifying and locating different categories of damage.

Valero et al. (2018) [4] presented an original algorithm for the automatic segmentation of individual masonry units and mortar regions in digitised rubble-stone constructions, using geometrical and color data acquired by terrestrial laser scanning (TLS) devices. Valero et al. (2019) [5] have also introduced a classification method that uses supervised machine-learning algorithms for the automatic detection and categorization of defects in masonry units.

With reference to masonry arch bridges, Brackenbury et al. [6] developed a workflow for an automated monitoring system to determine underlying faults in a bridge and suggest remedial actions based on a set of detectable symptoms. This workflow has been used to identify the main classes of defects so that a convolutional neural network is used to classify the defect classes.

Some others authors have proposed applications on concrete buildings.

Kabir, S. (2010) [7] proposed the application of the grey level co-occurrence matrix (GLCM) textural approach and an artificial neural network (ANN) classifier to obtain data on surface dam-age, such as the amount of superficial cracking and the total lengths and ranges of crack widths.

Moon and Kim (2011) [8], introduced an automatic crack-detection system to enable non-expert inspectors to analyse concrete surfaces and visualise cracks efficiently.

Cha et al. (2017) [9] described a vision-based method using a deep architecture of convolutional neural networks (CNNs) to detect concrete cracks without calculating the defect features. In particular, they proposed a visual inspection method based on a faster region-based convolutional neural network (Faster R-CNN) to achieve the quasi real-time simultaneous detection of multiple types of damage (2017) [10].

Li et al. (2019) [11], meanwhile, proposed a fully convolutional network (FCN)-based detection method to identify and localise multiple damage present in concrete structures.

Deng et al. [12] experienced a new type of region-based CNN (R-CNN) crack detector with deformable modules in which the traditional regular convolution and pooling operation are replaced with a deformable convolution operation and a deformable pooling operation, to improve the mean average precisions (mAPs) achieved, The detectors tested are able to detect the out-of-plane cracks that are difficult for regular detectors.

In this application a new damage-assessment methodology for optimising the management of traditional operational processes in existing buildings, which is based on the interconnection between two digital tools - BIM and AI [13]. In detail, what is proposed here is an advanced method for digitising information on seismic damage to support renovation or upgrading operations in masonry buildings.

4.2. A methodology for assessing damage in existing buildings

The role of structural engineering in the management of existing buildings consists of safety assessments and the planning of retrofit interventions, if required. The process begins with the acquisition of a set of data which represent the input when defining a structural model that is representative of the mechanical behaviour of a structure. This operation is also known as "knowledge building" and, according to Italian codes [14], is articulated in three phases: conducting critical historical analyses; performing geometric structural surveys; and mechanically characterising the structural materials.

It is well known today that these activities require considerable resources in terms of cost and human endeavour. In addition, it is only downstream of such procedures that it is possible to process the data required to conduct a safety assessment of a building. In the following, it is demonstrated how recent technologies can improve the approach used for the reproduction of a crack pattern, thereby reducing the time this takes for surveys and associated costs.

The methodology herein proposed, developed by the author, take into account digital support tools for safety assessment operations, taking advantage of the combination of two digital instruments: AI to process data acquired during the on-site surveys, and BIM for preliminary assessments and managing of the entire restoration/retrofit process. In Figure 4.1, the workflow of all the steps included in the digital support tools showed. After collecting the photographic images of occurred damage on site, taken with cameras or drones, ("survey on-site" box in figure 4.1), the outcomes are processed through AI, i.e. an algorithm is used to automatically detect the position and extent of cracks affecting the existing building, providing quantitative information ("quantitative measures" box). Although the latter are digitalized, they are not yet structured, hence the data collected need to adopt the BIM logic. In particular, all the processed visual damage data are converted into parameters compatible with BIM functioning; hence, those data are entered in the BIM model of the building thanks to the introduction of an ad-hoc BIM object, namely "crack" object, which is able to link the quantitative (position, shape and extent of damage) and qualitative information (building component affected, possible mode of failure etc.) - ("preliminary assessment for retrofit scheduling" box). It fallows that all the data extracted with AI becomes structured and also available into the BIM model for any subsequent design/assessment stage. Moreover, thanks to AI, the crack detection operations become faster and less susceptible to error, and, thanks to BIM, the same information become accessible and extractable from the model.

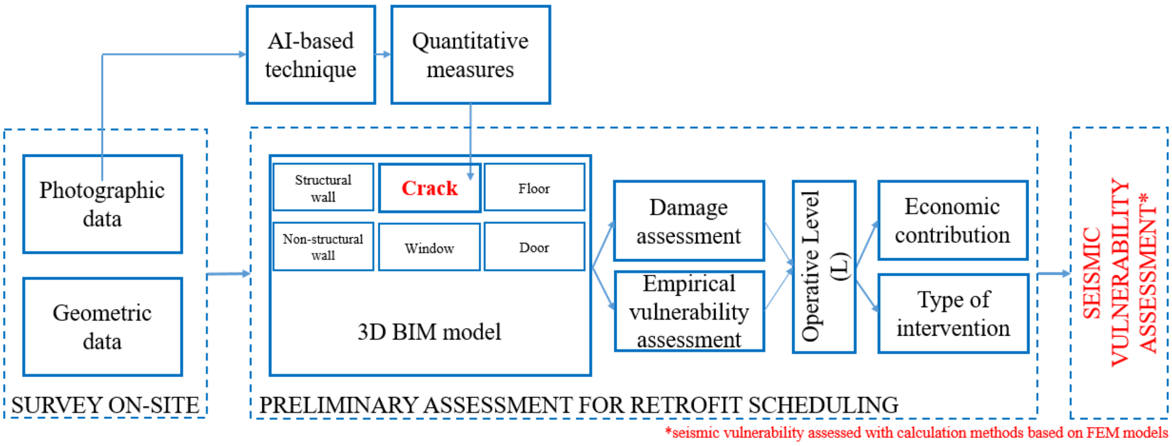


Figure 4.1: Workflow of the damage assessment process associated to the digital support tool

In the following, for the features of the proposed digital support tool, we focus on Machine Learning (ML), a subset of the AI. In detail, the use of ML consisted in the development of ConvNet-based crack classifiers able to detect cracks from on-site images of masonry and reinforced concrete existing buildings, training a CNN from scratch A CNN is a type of feed-forward (ANN) in which the pattern of connectivity between neurons is inspired by the organization of the animal visual cortex, whose individual neurons are arranged in such a way as to respond to the regions of overlap that tessellate the field of vision. CNN consists of input and output layers, as well as several hidden layers [15]. The main feature characterizing a CNN consists in the presence of convolutional layers whose aim is to act on the input data as pattern detectors. In particular, such layers compute the dot product of pattern-specific kernel matrices with sub-regions of the input, producing an activation map for that pattern. Then, accordingly, the activation map enables the CNN to detect the presence of specific sub-structures at some spatial position in the input. This study is focused on DL, which is a subset of the machine learning (ML) method. This enables an accurate connection to be made between the neurons in our network, and we used this to define two different NNs, with the aim being to automatise the crack recognition process. In detail, DL was used for the semantic segmentation of images, which involved the recognition of specific objects in the images processed (e.g. crack and building component affected) and the use of labels to identify all of the pixels representing the particular object or damage. Then, specific tools were used to develop quantitative measures such as dimensions, coordinates, or the position of the crack center. The input images, identified from the NN as simple arrays, therefore became semantic arrays and were labelled pixel by pixel with respect to the category to which an object belonged [16].

In order to create CNNs, after acquired a dataset of images, the following steps have been performed:

- Dataset preparation;
- Setting up networks;
- Training and testing the networks;
- Validating and checking the results;
- Quantifying the parameter outputs.

The networks validated and checked in this way were used to test damage images taken from the target building. The outputs of the final step became input data for the BIM informative model. This latter, was generated starting from the survey of the target building performed with traditional methods; it should be noticed that with innovative techniques, such as laser-scanning and photogrammetry, some further advantages could be achieved as the BIM modelling process could be further optimized. The BIM model thus became a valid support tool for the digital assessment/management process of the occurred damage [17]. According to the principles expressed by the MacLeamy curve [18], and downstream of our initial effort to construct the informative model, greater control over the project was possible because the operations are flowed in a more automated manner.

For the creation of the BIM model in terms of the geometry of the walls, floors and the roof, was obtained thanks to the survey on-site activities ("survey on-site" box in Fig. 4.1); then the "crack" BIM objects were added to the model and contained the parameters are automatically inspected on reinforced concrete elements or masonry walls images by the NNs ("quantitative measures" box) In particular, the cracks were modelled not only geometrically, but also by introducing the parameters that described them. The following steps were executed to create a digital model that reflected the real conditions of the building:

- Producing a BIM model of the structure;
- Encoding the occurred damage in a BIM environment and corresponding modelling;
- Visualization and quantification of the occurred damage in the BIM environment.

The BIM model was the central database around which all the management processes and professionals involved in the project retrieve information about the current status of the building. In more detail, the BIM tool supported:

- The creation of a central database;
- The automatic extraction of graphic drawings from the model, which remain up-to-date if changes occur;
- The digitalisation of the crack pattern via the parametrisation of the cracks, enabling all the information to be organised in a systematic manner, thus simplifying the damage assessment procedure.

The final goal of the proposed digital framework is to speed up the structural assessment of the existing building, having digitally stored all the relevant data concerning the occurred damage. This will support the decision-making process concerning actions that may be undertaken for the existing structure. Indeed, the actual conditions of the damaged elements, which are automatically extracted from the model, enable the scheduling of adequate restoration/retrofit interventions, also accessing in an effective manner the financing incentives if available.

4.3. Encoding the seismic damages in a BIM environment

All of the information collectable need to be added to a BIM model to digitalise the seismic damage. An ad hoc BIM encoding system (i.e. the classification system that identifies specific alphanumeric properties of BIM objects), which took into account all the quantitative and qualitative parameters, was developed with the aim of adding all the relevant information to the BIM model.

The definition of an encoding system is a very delicate phase so that it has to be performed by structural engineers in order to ensure the achievement of the aims of a project. Effective damage encoding in a masonry application takes into account all the types of in-plane and out-of-plane damage mechanisms.

With reference to the in-plane mechanisms, these consist of shear (traction shear and sliding shear) and flexural failure, which become apparent through diagonal cracks in the former or broken edges in the latter. We defined a set of parameters a belonging to two different families: geometrical and parameters related to damage (Table 4.1). The first of these involved the plan area corresponding to: the cross-section of the wall; the X or Y direction; the discontinuity index that highlights if a wall is continuous to the upper and lower floors; and identification of the wall number, floor number, and the perspective surface associated with the wall surface where the door and window -openings are subtracted, and where the structural wall with a load-bearing capacity is distinguished from the walls without such a capacity.

The second family involved: the collapse index that identifies if an element, or part of it, has collapsed; the crack extent that corresponds to the width of a crack; and the cracked surface, which specifies the surface affected by the damage and corresponds to the potential intervention area.

Table 4.1: Damage encoding of in-plane seismic damage in masonry structures.

TYPOLOGY	PARAMETER	DESCRIPTION	VALUE
Geometrical parameters	plan area	wall plan area	to be measured
	direction	- horizontal direction - vertical direction	X Y
	i_disc	discontinuity index - discontinuous vertical wall - non-discontinuous vertical wall	1 0
	n_wall	wall number	
	n_floor	floor number	
	persp _surf	perspective surface	to be measured
	type	- load-bearing wall - non-load-bearing wall	LB NLB
Parameters related to the damages	i_collapse	- collapsed - not collapsed	1 0
	e_crack	crack extension	to be measured
	cracked_surf	extension of the damaged surface - red for load-bearing wall - green for non-load-bearing wall	to be measured

The parameters are to be assigned to all of the potentially damaged BIM objects. This corresponding operation can be done in different ways according to the class to which an object be-longed. In detail, the object array (Table 4.2) shows the association of parameters and BIM objects.

Table 4.2: Object array for masonry structures.

PARAMETER	Load-bearing walls	Non-load-bearing walls	Floor	Windows and doors	Cracked surface	Crack
plan area						
direction						
i_disc						
n_wall						
n_floor						
persp_surf						
type						
i_collapse						
e_crack						
cracked_surf						

Moreover, each of the cracks inspectable on structural elements has to be labelled as follows:

- PVC_i: i-th passing vertical crack;
- POC_i: i-th passing horizontal crack;
- LDP_i: i-th passing diagonal crack;
- NPVC: non-passing vertical crack;
- NPOC: non-passing horizontal crack;
- NPDC: non-passing diagonal crack;
- PLC: passing slab crack;
- NPLC: non-passing slab crack;

in which i-th corresponds to the passing crack number.

It should be noted that the passing cracks were distinguished from the non-passing ones (Fig. 4.2) using dedicated parameters, because of their impact on the overall structural behavior, and residual structural capacity: the passing cracks led to the complete loss of the load-bearing capacity of the affected element, while the non-passing cracks led to just a local reduction of the mechanical properties.

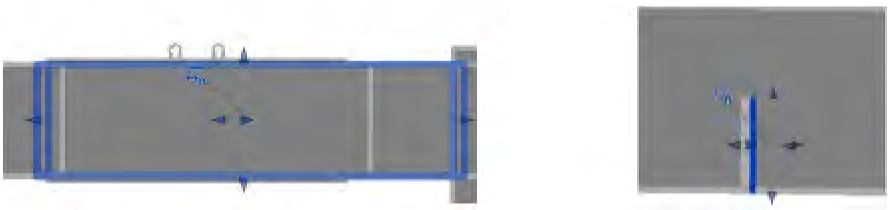


Figure 4.2: Modelling the passing (left) and not-passing (right) cracks in a BIM environment.

Other type of damage to masonry structures concerns out-of-plane mechanisms. They can be classified as follows:

- Simple overturning;

- Compound overturning;
- Cantonal overturning;
- Vertical bending;
- Horizontal bending;
- Tympanum breakthrough.

Even in this case a set of parameters describing the phenomena has been defined (Tab. 4.2): out-of-plumb, which occurs when the upper part of the wall protrudes from the lower one, the detachment, that occurs when part of the material is ejected, swelling, which manifests itself with a bulge of the wall.

Table 4.3: Damage encoding of out-of-plane seismic damage in masonry structures.

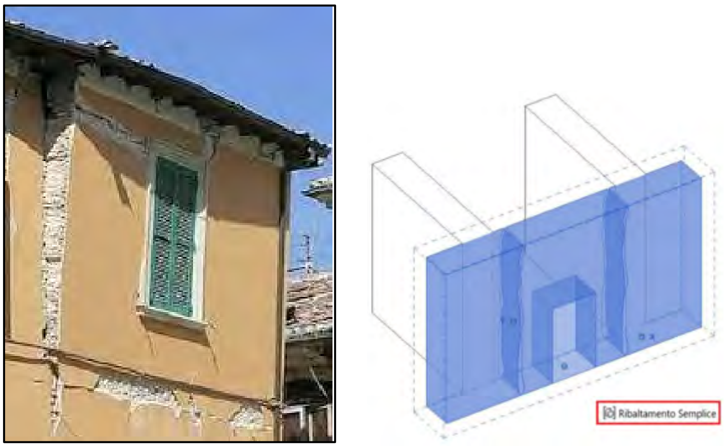
PARAMETER	DESCRIPTION	VALUE
n_wall	wall number	
n_floor	floor number	
i_out-of-plumb	The upper part of the wall protrudes from the lower one - Yes -No	1 0
i_detachment	Loss of material: - Yes - No	1 0
i_swelling	Bulge of the wall: - Yes - No	1 0

The parameters have been assigned to each of the out-of-plane mechanisms as showed in the mechanisms array in Tab. 4.4.

Table 4.4: Object array for masonry structures.

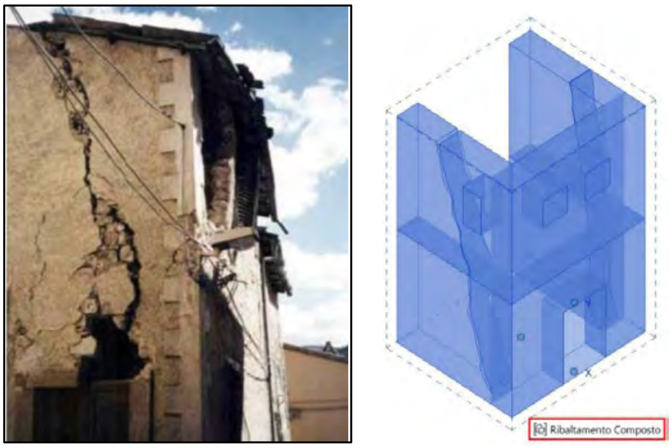
PARAMETER	**Simple overturning**	**Compound overturning**	**Cantonal overturning**	**Vertical bending**	**Horizontal bending**	**Tympanum breakthrough**
n_wall						
n_floor						
i_out-of-plumb						
i_detachment						
i_swelling						

The mechanisms can be modeled in Revit by creating groups of objects containing the elements affected by the mechanisms and the cracks that characterize them, and then assigning the parameters directly to the groups (Fig. 4.3-4.8).



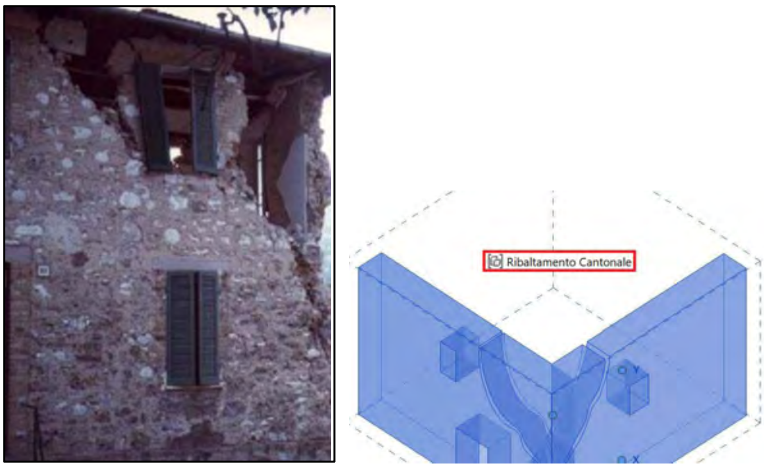
Dimensioni	
n_muro	1.0000
n_piano	0.0000
i_fuoripiombo	1.0000
Lunghezza	5.0000
Area	13.400 m²
Volume	8.040 m³
Dati identità	
Immagine	
Commenti	LVP
Contrassegno	

Figure 4.3: Encoding simple overturning in a BIM environment



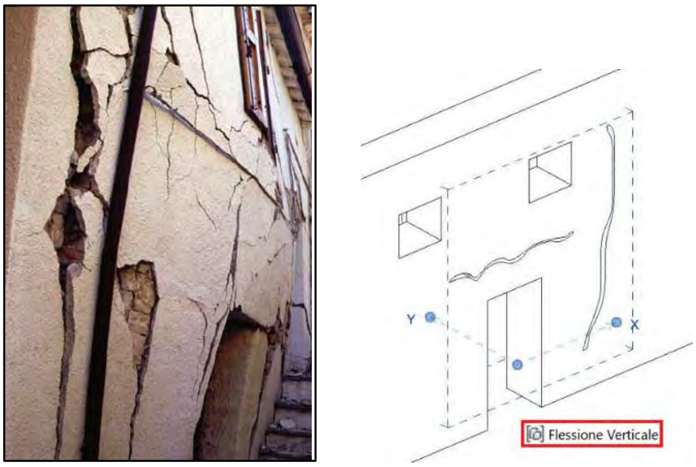
Dimensioni	
n_muro	2.0000
n_piano	1.0000
i_fuoripiombo	1.0000
Lunghezza	3.0000
Area	7.452 m²
Volume	4.472 m³
Dati identità	
Immagine	
Commenti	LDP
Contrassegno	

Figure 4.4: Encoding compound overturning in a BIM environment



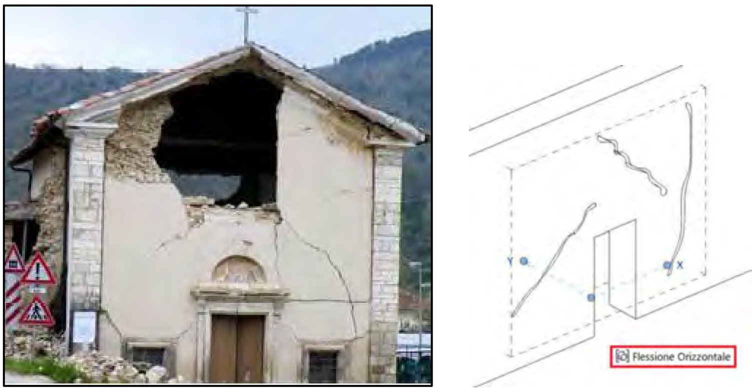
Dimensioni	
n_muro	43.0000
n_piano	2.0000
i_fuoripiombo	
i_spanciamento	
i_distacco	1.0000
Lunghezza	4.0000
Area	10.860 m²
Volume	5.430 m³
Dati identità	
Immagine	
Commenti	LDP
Contrassegno	

Figure 4.5: Encoding cantonal overturning in a BIM environment



Dimensioni	
n_muro	23.0000
n_piano	0.0000
i_fuoripiombo	1.0000
i_spanciamento	1.0000
Lunghezza	9.0000
Area	33.834 m²
Volume	20.192 m³
Dati identità	
Immagine	
Commenti	LOP, LVP
Contrassegno	

Figure 4.6: Encoding vertical bending in a BIM environment



Dimensioni	
n_muro	29.0000
n_piano	0.0000
i_fuoripiombo	0.0000
i_spanciamento	0.0000
Lunghezza	9.0000
Area	34.574 m²
Volume	20.573 m³
Dati identità	
Immagine	
Commenti	LVP, LDP
Contrassegno	

Figure 4.7: Encoding horizonral bending in a BIM environment

Dimensioni	
n_muro	57.0000
n_piano	0.0000
i_fuoripiombo	
i_spanciamento	
i_distacco	1.0000
Lunghezza	5.0000
Area	22.527 m²
Volume	13.516 m³
Dati identità	
Immagine	
Commenti	Distacco
Contrassegno	

Figure 4.8: Encoding tympanum break-through in a BIM environment

4.4. Application of the methodology to a masonry building

The methodology proposed in this chapter has been implemented as a support strategy for determining the operative level (L) of an existing building according to the Italian code [19]. L is defined as the combination of the damage state and the degree of seismic vulnerability of the structure. L enables those involved in the structural assessment process to define the parameterised costs associated to the type of retrofit interventions required, distinguishing the following categories: i) seismic reconstruction, ii) seismic improvements and iii) local reinforcement to repair occurred damage.

The case study investigated concerns a masonry structure damaged by the seismic events affecting Central Italy in 2016, which has been affected by in-plane diffused damages. This building, situated in a town in the Marche region of Central Italy, is a damaged palace with historical, artistic and architectural restrictions (art.10, D.lgs. 42/2004), meaning that a more accurate, transparent and novel approach to undertaking information management was required.

The knowledge-acquisition process was performed using digital tools, and in particular two CNNs obtained with the DL method. The first network (NN1) identified the crack and background classes (interior plastered walls), while the second (NN2) highlighted the crack and masonry-component categories (i.e., bricks and mortar), (Figure 4.9). The workflow implemented involved the steps described below.

Dataset preparation

The initial sample was composed of 200 images of different sizes. These were resized to 256 x 256 x 3 (height, length, RGB channels) to optimise the run-time of the analysis while also losing the lowest amount of detail. The number of images was reduced in several steps using an iteration procedure, taking into account different features that were more suitable for the learning process. Low brightness and noise in images lead to overfitting, namely the production of an analysis that corresponds too closely, or precisely, to a particular set of data, meaning that it may fail in future observations. Furthermore, adding irrelevant predictors can make calculations worse, because the coefficients fitted to them add random variations to subsequent estimations [20].

Setting up the networks

The CNN architecture consisted of multiple levels divided into feature-detection and classification layers. The former included convolution, pooling and rectified linear unit (ReLU) processes, while the latter were expressed in fully-connected layer and softmax operations [21]. In Annex A is shown the details of the scripts implemented in matlab for setting CNNs.

Training and test results

While 70% of the images containing cracks were used for training operation, the remaining 30% were randomly selected from the dataset for each of the two networks and used to test them.

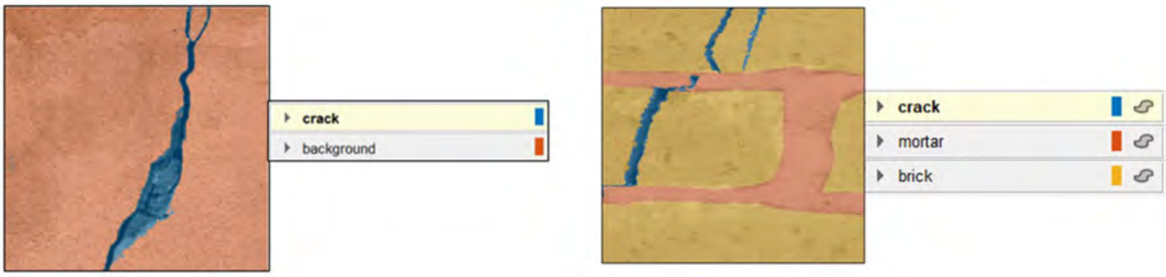


Figure 4.9: Output images from NN1 (left) and NN2 (right).

The main operations for the training were defined once the training images had been selected. Then, in order to evaluate the accuracy of the classifiers, the following parameters were monitored:

- *Initial learn rate*: this is a positive scalar used for training. Its value is important because, if the learning rate is too slow, the training takes a long time; however, if the learning rate is too fast, then the training might produce a suboptimal result or diverge.
- *Epochs*: this is where an epoch represents one forward and one backward pass through all the training data; each time the algorithm has "seen" all of the samples in a dataset, an epoch has been completed [22].
- *Batch*: this consists of all of the units' receptive fields below the loss for an image (or collection of images) [23]. The training process can start when all of the preparations have been completed.

The training results are evaluated using the following parameters:

- *Accuracy*, which indicates the percentage of correctly identified pixels for each class.
- *IoU* (intersection over union), also known as the Jaccard similarity coefficient. This is the metric most commonly used for penalising false positives, and consists of the ratio between correctly classified pixels labelled manually and predicted pixels in that class.

BF score (boundary F1) - this contour-matching score indicates how well the predicted boundary of each class aligns with the true boundary.

<u>*Validating and checking the networks*</u>

A validation process was performed through several iterations after training the networks. The most suitable CNN architecture was established using a variety of convolutional parameters. In particular, the iterations involved parameters such as filter size, the number of filters and stride. In terms of image processing, the filters were used to perform new tasks: each time a filter slides to the various parts of the image and the convolution operation is performed, a new pixel is generated in the output image. The stride, meanwhile, is the number of pixels by which the filter slides [24]. Having chosen the parameters and trained the networks, the CNNs were validated in a tabular form (Figure 4.10) using a confusion matrix (CM), which shows the relationship between correctly classified pixels that were labelled manually and the predicted pixels in that class.

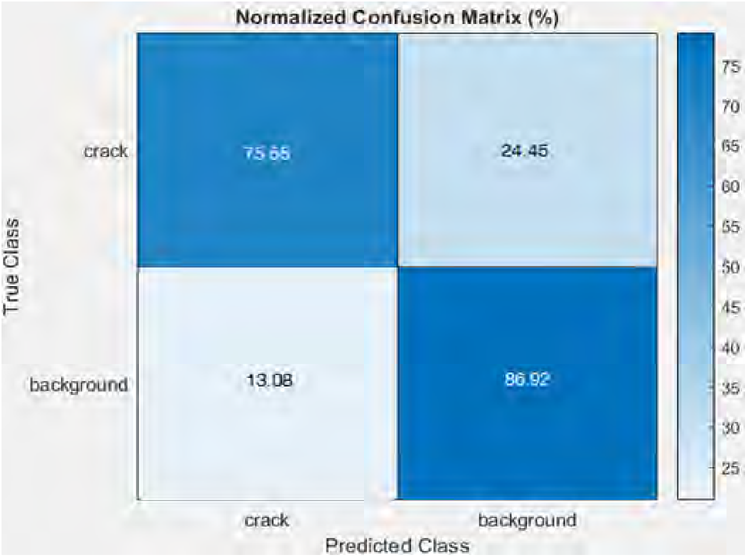


Figure 4.10: Normalised confusion matrix.

Quantitative parameter outputs

The main goal of this study was to use only image-based data to generate direct quantitative estimates of cracks and damaged walls (Figure 4.11). The quantitative measures were determined in a fully automated process using specific tools (Figure 4.12). These pixels were then converted into a measurement system of interest using a simple conversion process (Table 4.5).

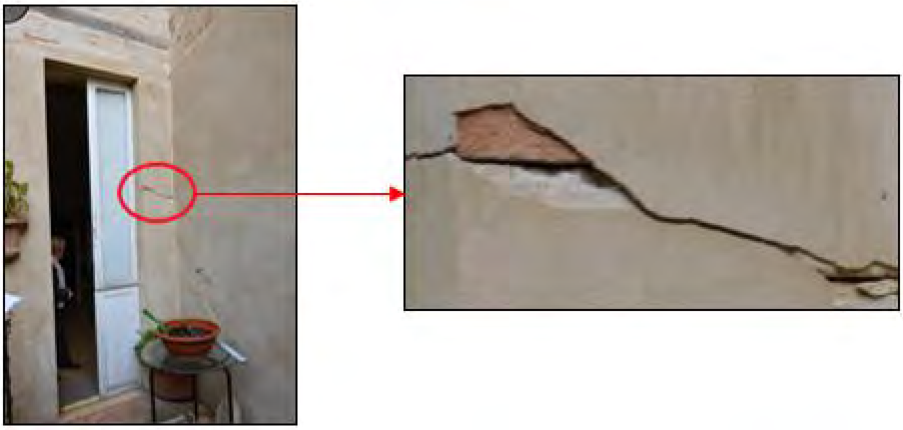


Figure 4.11: The passing crack inspected in the target building (left) and in detail (right).

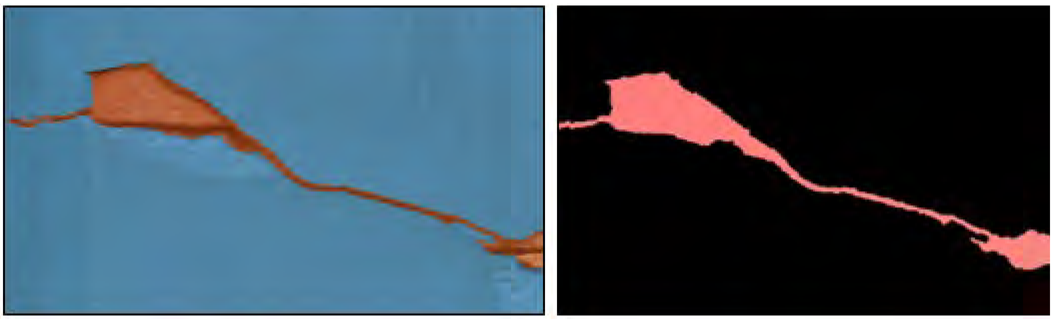


Figure 4.12: The image processed by the CNN (left) and the image processed for the quantification of the parameters (right).

Table 4.5: The results processed by the CNN.

Filled area (mm^2)	Major axis length (mm)	Minor axis length (mm)	Perimeter (mm)
1798.90	495.98	45.98	100.43

Therefore, when the BIM model has been built, any labels have been assigned to the inspected cracks, so that they are automatically reported in drawings for the clear identification of the cracks' features. In the model only the in-plane cracks have been modeled, as no out-of-plane has been inspected on the building, as shown in Figure 4.13.

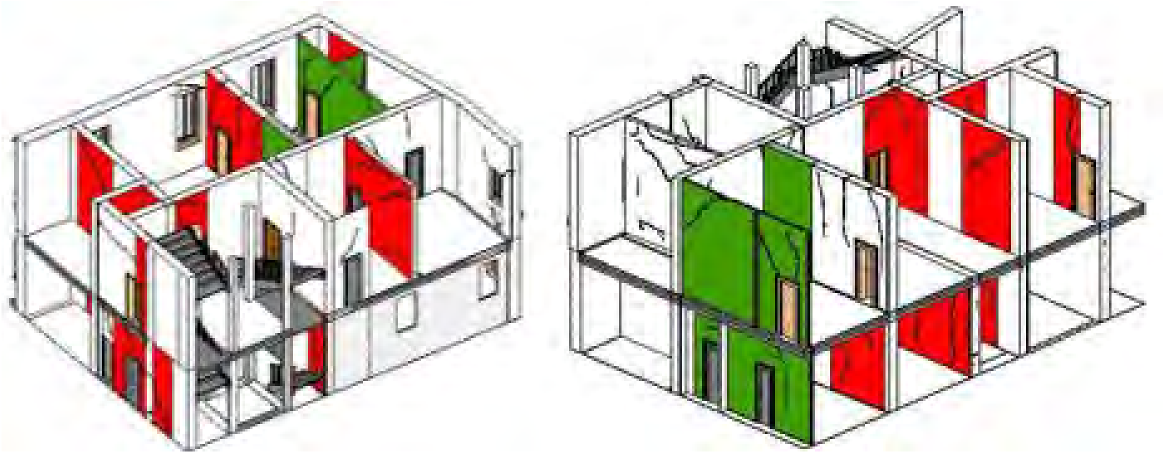


Figure 4.13: Views of the BIM model of the building, with the passing and non-passing cracks highlighted.

The main aim of the described procedure was to organise and extract the quantitative data directly from the BIM model. In this regard, and thanks to the BIM software tool, the information related to the parameters assigned to the BIM objects were extracted in a tabular form, as reported in Table 4.6. As a result, and to make the data visualisation and control easier, all of the information was structured and organised in the tables for each plan and direction using appropriate filtering operations.

Table 4.6: Crack dataset.

n_floor	n_wall	Type	Label	cracked_surf (m^2)
1	7	LB	PVC	10.41
1	8	LB	LDP	9.32
1	14	LB	NPOC	11.85
1	24	LB	POC	11.37
Tot				42.95

Quick and precise counting operations were performed using these tables to empirically define the damage state of the building, basing on criteria established in the code, which depends on the width of the cracks and on the extent on the surface of the structural elements. In detail, four thresholds for the state of damage are defined:

- State of damage 1, when the damage is classified as “light”;
- State of damage 2, when the damage is classified as “severe”;
- State of damage 3, when the damage is classified as “very severe”;
- State of damage 4, when the damage is classified as “extremely severe”.

The seismic vulnerability assessment was evaluated empirically, through the analysis of the number of structural deficiencies exhibited in the building. Both the empirical vulnerability indexes were defined using checklists provided by the standard of reference [19]. The L parameter was obtained by combining the damage state and the vulnerability as shown in Table 4.7.

Table 4.7: Operative level: combination of the damage state and vulnerability grade.

Vulnerability	State of damage 1		State of damage 2		State of damage 3		State of damage 4	
Low	o	L0	o	L1	o	L2	o	L4
Medium	o	L0	x	L1	o	L3	o	L4
High	o	L0	o	L2	o	L3	o	L4

There was a parametric cost and kind of intervention related to each L value obtained from the vulnerability assessment [19]. In detail, five levels of L are defined ranging from L0, where the building exhibits minor damage and even a low level of vulnerability, to L4 as the damage and vulnerability increase. In any case, a building with a damage state classified as “light” is always classified as L0 while a building with a state of damage classified as “more than the very severe” is always classified as L4. Depending on the L obtained, the intervention category is then defined. In particular, either demolition and reconstruction or seismic-improvement retrofitting are needed for L4, while seismic improvement retrofitting is required for L1, L2 and L3, and just local improvements to repair the damage in L0. The parametric costs were funds granted by the public administration for each square meter of the floor area for buildings with severe seismic damage. This funding scheme includes technical and investigation expenses, as well as intervention costs (Table 4.8).

Table 4.8: Parametric costs

Parametric costs	Operative level: L0	Operative level: L1	Operative level: L2	Operative level: L3	Operative level: L4
≤ 130 m^2	400 €	850 €	1100 €	1250 €	1450 €
130–220 m^2	300 €	750 €	900 €	1100 €	1250 €
≥ 220 m^2	300 €	650 € (X)	800 €	950 €	1100 €

Only after the parametric costs are defined as well as the financial incentives determined, it is possible to move toward planning the details of the retrofit interventions, performing the seismic vulnerability of the building with the most suitable method of structural analysis. As explained above, this funding scheme for reconstruction is not the only initiative in Italy; indeed, other incentives have been implemented in different Italian regions. For instance, a different reconstruction funding scheme was introduced in L’Aquila, after the seismic event on April 6th, 2009 [25]. Both the approaches enabled the definition of the financial aid required for the reconstruction, even with some differences due to the fact that the contexts in which they were developed were dissimilar. Although the reference standards were different in the two regions, the digital assessment and modelling procedure proposed in this study could be applied to both of the regulatory frameworks used for calculating the funding required from the public administrations, which provide valuable support for the reconstruction operations that occur after catastrophic events.

Conclusions

This study has described the implementation of a digital methodology to be used when managing existing damaged buildings. Two innovative technologies have been combined to speed up intervention strategies: AI for the initial inspection stage and BIM for the damage information management. Their application has been researched to identify the modality and instruments that can be used to speed up the reconstruction phase in a short period of time. With reference to masonry buildings, the process of evaluating the operative level (L) of a historical building located in the Marche region damaged by earthquake was illustrated. Starting from the damage that can be inspected in the building, a damage encoding system has been defined, whose parameters are detected by AI systems and transferred to the "crack" BIM objects for a structured organization of the information. It follows that they can be structured and extracted in a tabular way to facilitate the assessment of the building. Downstream of such operations, the retrofit interventions can be defined and dimensioned in detail, using the structural analysis methods to assess the variation of the seismic vulnerability. The whole procedure is more convenient than the traditional one, since it is carried out according to the principles of quality management thanks to the introduction of digital methods and tools that allow to have always a greater control of all the operations, as well as a better communication between all the actors of the process ensuring the availability of all the information. In addition, the entire process is centralized on a BIM model, which will remain available at the end of operations and therefore will be a significant simplification tool for all subsequent phases of the building life cycle, and reducing the time and cost of implementing all subsequent monitoring and retrofit phases. Thanks to the combination of AI and BIM, it was automatically found that the building is affected by a damage state 2, has a medium degree of vulnerability so that, combining the two indexes, the operative level resulted equal to L1. Related to L1 level, the public administration guarantees parametric costs of 650 euros for each m^2 of floor area, to support the costs for seismic improvement of the building.

In conclusion, these tools have made it possible to digitalize all the operations that are traditionally conducted manually, summarizing those performed in an informative model. The methodology does not result bound to specific peculiarities of the building under study, and is therefore reproducible on all masonry buildings damaged by seismic events.

As a future development, it is possible to evaluate the extensibility of the method also to concrete buildings, which need, however, the development of ad hoc AI systems, and which take into account not only the detection of cracks and the extraction of metric parameters but also other sets of information. In fact, it is necessary to define if the cracks are placed in the middle or at the endings of the structural elements, if they belong to beams or columns and if they are related to shear or bending phenomena, in order to making reliable vulnerability assessments.

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Chapter 5:

THE COMMON DATA ENVIRONMENT FOR THE INFORMATION MANAGEMENT OF DAMAGED EXISTING BUILDINGS

* Any of the research outcomes reported in this chapter were published in the following conference paper:

Musella C., Serra M., Salzano A., Menna C., Asprone D. - H-BIM – innovative and digital tools to improve the management of the existing buildings – *Proceedings of the 4th International Conference on Protection of Historical Constructions PROHITEC*, Athens, October 2021

**Any of the research outcomes reported in this chapter were part of the following industrial research project:

BIM ReCulT - *Il metodo BIM per il Recupero del patrimonio CulTurale* (POR Campania FESR 2014-2020)

Abstract

The management of existing buildings is almost always characterized by the presence of numerous documents in which a large amount of information is scattered. In this regard, the implementation of the Common Data Environment (CDE) is a valuable support to the management of data and information of different nature, even if included in paper sources. In the passages below is discussed how to set up the CDE, and in particular how to develop processes for existing structures taking advantage of appropriate structure of folders, assigning permissions and define tasks.

Subsequently, two complex case studies of an ordinary German building and a historical Neapolitan one are dealt with, in which the theme of digitization of information is addressed, with particular attention to the damages suffered, identifying strategies for digitalization appropriated to the importance of the building.

Thanks to the development of such applications, the digital tools that would allow a more effective application of the BIM methodology to existing buildings are identified, defining the specifications for their development carried out thanks to the collaboration with ACCA software.

5.1. CDE for the information management of existing buildings

The current standards aim to define guidelines for the development of the so-called BIM level 2 (ISO19650), which consists in the elaboration of many informative models, one for each discipline and reproducing different behaviors of buildings. It consists in modelling a building by overlapped layers, while it is not possible yet to build a central model-database, so that the information concerning the different disciplines of the building are collected in as many different models. Moreover, given the large amount of information collected in numerous documents, such as reports, datasheets and drawings, the fragmentation of the information is remarkably accentuated. It follows that there is a bigger container that aims to include all the information, which is the Common Data Environment. Below are discussed two case studies which illustrate the development of CDE that provides support for Facility Management operations, both for ordinary buildings and historic ones and using the “usBIM.platform” software, developed by the Italian firma ACCA software, company partner for the Ph.D program. It consists in developing structure of folders in which the workflows take place and is provided with different useful features. Thanks to the assignment of permissions, although all the files are uploaded on the platform, the visualization or the editing of the files are managed distinctly by each team member, depending on the role covered in the project. Some other features have been implemented, such as the #tagBIM, workflows and linking between documents, as explained more in detail in the following paragraphs.

5.2. UsBIM integrated system by ACCA software

The first example of Italian collaborative platform is usBIM.platform by ACCA software: it is a platform built to comply with the Codice Appalti and the decreto BIM that make the use of BIM technologies and processes mandatory for all public procurement, starting from 2019 and progressively by 2025. In addition to fully responding to the features of a collaborative platform as described above, usBIM.platform has additional important and useful features (Fig. 5.1):

Figure 5.1: usBIM integrated system by ACCA software [1]

- Archiving, monitoring, analysis of the most significant information of the building through dashboards and their georeferencing on BIM model in IFC format. (BIM Data Management) | *usBIM.data*;
- Organization of the space (CDE), the data and documents contained in the platform for the optimization of work activities | *usBIM.project*;
- Integration of the GIS systems with the platform to have available BIM data in the CDE, allowing the creation of ad hoc thematic maps and the constant updating of spatial information | *usBIM.gis*;
- Integration of the digital surveying process into the BIM process with the management of point cloud and textured mesh | *usBIM.pointcloud*;
- Online sharing of information and issues related to the project with the team members via the BIM model in IFC format | *usBIM.share*;
- Management and federation of IFC models of large and very large size | *usBIM.browser BIM2*;
- Generate professional renderings of shared model views on the platform directly online and in a very short time thanks to AI | *usBIM.rendering*;
- Navigation of shared models in IFC, EDF, RVT, SKP formats directly from the browser with real-time rendering and immersive virtual reality features, to check the effectiveness of the model and the presence of any conflicts | *usBIM.reality*;
- Create and edit documents produced with one of Microsoft's Office suite programs directly online in the browser, without the need for upload or download | *usBIM.office*;
- Creation and management of online documents (drafting of a report, description of the features of an object, notes, etc.) with a specific word processor integrated in the platform | *usBIM.writer*;
- Connection between building integrated IoT sensor technology and BIM model in IFC format uploaded on the platform: the data sent by the sensors make the BIM model 'as alive', which acquires continuously updated information and changes itself | *usBIM.IoT*;
- Creation and management of quantity take offs and accounting documents directly online in the platform | *PriMus*;
- Drafting and management of site safety plans directly online on the platform | *CerTus*;

Thanks to the storage and structured of models, documents and data in open formats (free Models, Documents and Data) within the platform, the BIM model can be visually navigable from the internet. Thus, the platform itself becomes a container of information greater than the BIM model (and that includes him). Data and documents are explored and managed in open structured formats linked to the model or its objects. The platform has therefore adopted the openBIM approach, i.e. a universal method for the development of collaborative design and the construction and management of buildings and infrastructure based on open standards and processes.

5.3. Four examples of the development of CDEs for the management of existing structures

Starting from national standards, such as the Norma Tecnica delle Costruzioni DM 17 gennaio 2018 and attached explanatory circular Circolare n°7 del 21 gennaio 2019, and international codes, such as Eurocode UNI EN 1998:2013, the processes traditionally performed and retraced with a digital approach have been analyzed. According to UNI 11337:2017 “Gestione digitale dei processi informativi delle costruzioni”, therefore, the processes have been developed in dedicated CDE from which it was possible to develop workflows, i.e. structured protocols for a more efficient exchange of information between the several actors involved. Below are four examples of CDEs developed concerning the structural engineering procedures usually applied to existing buildings and appropriately transposed in digital way. The four cases analyzed are the following:

- Case 1: Survey on existing structures
- Case 2: Seismic vulnerability assessment of existing buildings
- Case 3: Structural retrofit interventions on a building with restrictions
- Case 4: Structural and architectural retrofit interventions

These examples have been implemented on usBIM.platform as described below.

5.3.1. Case 1: Survey on existing structures

The CDE has been structured by identifying the 4 working areas according to the UNI11337 standards (*Work in Progress* - *Shared* - *Published* - *Archive*), each of which has been divided into the 3 disciplines involved in the process, i.e. survey, architecture and structure. In particular, the *Survey* folder contains all the documents and files produced during this phase, such as photos, drawings, and notes, divided according to the type of file. According to the aim of the survey (architectural purposes or structural purposes), all the models, drawings and report produced are placed in the *Architecture* and *Structure* areas defined (Fig. 5.2).

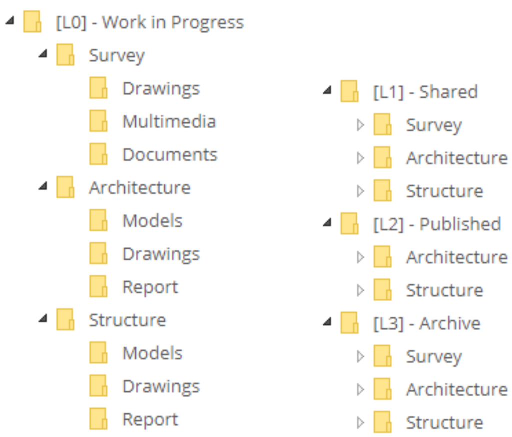


Figure 5.2: CDE folder structure for a process of survey on existing buildings

In order to support this process, 3 workflows have been defined, in which are listed all the steps to follow in order to carry out digital survey operations using photogrammetry and laser-scanning techniques, or even a more traditional approach, so that it can adapt to survey method chosen by the specific case. Therefore, in Fig. 5.3-5.4 are illustrated all the details of the workflows. For each of the steps have been summarized the permissions assigned to the working areas, the annotations implemented and the ACDat folders considered. For the assignment of the permissions to the steps, with E is indicated a permission for the execution of the activity while with V the only its visualization (Tab. 5.1-5.3).

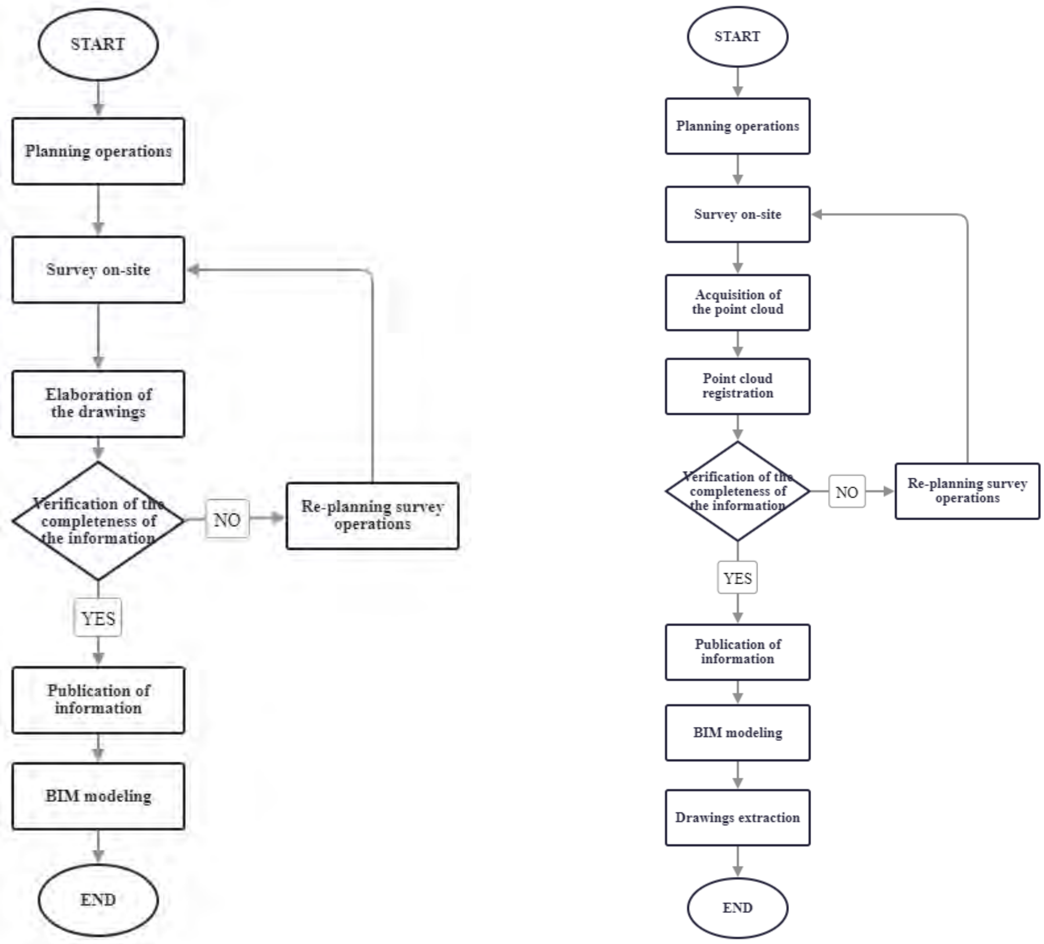


Figure 5.3: Workflow for traditional survey (left), workflow for digital survey (right)

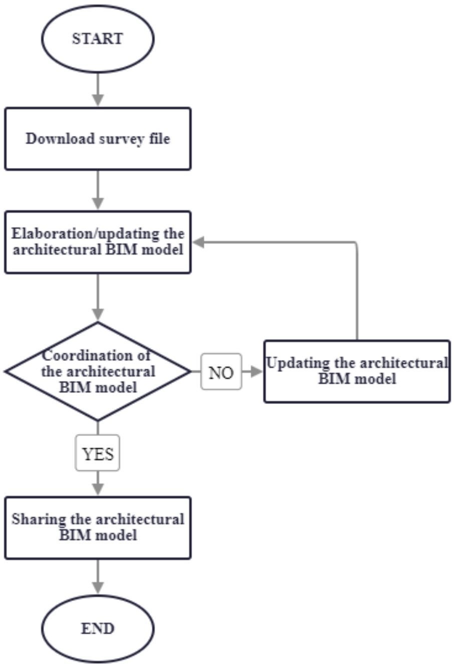


Figure 5.4: Workflow for architectural modeling

Table 5.1: Details of the steps of the workflow for traditional surveying of existing buildings

Workflow 1: Traditional survey			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Planning operations	Survey technitian (E)	-	-
Preparation of the devices	Survey technitian (E)	-	-
Survey on-site	Survey technitian (E)	-	Work in Progress - Survey
Drawings elaboration	Survey technitian (E)	Development of plans, elevations and sections	Work in Progress - Survey
Verification of the completeness of the information	BIM Coordinator (E) Survey technitian (V)	-	Shared - Survey
Publication of information	BIM Coordinator (E)	-	Published - Survey
BIM modeling	BIM modeler (E)	-	Work in Progress - Structure Work in progress - Architecture
Re-planning survey operations	Survey technitian (E)	-	-

Table 5.2: Details of the steps of the workflow for digital surveying of existing buildings

Workflow 2: Digital survey			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Plan operations	Survey technitian (E)	-	-
Preparation of the devices	Survey technitian (E)	-	-
Survey on-site	Survey technitian (E)	-	Work in Progress - Survey
Acquisition of the point cloud	Survey technitian (E)	Point cloud elaboration	Work in Progress - Survey
Point cloud registration	Survey technitian (E)	Elaboration of plants, elevations and sections	Work in Progress - Survey
Verification of the completeness of the information	BIM Coordinator (E) Survey technitian (V)	-	Shared - Survey
Publication of information	BIM Coordinator (E)	-	Published - Survey
BIM modeling	BIM modeler (E)	-	Work in Progress - Structure Work in progress - Architecture
Re-planning survey operations	Survey technitian (E)	-	-

Table 5.3: Details of the steps of the workflow for the elaboration of the architectural BIM model

Workflow 3: Architectural modeling			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Download survey file	Architectural BIM modeler (E)	-	Shared - survey
Elaboration/updating the architectural BIM model	Architectural BIM modeler (E)	-	Work in Progress - Architecture
Coordination of the architectural BIM model	BIM Coordinator (E) Architectural BIM modeler (V)	LC1	Work in Progress - Architecture
Sharing the architectural BIM model	BIM Coordinator (E)	-	Shared - Architecture
Updating the architectural BIM model	BIM Coordinator (E) Architectural BIM modeler (V)	-	Work in Progress - Architecture

5.3.2. Case 2: Seismic vulnerability assessment of existing buildings

The CDE has been structured by identifying the 4 working areas according to the UNI11337 standards (Work in Progress - Shared - Published - Archive), each of which has been divided into the 2 disciplines involved in the process, i.e. survey, and structure. In particular, the Survey folder contains all the documents and files produced during this phase divided into those relating to the survey of the geometry, performed by the expert surveyor, and the on-site tests and investigations under the responsibility of a technical operator, which could result in separate figures with different permissions within the CDE. In the Structure area are collected models, processes and reports produced during the seismic vulnerability assessment (Fig. 5.5).

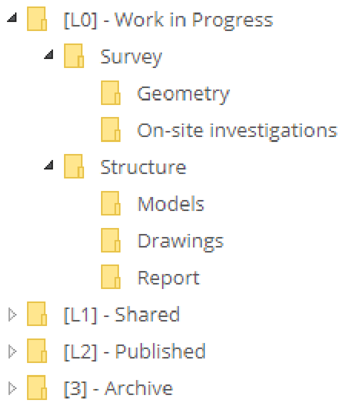


Figure 5.5: CDE folder structure for a process of seismic vulnerability assessment of existing buildings

To support this process, 3 workflows have been defined (showed in Fig. 5.6), in which are listed all the steps to carry out the operations of digital or traditional survey, structural modeling and seismic vulnerability assessment. For each of the steps have been summarized the permissions assigned to the working areas, the annotations implemented and the ACDat folders considered. For the assignment of the permissions to the steps, with E is indicated a permission for the execution of the activity while with V the only its visualization (Tab. 5.4-5.6).

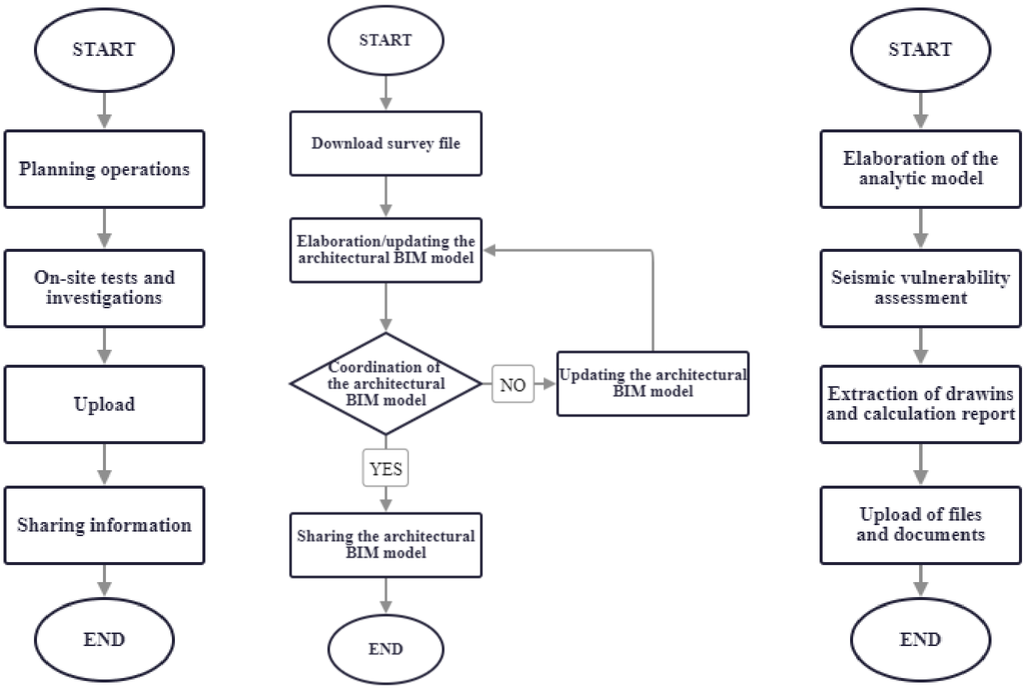


Figure 5.6: From left to right: workflow for tests and investigations, structural modeling and seismic vulnerability assessment

Table 5.4: Details of the steps of the workflow for the geometrical survey and on-site investigations

Workflow 1: Geometrical survey and on-site investigations			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Planning operations	Technical oeprator (E) Survey technitian(E)	-	-
On-site tests and investigations	Technical oeprator (E) Survey technitian(E)	-	-
Upload	Technical oeprator (E) Survey technitian(E)	-	Work in progress - Geometry Work in progress - on-site investigations
Information sharing	Technical oeprator (E) Survey technitian(E)	-	Shared - Geometry Shared - on-site investigations

Table 5.5: Details of the steps of the workflow for the elaboration of the structural BIM model

Workflow 2: Structural modeling			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Download survey file	Structural BIM modeler (E)	-	Shared - survey
Elaboration/updating the architectural BIM model	Structural BIM modeler (E)	-	Work in Progress - Structure
Coordination of the architectural BIM model	BIM Coordinator (E) Structural BIM modeler (V)	LC1	Work in Progress - Structure
Sharing the architectural BIM model	BIM Coordinator (E)	-	Shared - Structur
Updating the architectural BIM model	BIM Coordinator (E) Structural BIM modeler (V)	-	Work in Progress - Structure

Table 5.6: Details of the steps of the workflow for the seismic vulnerability assessment

Workflow 3: Seismic vulnerability assessment			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Elaboration of the analytic model	Structural engineer (E)	-	Work in Progress - Structure
Seismic vulnerability assessment	Structural engineer (E)	-	Work in Progress - Structure
Extraction of drawings and calculation report	Structural engineer (E)	Extraction of reports and calculations	Work in Progress - Structure
Upload of files and documents	Structural engineer (E)	-	Published - Structure

5.3.3. Case 3: Structural retrofit interventions on a building with restrictions

The CDE has been structured by identifying 3 working areas according to the UNI11337 standards (*Work in Progress* - *Published* - *Archive*), each of which has been divided into 2 disciplines involved in the process, i.e. survey and structure. The working phase L1 (*Shared*) has not been considered because in this specific case the processes are linear and do not provide for iterations of information exchange between disciplines. In particular, the *Survey* working area contains all the documents and files produced during this phase divided into those relating to the geometrical survey, performed by the expert surveyor and the on-site tests and investigations under the responsibility of a technical operator, which could result in separate figures with different permissions within the CDE. In the *Structure* area are collected models, processes and reports produced during the structural BIM modeling and subsequent planning of structural retrofit interventions (Fig. 5.7).

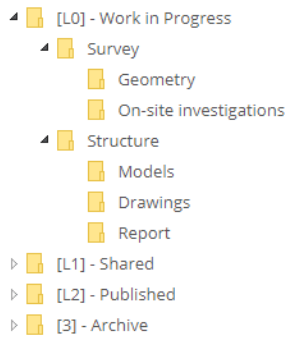


Figure 5.7: CDE folder structure for a process of structural retrofit interventions on a bounded building

In order to support this process, 3 workflows have been defined, illustrated in Fig. 5.8, in which are listed all the steps to follow to carry out for the operations of survey (with a digital or a traditional approach), structural modeling and structural retrofit interventions. It has to be noticed that since the target building is subject to historical and architectural constraints, it is appropriate that at the end of the project of the intervention it is verified that it complies with municipal regulations and regional and national laws. These operations are part of the code checking that is the final step of the process. For each of the steps have been summarized the permissions assigned to the working areas, the annotations implemented and the CDE folders considered. For the assignment of the permissions to the steps, with E is indicated a permission for the execution of the activity while with V the only its visualization (Tab. 5.7-5.9).

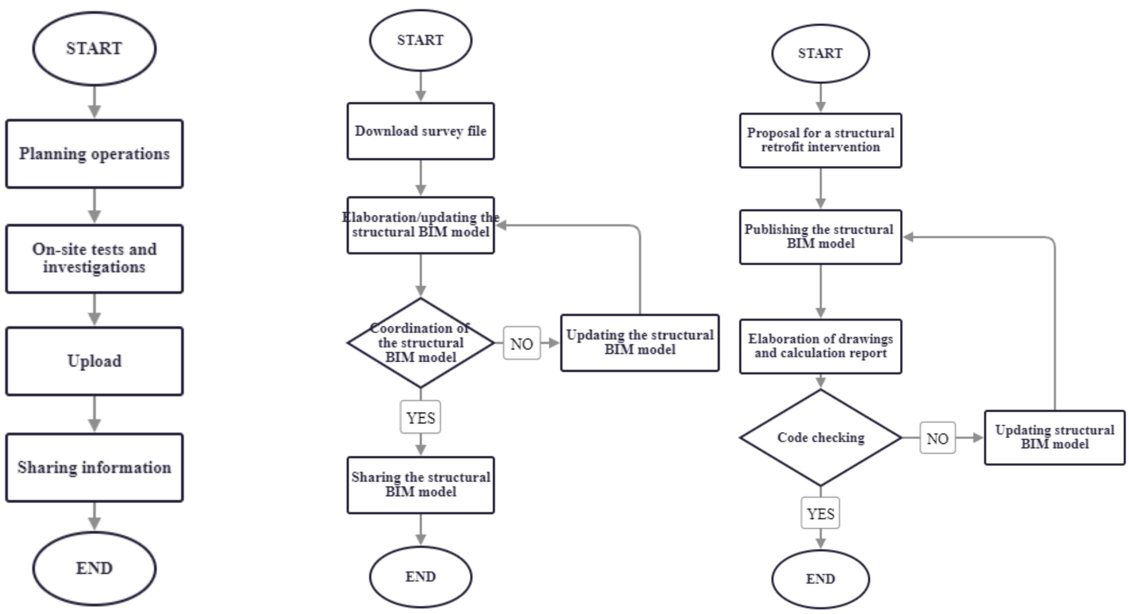


Figure 5.8: From left to right: workflow for survey operations, structural modeling and structural retrofit interventions

Table 5.7: Details of the steps of the workflow for the geometrical survey of the building and on-site investigations

Workflow 1: Survey of the building and on-site investigations			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Planning operations	Technical operator (E) Survey technitian (E)	-	-
Geometrical survey and on-site investigations	Technical operator (E) Survey technitian (E)	-	-
Upload	Technical operator (E) Survey technitian (E)	-	Work in Progress - Survey
Information sharing	Technical operator (E) Survey technitian (E)	-	Work in Progress - Survey

Table 5.8: Details of the steps of the workflow for the elaboration of the structural BIM model

Workflow 2: Structural modeling			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Download survey file	Structural BIM modeler (E)	-	Shared - survey
Elaboration/updating the structural BIM model	Structural BIM modeler (E)	-	Work in Progress - Structure
Coordination of the structural BIM model	BIM Coordinator (E) Structural BIM modeler (V)	LC1	Work in Progress - Structure
Sharing the structural BIM model	BIM Coordinator (E)	-	Shared - Structur
Updating the structural BIM model	BIM Coordinator (E) Structural BIM modeler (V)	-	Work in Progress - Structure

Table 5.9: Details of the steps of the workflow for the structural retrofit interventions

Workflow 3: Structural retrofit interventions			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Proposal for a structural retrofit intervention	Structural BIM modeler (E)	-	Work in Progress - Structure
Publishing the structural BIM model	Structural BIM modeler (E)	-	Published - Structure
Extraction of drawings and calculation report	Structural BIM modeler (E)	-	Published - Structure
Code checking	BIM Coordinator (E)	Verification of consistency with municipal regulations, regional and national laws	Published - Structure
Updating structural BIM model	Structural BIM modeler (E)	Updating the structural BIM model with structural interventions	Work in progress - Structure

5.3.4. Case 4: Structural and architectural retrofit interventions

The CDE has been structured by identifying 4 working areas according to the UNI11337 standards (*Work in Progress* - *Shared* - *Published* - *Archive*), each of which has been divided into the 3 disciplines involved in the process, i.e. survey, architecture and structure. Differently from the previous case, the working phase L1 (*published*) was considered because of the need for iterations in the exchange of information between the structural and architectural disciplines before reaching convergence around a common and shared design idea. This exchange of information takes place precisely in the *shared* area. In particular, the *Survey* working area contains all the documents and files produced during this phase divided into those related to the survey of geometry, performed by the expert surveyor, the on-site tests and investigations under the responsibility of a technical operator, which could result in separate figures with different permissions within the CDE. In the *Architecture* and *Structure* areas are collected models, drawings and reports produced during the structural BIM modeling and the subsequent planning of structural and architectural retrofit intervention operations (Fig. 5.9).

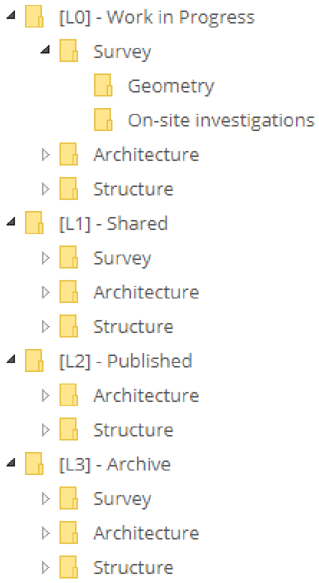


Figure 5.9: CDE folder structure for a process of structural and architectural retrofit intervention

To support this process, 6 workflows have been defined, as illustrated in Fig. 5.10-5.11, in which are listed all the steps to follow in order to carry out surveying operations (with a digital or a traditional approach), modeling and planning of structural and architectural retrofit interventions. A further workflow has been implemented for the publication of the intervention due to the introduction of the L1 processing level, not considered in the previous case. For each of the steps have been summarized the permissions assigned to the working areas, the annotations implemented and the CDE folders considered. For the assignment of the permissions to the steps, with E is indicated a permission for the execution of the activity while with V the only its visualization (Tab. 5.10-5.15).

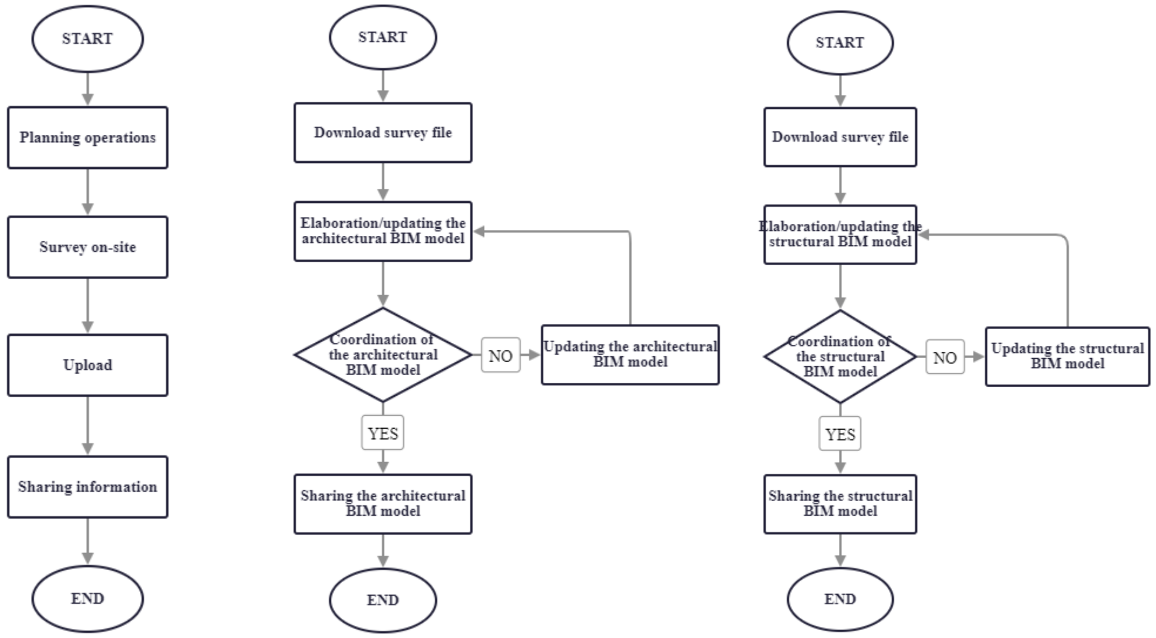


Figure 5.10: From left to right: workflow for survey operations, for architectural BIM modeling, and for structural BIM modelling

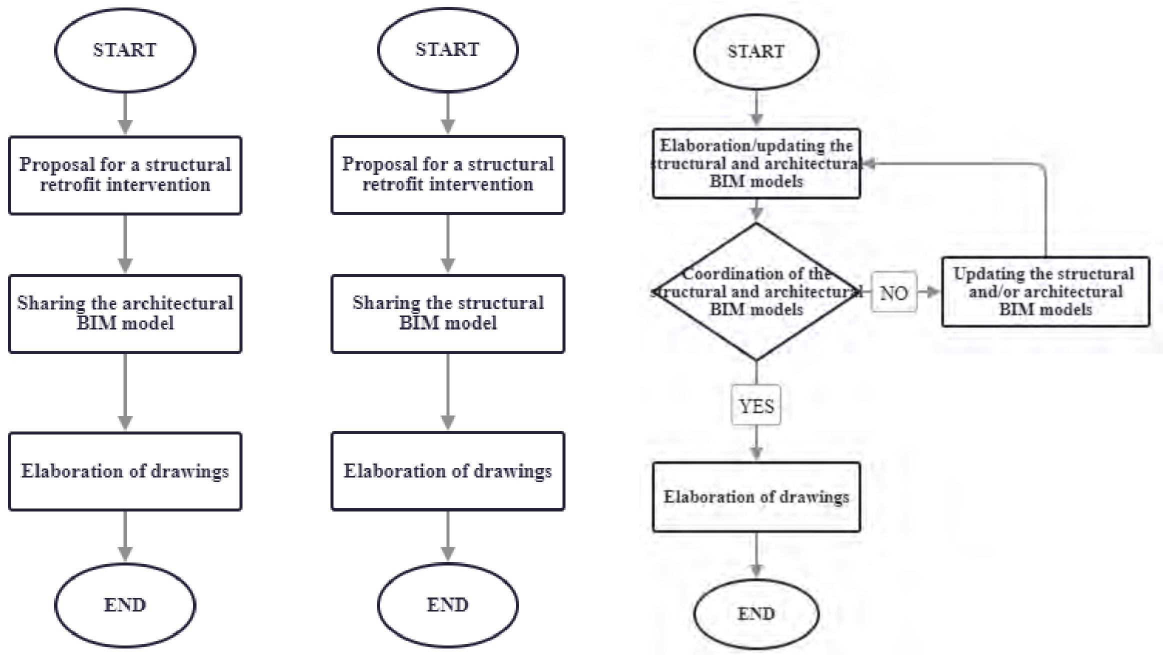


Figure 5.11: From left to right: workflow for architectural retrofit intervention, for structural retrofit intervention and for publishing the retrofit interventions.

Table 5.10: Details of the steps of the workflow for the geometrical survey and on-site investigations

Workflow 1: Geometrical survey of the building and on-site investigations			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Planning operations	Technical operator (E) Survey technitian (E)	-	-
Geometrical survey and on-site investigations	Technical operator (E) Survey technitian (E)	-	-
Upload	Technical operator (E) Survey technitian (E)	-	Work in Progress - Survey
Information sharing	Technical operator (E) Survey technitian (E)	-	Work in Progress - Survey

Table 5.11: Details of the steps of the workflow for the elaboration of the architectural BIM model

Workflow 2: Architectural modeling			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Download survey file	Architectural BIM modeler (E)	-	Shared - survey
Elaboration/updating the architectural BIM model	Architectural BIM modeler (E)	-	Work in Progress - Architecture
Coordination of the architectural BIM model	BIM Coordinator (E) Architectural BIM modeler (V)	LC1	Work in Progress - Architecture
Sharing the architectural BIM model	BIM Coordinator (E)	-	Shared - Architecture
Updating the architectural BIM model	BIM Coordinator (E) Architectural BIM modeler (V)	-	Work in Progress - Architecture

Table 5.12: Details of the steps of the workflow for the elaboration of the structural BIM model

Workflow 3: Structural modeling			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Download survey file	Structural BIM modeler (E)	-	Shared - survey
Elaboration/updating the architectural BIM model	Structural BIM modeler (E)	-	Work in Progress - Structure
Coordination of the architectural BIM model	BIM Coordinator (E) Structural BIM modeler (V)	LC1	Work in Progress - Structure
Sharing the architectural BIM model	BIM Coordinator (E)	-	Shared - Structur
Updating the architectural BIM model	BIM Coordinator (E) Structural BIM modeler (V)	-	Work in Progress - Structure

Table 5.13: Details of the steps of the workflow for the elaboration of the architectural retrofit intervention

Workflow 4: Architectural retrofit intervention			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Upload the architectural BIM model	Architect (E)	-	Work in Progress - Architecture
Proposal for an architectural retrofit intervention	Architectural BIM modeler (E)	-	Work in Progress - Architecture
Sharing the proposal for the architectural retrofit intervention	Architectural BIM modeler (E)	-	Shared - Architecture

Table 5.14: Details of the steps of the workflow for the elaboration of the structural retrofit intervention

Workflow 5: Structural retrofit intervention			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Upload the structural BIM model	Structural engineer (E)	-	Work in Progress - Structure
Proposal for a structural retrofit intervention	Structural BIM modeler (E)	-	Work in Progress - Structure
Sharing the proposal for the structural retrofit intervention	Structural BIM modeler (E)	-	Shared - Structure

Table 5.15: Details of the steps of the workflow for the publication of the retrofit interventions

Workflow 6: Publication of the retrofit interventions			
STEP	**PERMISSIONS**	**ANNOTATIONS**	**CDE WORING AREA**
Elaboration/updating the architectural and structural BIM models	BIM Coordinator (E)	-	Shared - Architecture Shared - Structure
Coordination of the structural and architectural BIM models	BIM Coordinator (E) BIM modelers (V)	LC2 + LC3	Shared - Architecture Shared - Structure
Publication of the structural and architectural BIM models	BIM Coordinator (E)	-	Published - Architecture Published - Structure
Updating the structural and/or architectural BIM models	BIM Coordinator (E) BIM modelers (V)	-	Work in progress - Architecture Work in progress - Structure

The above application cases illustrate the development of information exchange protocols for existing buildings. In the following paragraphs, these processes will be analyzed in more detail thanks to applications on real case studies of both common buildings, in a simplified way, and historical buildings, in a more rigorous way.

5.4. The #TagBIM in the CDE for the management of applicative case studies

Some of the processes analyzed above have been applied in the following case studies, thanks to the availability of the necessary documentation useful to simulate real processes. In detail, a case study has been analyzed during the period spent in Germany, concerning an ordinary building used as an office building, up to the management of complex historical buildings, characterized by the production of a considerable amount of data, analyzed during the internship period spent in the company ACCA software.

Actually, while developing these case studies, some of the difficulties analyzed in paragraph 4.3 were faced, such as the management of information that is not currently coded in the IFC standard up to the management of documents not extracted from the model but related to it. The developments made are aimed precisely at the definition of new digital archives, which represent a natural evolution of the traditional paper-based archives thanks to the use of new computer applications, and which have the great advantage of allowing a direct search for information in any source they contain, i.e. drawings, reports, models, etc..

For this purpose, markers called #tagBIM have been developed by CCA software and introduced; they consist of structured alphanumeric strings containing attributes (#Tag), which can be added as metadata to documents and objects of a BIM model.

These alphanumeric code strings are inserted directly into the IFC schema, and are therefore likely to be integrated into openBIM processes, and will also be incorporated into national standard UNI11337-2. They offer the opportunity to quickly input or extract information about BIM objects directly into the IFC model.

In summary, we can say that the use of #TagBIM strings has many advantages:

- is an open format, can be written with any text editor, and can be read and easily interpreted by both the computer and the technitians;
- can be stored in any database and easily managed by any software;
- is extremely flexible and scalable (does not require predefined and rigid structures);
- offers very modern search and indexing methods with the use of #Tags (see Google, Facebook, etc.).

In fact, this indicator offers an opportunity for digitization of information very flexible, and alternative to the rigid parameterization provided by the IFC scheme, which can be very useful for the management of existing buildings, as the processes that characterize them are less akin to the logic of standardization.

5.4.1 CDE for ordinary buildings (case study: Deutsche Bahn building)

The case study for this commitment was provided by an industrial customer, i.e. is the Leipzig branch of "Deutsche Bahn – DB Immobilien", thanks to the collaboration carried out during the study period spent in Germany, with the supervision of Professor Rossi-Schwarzenbeck's research group of German University Hochschule für Technik, Wirtschaft und Kultur - HTWK Leipzig.

HTWK Hochschule für Technik, Wirtschaft und Kultur Leipzig

Figure 5.12: HTWK logo

5.4.1.1 The client

Deutsche Bahn AG (DB) is a German railway company based in Berlin. The company, owned by the Federal Republic of Germany, is the largest railway operator and the largest infrastructure manager in Germany, and is also active in other countries. The company's structure is pyramidal and

DB

Figure 5.13: Deutsche Bahn logo

includes several subsidiaries whose names and specific expertise are subject to continuous change but which can be traced back to three specific groups of interest:

- DB Netz AG, DB Station und Service and DB Energie, as operators of the railway infrastructure;
- DB Fernverkehr or DB Regio, as passenger railway companies;
- DB Cargo and DB Schenker, as Logistic and freight transport companies.

5.4.1.2 The commitment and the case study

During an initial briefing, Deutsche Bahn operators expressed their need to experience the advantages of the digitization of the internal business processes, given the upcoming transition to BIM methods. More in detail, their interest related to the management of existing buildings and tools that give support to the Facility Management (FM) operations, so that an office building (Fig. 5.14) was granted as case study settled in Rackwitzer Straße 3 (Leipzig).

Figure 5.14: Office building in Rackwitzer Straße 3 (Leipzig)

In order to carry out the assigned task, free access to the business archives containing the preserved documentation has been guaranteed. Among this, the technical reports of surveys carried out in 2006 and 2009 with a clear identification of the damages detected, the plants with the representation of the firefighting system, and the elevations has been selected which proved to be enough to define the spatial organization of the building and to obtain information pertaining any technical aspects (Fig. 5.15).

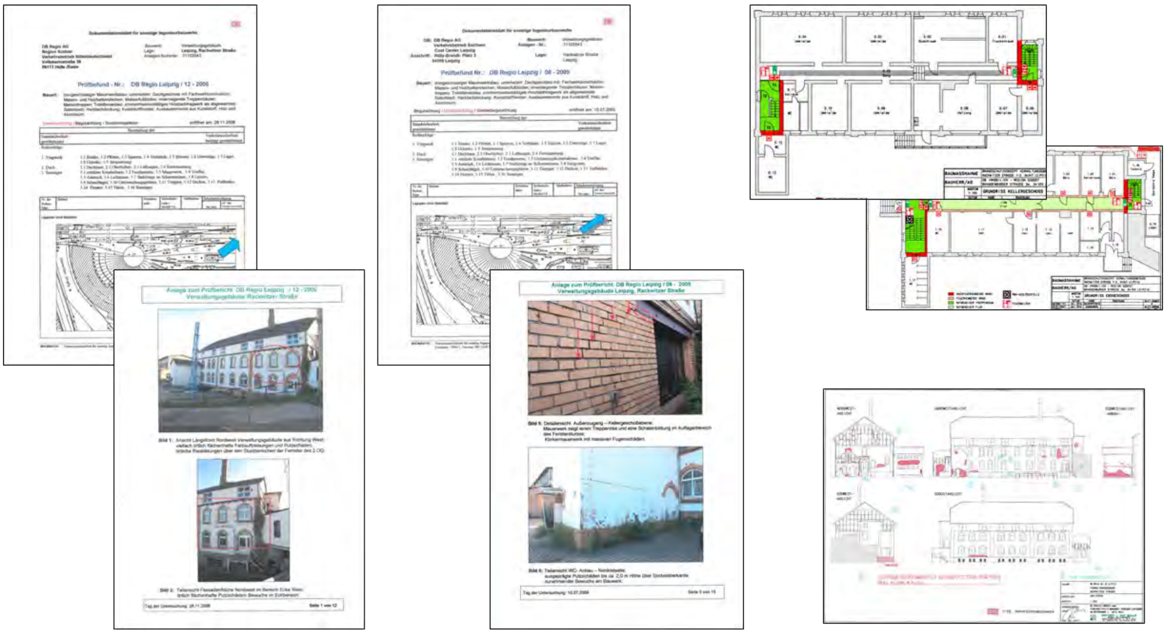


Figure 5.15: Damage report, plants and elevations of the building in Rackwitzer Straße 3 (Leipzig)

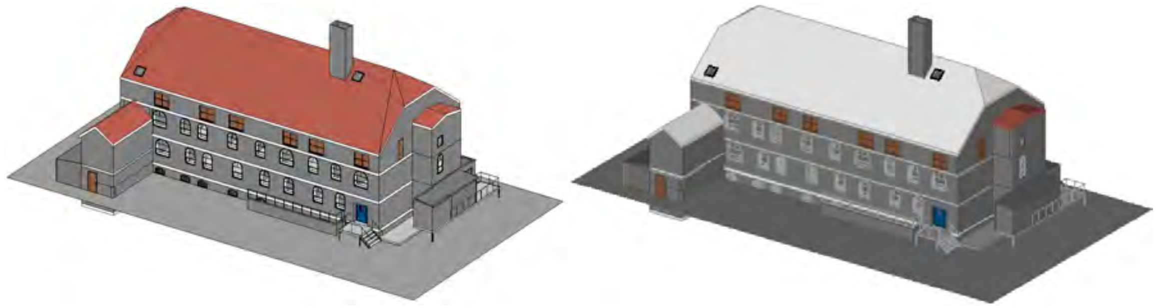
5.4.1.3 The approach used

The application experienced consists in the creation of an Asset Information Model (AIM), that corresponds to the building virtualization in its as-is state. In fact, the BIM model has been used as a central database in which all the information available have been added, regardless of the nature of information sources (reports, documents, etc.). The folder structure consisted of 5 working areas:

- an “Incoming” area, in which all the documentation, once digitalized, was uploaded;
- a “Work In Progress” area, accessible just by the architectural BIM modeler (i.e. the only discipline involved in the commitment);
- a “Shared” area, in which the documentation was shared with the client;
- a “Published” area, in which the final and correct documentation was uploaded;
- an “Archive” area.

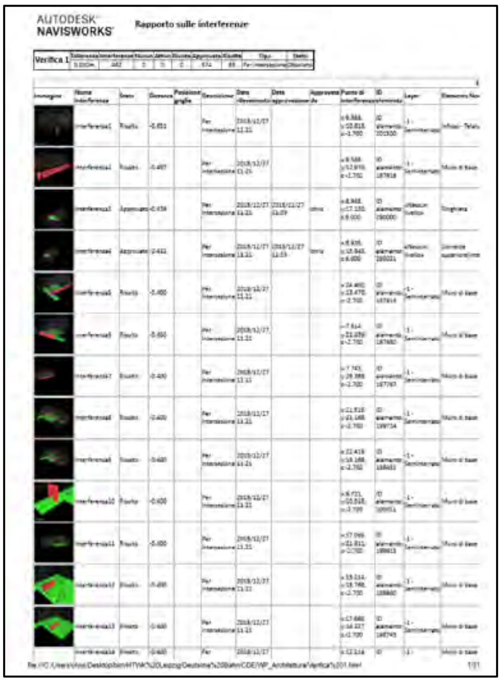
Taking advantage of the linking function available on the platform, a smart BIM environment easy to handle by both the technical experts in the matter and the client was developed. The procedure implemented was aimed at finding a more suitable way of managing the information available rather than performing further operations. Form a first analysis of the documentation, it was observed that drawings were uncoordinated because the upward direction of the stairs changed in the plants of consecutive levels, but it was a mere misrepresentation as it certainly was not possible in reality. As there were both wrong and missing information in the documents, a survey of the building was required in order to define the correct spatial organization of the building and create an architectural BIM model which really represented the building. All the documents uploaded into the CDE were marked with the #tagsBIM, an indicator that provide a very fast way of researching information into documents and models, concerning date of delivery. Moreover, the photos with the evidences of the damages affecting the building were extracted from the report and re-uploaded into the CDE, adding further #tagBIM pertaining the source of degradation, the affected areas, and the dates of shooting.

The BIM model was uploaded in the WIP area (Work In Progress) as the modelling process progressed both in proprietary format and IFC format. The entire procedure explained below was performed using the IFC file, so that a perfect openBIM methodology was implemented while the proprietary format was uploaded just to avoid any loss of information (Fig. 5.16).



a) b)

Figure 5.16: Architectural BIM model of the building in Rackwitzer Straße 3 (Leipzig) in a) .rvt format and b) in .ifc format



AUTODESK NAVISWORKS

Rapporto sulle interferenze

Figure 5.17: Report of the interference analysis carried out with Autodesk Navisworks

Once the BIM model was built, it was checked with Autodesk Navisworks to verify if any mistake may have occurred, performing a Level of Coordination 1 (LC1). Being both Revit and Navisworks software belonging to the same Autodesk Inc. software house, the exchange of information was optimal using only the proprietary format (.rvt). A total of 462 interferences were detected (Fig. 5.17) but not all of them were relevant. The interferences were classified basing on their importance; more in detail, 374 of them were considered "approved", as not significant, but 88 were real mistakes, so that they have been "solved". The operation was documented with an interferences report, in which are showed an image for each interference and its classification (in approved or solved). The final version of the model was finally moved in the "Published" area and was used for the implementation of the Virtual Reality with the Voyager application, developed by ACCA software. It consists in a cloud area in which the IFC format was uploaded, so that using a link the model was remotely navigable with just a mobile-phone or VR-glasses. In follows that it was easier to visualize all the object of the model that need to be maintained. The IFC model settled in Published has been used as a central database for the connection of all the information. More in detail, each element was linked with all the images that captured it and marked with #tagsBIM pertaining the source of degradation and the affected area. The #tagsBIM were structured as follows:

#Source_of_degradation=Affected_area

i.e. #Water_infiltration=Wall, #Exposition_intermperies=Wooden_trusses, #Exfoliation=Plaster.

The last application concerns the implementation of workflows to monitor the progress of the Level of Development (LoD) the Level of Information (LoI) of the model during the modelling process. The American scale of LoD and LoI developed by the AIA was considered, as suggested by the company's guideline. At the end of the entire process were reached a LoI 400, that consists in the as-built status, and a LoD 200. As not all the objects were modelled with the same degree of detail, the minimum LoD was considered for the entire model, while in a more detailed description could be distinguished the degree of detail for each type of object. The LoD rached a low level since in the object libraries available not all the object placed in the building were found, and, for reaching a higher LoD, more advanced knowledge should be needed for creating customized object families (Fig. 5.18).

Figure 5.18: workflow for the progression of LoD and LoI

5.4.1.4 Results

Repeating the #tagBIM operation for all sources of damage, a digital list of damages was automatically generated by the platform, suitable for finding the element damaged within the model. As a result, ticking on a box all the element affected by specific source of damage were rapidly found and highlighted in the model. In the same way, ticking two or more boxes the information was crossed and the element affected at the same time by different pathologies were detected (Fig. 5.19).

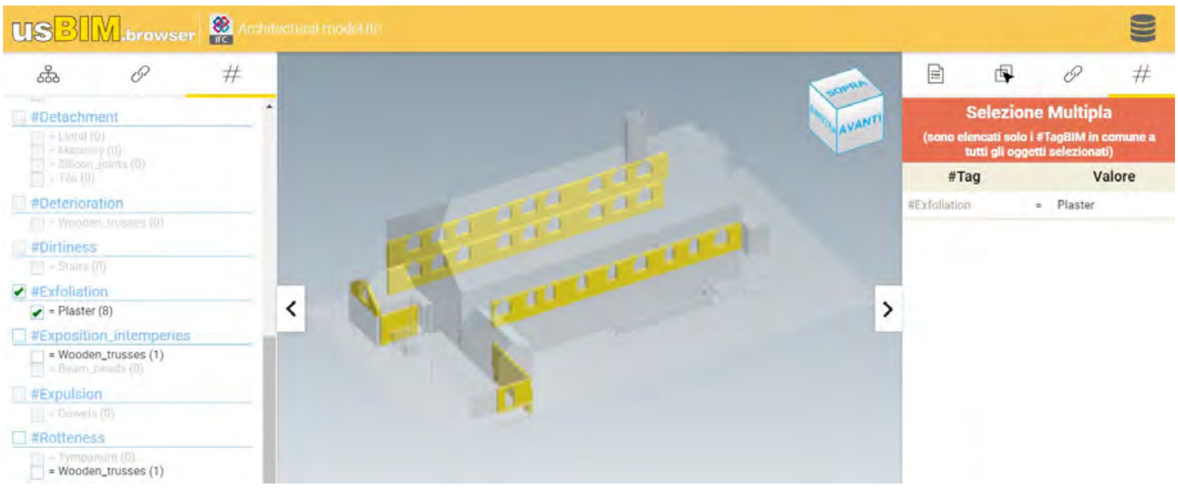


Figure 5.19: Digital list of the damages detected in the building in Rackwitzer Straße 3 (Leipzig)

Clicking on the target object, the photos taken in the past years could be visualized and help the diagnosis process thanks to real views of the building (Fig. 5.20).

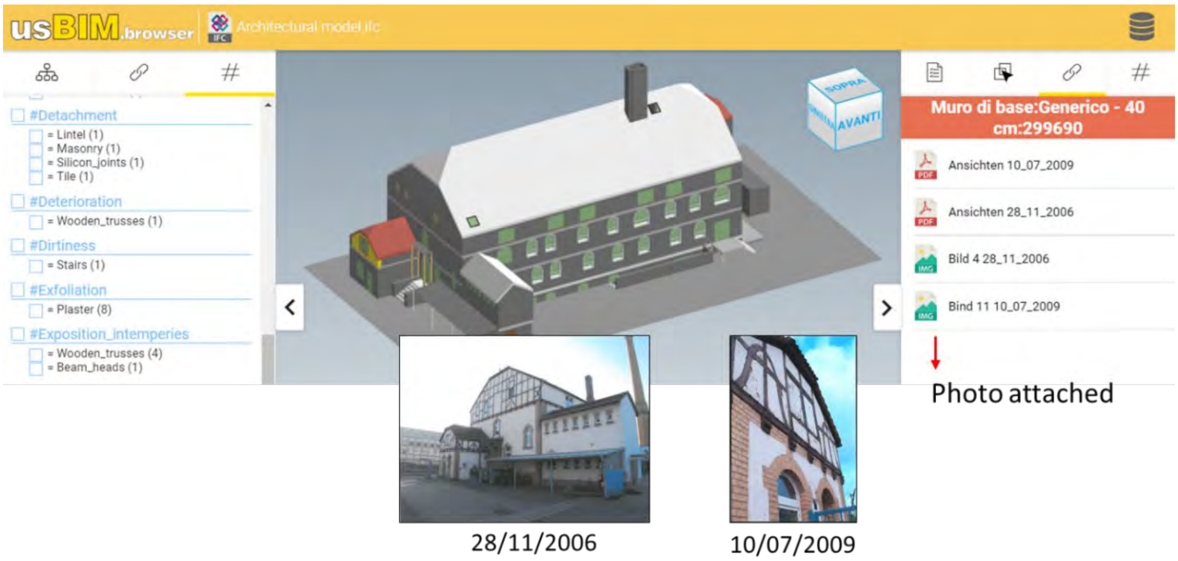


Figure 5.20: Linking information on the BIM model of the building in Rackwitzer Straße 3 (Leipzig)

In a similar way was managed even the documentation. Marking the documents with the #tagBIM concerning the year of delivery (in the specific case) and the degradations reported, a fast research among all the documents uploaded on the platform can be executed (Fig. 5.21).

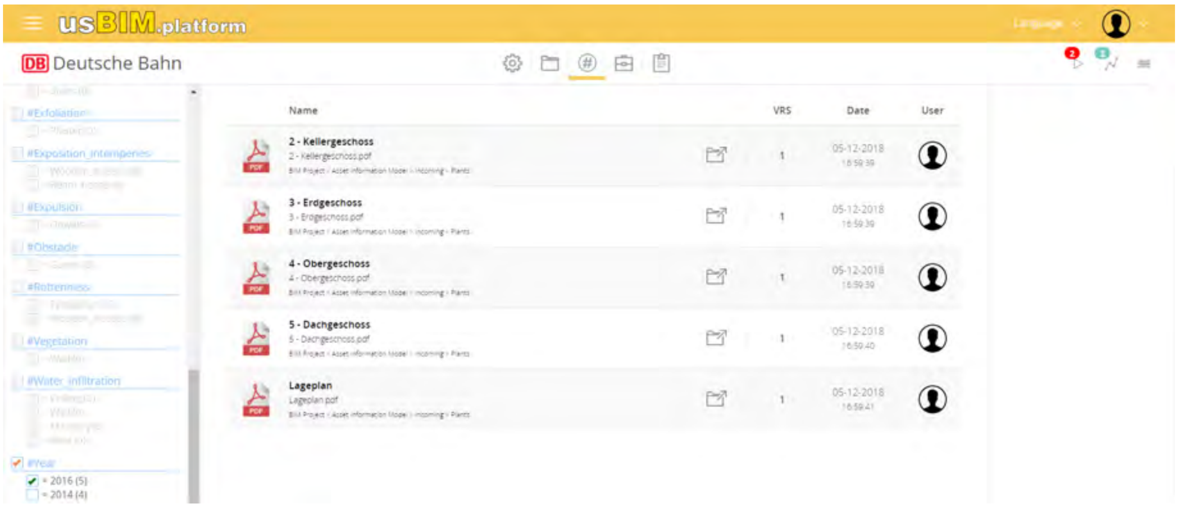


Figure 5.21: #tagBIM for the documents of the building in Rackwitzer Straße 3 (Leipzig)

5.4.1.5 Discussion

The application illustrated above showed how the communication of information related to existing buildings is rather simplified and improved with the implementation of the CDE. In particular, a digital archive has been created containing all the documents related to the building with the aim of finding a solution that could potentially replace the classic bulky and difficult to manage paper-based archives. Moreover, any of the functionalities provided by the platform were exploited to further improve the use of information:

- setting links between the documents placed I the CDE and the model’s objects is ensured a smarter fruition of both of them;
- the implementation of #tagsBIM on the documents turned out to be very useful to “google” information contained in the documents with a search engine;
- the implementation of #tagsBIM on the BIM objects allow to add relevant information on the model that is not directly coded in the IFC format. In the specific case analyzed, a list of the damage detected on the building was created.

5.4.2 CDE for historical buildings (case study: Palazzo Penne)

5.4.2.1 Framework of the activity

The case study discussed below was analyzed within the activities of the research project BIM ReCult (BIM Methodology for Cultural Heritage retrofit – trad. *Il metodo BIM per il Recupero del patrimonio Culturale*) which aimed to apply the BIM methodology to monumental buildings. It is a methodology defined HBIM, which stands for Heritage Building Information Modeling, that takes advantage to the creation of a specially dedicated platform that supports all decision-making phases including those related to the maintenance, upgrading and management of the asset. More in detail, the applications developed can be implemented within the entire process thanks to the creation of an HBIM model. Starting from the knowledge phase of the asset, the historical studies pertaining the different construction phases were analyzed, including the stratigraphy, transformations, etc., which characterize almost the totality of the national historical building. Subsequently, campaigns of in situ surveys, geometric surveys using more or less advanced manual and digital tools (laser scanner, total station, etc.) combined with inspections, more or less invasive, (samples, thermography, geo-radar, etc.) lead to the geometric construction of the model, which increases its information content, pertaining no longer just geometrical data.

Figure 5.22: STRESS S.c.a.r.l. logo

The project included the development of ad hoc methodologies for digital management and interoperability of process information. In fact, the "Information Delivery Manual" (IDM) and a "Model View Definition" (MVD) were also developed for the platform, according to the international standard ISO 29481. From an IT point of view, a server infrastructure has been studied for the digital platform, able to manage Big Data coming from complex historical and monumental buildings. It is thus composed of an interoperable and holistic system of collection, storage and analysis of the data of the historical monumental building for its management throughout its entire life cycle. During the project, software applications were developed to visualize and query the HBIM models even with a simple smart device (e.g. tablet). The HBIM models, through these

Figure 5.23: ACCA software S.p.A. logo

applications, were used through augmented reality (AR) tools to offer immersive experiences, useful to support policies of incentives and enhancement of the cultural heritage sector.
The working group consisted in the following academic and industrial partners:

- ACCA software S.p.A., software house responsible for the development of software applications and industrial partner of the doctorate;
- STRESS S.c.a.r.l., a non-profit consortium company, founded in Naples in 2010, with the aim of promoting innovation as a qualifying element of the construction industry;
- ETT solutions S.p.A., company specialized in providing virtual and augmented reality services;
- Università degli studi di Napoli Federico II, composed of a joint working group of structural engineers and architects for the definition of the specifications of the BIM methodology.

Figure 5.24: ETT solutions S.p.A. logo

5.4.2.2 The case study of Palazzo Penne

The application of the new methodology proposed, has been experienced in occasion of Palazzo Penne's renovation, a renaissance masonry palace located in the historical center of Naples and built in 1406. The renovation project was elaborated a few years ago in the traditional way so that the interventions will have to start soon. Indeed, a digital and innovative method for the information management has been simulated, thanks to the extensive and accurate documentation available relating to all the phases of the project, which goes from the acquisition of information on mechanical properties of the materials and the geometry of the construction up to the design of retrofit interventions.
The building is an example of civil habitation of XV century, one of the few constructions that did not collapsed after the devastating earthquake of 1456. Several changes of the building have undergone several time, as witnessed by the walled arches and the slabs built with different construction systems, such as wooden, steel, and reinforced concrete. The complex has been dived into three Minimal Unit of Intervention (MUI) that is a part of a construction consisting in uniform structural unit subject to the same retrofit interventions. Moreover, the number of levels results variable even for each MUI, because of the presence of lofts that raise the complexity of the building. Actually, the difficulties acknowledged in Palazzo Penne (Fig. 5.25) are rather common in the cultural heritage, so that it can be considered representative of a big amount of buildings. Indeed, due to the complexity and the importance of this construction, a workflow was developed taking into account all the difficulties in its management can result an accurate and transparent example for the information management. The aim of this process is to create adequate guidelines to improve the management of the existing buildings.

Figure 5.25: Palazzo Penne building

5.4.2.3 Workflows for the H-BIM management

Because of the complexity of the task, a dedicated workflow has been engineered for the improvement of the asset management. All the steps of the traditionally performed have been deployed but in a digital way. The use of a collaborative platform resulted a simple tool that can be deployed quickly and on a large scale, so that all the operations that goes from the determination of the stat-of-art to inspections and subsequent actions to be taken, make up a continuous information stream that does never stops. Thanks to a clear definition of the tasks of the processes, the possibilities of making mistakes are drastically reduced, thus raising the results and reducing the costs. The steps for the H-BIM management are summarized in Fig. 5.26.

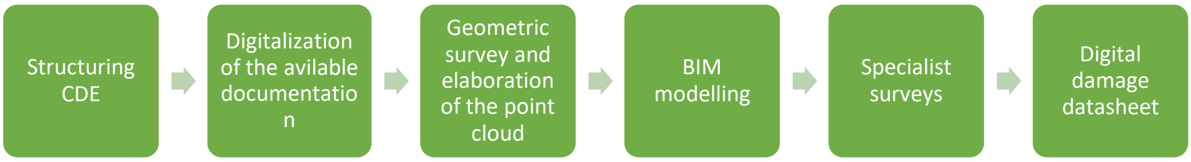


Figure 5.26: Tasks for H-BIM processes

More in detail, all the specific activity to carry out in each step have been summarized in flow charts called "workflows", which should be established well in advance, before starting any operation. As a way of example, the workflows for the geometric survey, the BIM modelling and the damage assessment (one of the activities to carry out during the specialist surveys) are reported in Fig. 5.27.

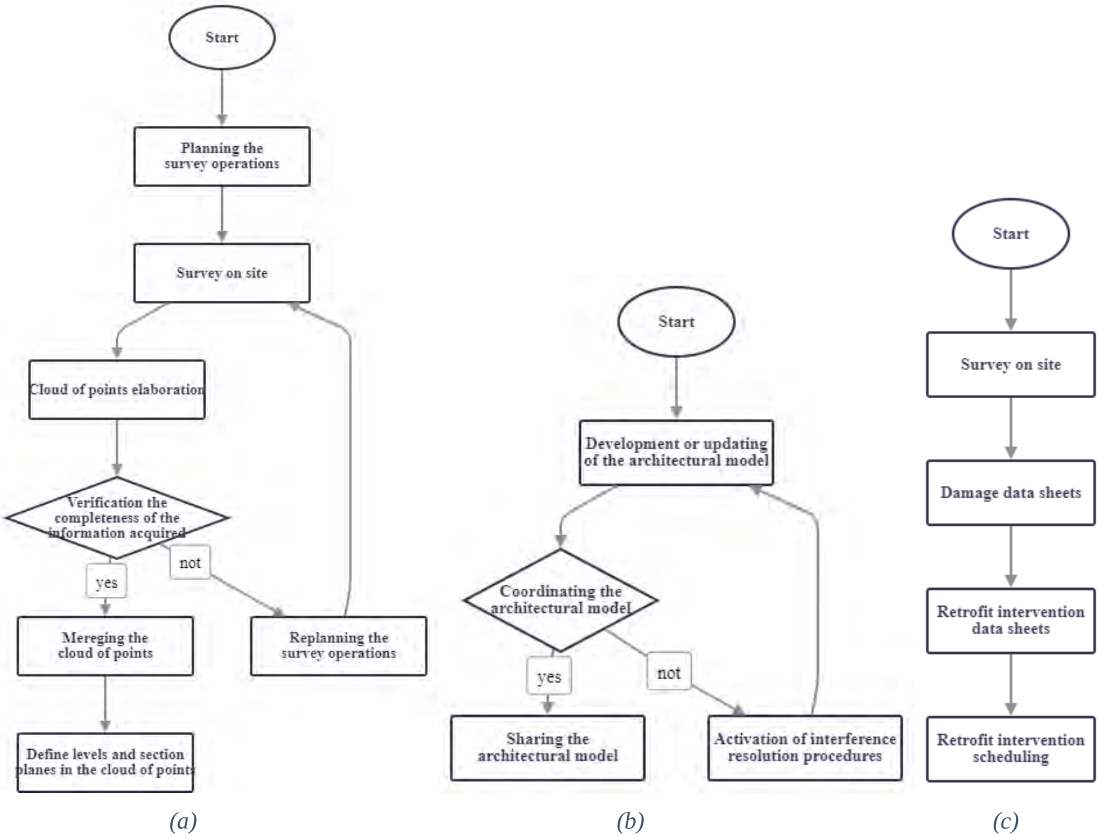


Figure 5.27: Workflows for the geometric survey (a), the BIM modelling (b) and the damage assessment (c)

In particular, the interactions among the different actors involved are managed making clear the exchange of information. Having a definite road map, in fact, make the progress status of the project clear to all the team members that always know when to perform their tasks. Moreover, they provide support in case of delays or unforeseen events, to take some actions aimed at bringing the project in the pre-arranged path.

5.4.2.4 Platform organization

For the performance of all these operations, an IT structure has been established and identified in the CDE, which is the unique working environment in which all the information is shared among the team members. This instrument allows the complete stream of information and it is smartly accessible thanks to some platform tools. More in detail, the CDE includes folders according to a Structured Query Language SQL [2] database and it is organized according to the process phases, i.e. State-of-art, Survey, Investigation and tests and the Retrofit interventions. Each area has been sub-divided in Work in Progress, Shared, Published and Archive, i.e. the four processing states of the files within the CDE, according to ISO 19650-1 (Fig. 5.28).

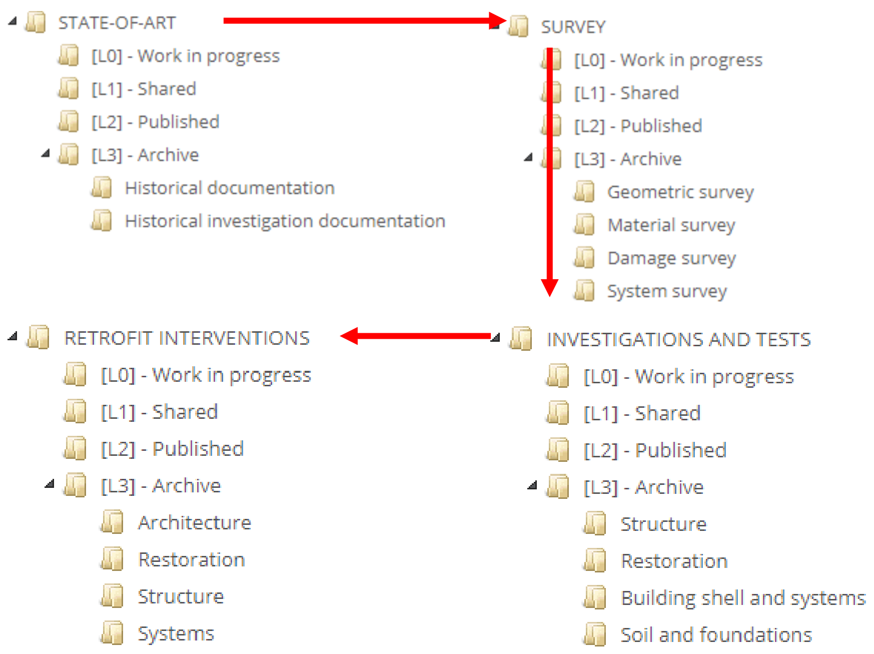


Figure 5.28: Information flow in the Common Data Environment

In order to set the CDE in usBIM.platform, a BIM manager creates the project, add the team members to the project and then define the roles that each user have to endorse, taking into account both the technical roles (such as the structural engineer, the architect, etc.) and the informative ones (BIM modeler, BIM coordinator and BIM manager). Thanks to the implementation of workflows, a connection was established between each user and the tasks to be performed, so that each activity is defined and well-organized. Moreover, other important platform features are the definition of limitations to the access to each folder, ensuring the information security and confidentiality, and the historical storage of all the operation carried out.

5.4.2.5 Digital archive in the CDE

After establishing the CDE, a careful research of paper documentation, such as old reports, plants, elevations and sections was carried out. Together with the documentation produced for the renovation project, they have been digitalized to move the paper archives into digital ones. It resulted that in the platform have been uploaded:

- 97 documental report, including the damage data sheets, report for the state-of-art, report for the design project and reports for the investigations;
- 30 multimedia documents, including material relief drawings, damage relief drawings;
- 39 graphic documents, including plants, elevations and sections;
- 5 digital models, including BIM models and 3D cloud of points.

As a result, 171 documents have been uploaded in the platform so it has to be noticed that even after a structuring in a comfortable way the CDE, it could still be difficult the research especially for stakeholders, such as the client, who may not be able to understand the logic used by the project team. In fact, the structuring of a digital archive is accomplished by creating connections between the information of the different containers and facilitating their rapid search through:

- The management of drawings;

- The management of documents;
- The management of the model.

For the organization of drawings any links have been e between the drawing lines and the documents in the CDE loaded in CAD formats (e.g. .dwg or .dxf). With reference to a plan of the building obtained as a restitution of the geometric survey, links have been created between the section lines and the section drawings, between the heights measurements and the plans at different heights, between the walls and wall datasheets, between the optical cones and the photos taken. Thus, clicking on each element of the drawing, all the other documents with specific information are automatically retraced. Repeating these operations for all the drawings within the CDE, some cross links are established between all drawings so that they can be intelligently displayed one within each other (Fig. 5.29).

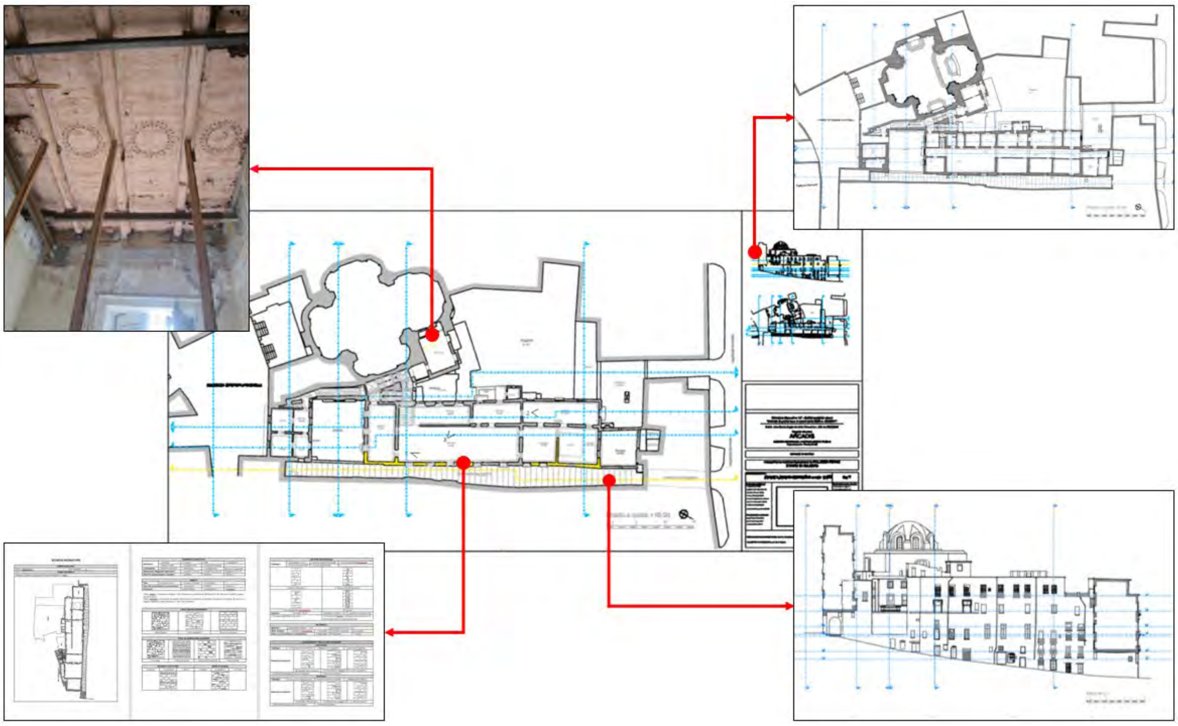


Figure 5.29: Smart organization of the Palazzo Penne plan at an altitude of +10.00 m

For the management of documents, any #TagBIM have been introduced as an encoding system (Fig. 5.30).

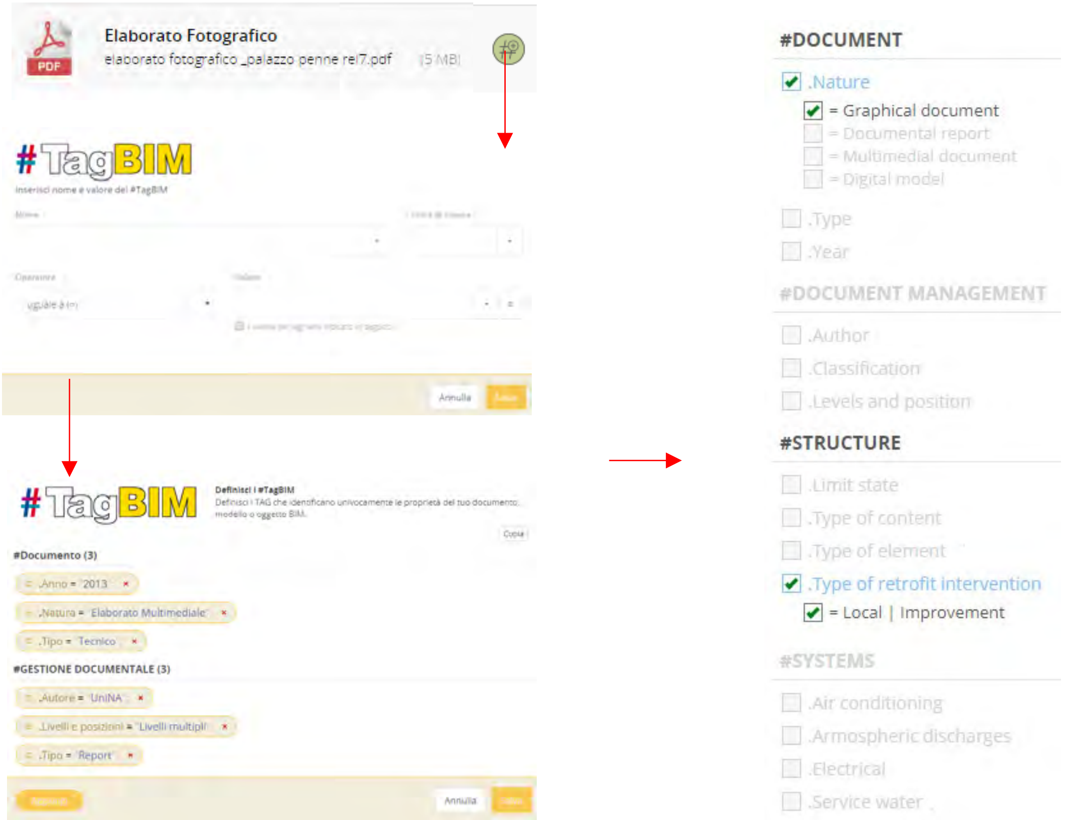


Figure 5.30: #TagBIM for Palazzo Penne documentation

They allow filter operations among documents thanks to the introduction of markers on each document and to draw attention to specific information in a quick and smart way for the dynamic recovery of the file searched. Therefore, the #TagBIM, according to the Not only SQL (NoSQL), make possible transversal pathways within the different folders regardless of the folder structure. Indeed, in order to facilitate the research of the documents, they have been defined referring to the document year, type and nature, to the discipline involved and to the document content. They have been allocated to all documents of CDE as showed in Fig. 5.31.

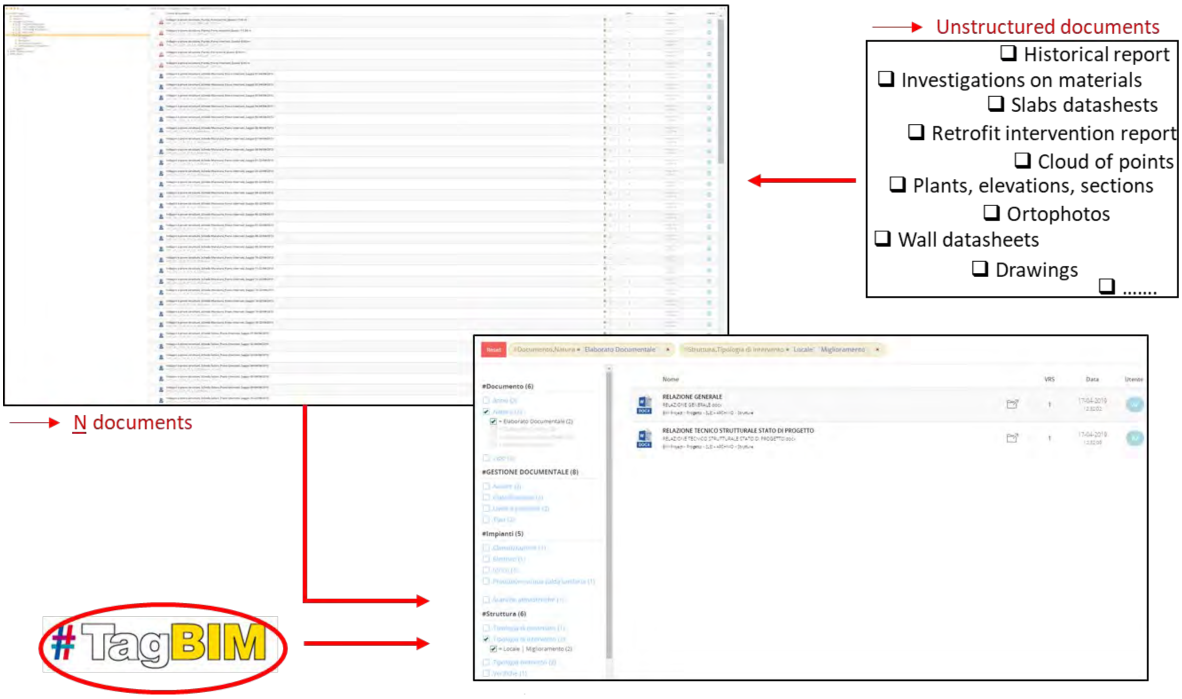


Figure 5.31: Documental research with #tagBIM

Moreover, going into detail of the information contained within the documents, bookmarks have been implemented in the .pdf files, which allow quick access to the different sections of the documents, and #tagBIM to highlight the most relevant information in the document. Some examples for that are showed in Fig. 5.32-5.33, with the application on a structural report on the actual state of the building and on its design state.

Figure 5.32: Bookmars (left) and #tagBIM (right) applied on a structural report of the actual state of Palazzo Penne

Figure 5.33: Bookmars (left) and #tagBIM (right) applied on a structural report of the design state of Palazzo Penne

5.4.2.6 H-BIM modelling and management

With reference to the geometric survey, the traditional method, especially for historical construction as Palazzo Penne, difficult to carry out due to the complexity of the building. This operation, indeed, is simplified thanks to the support given by modern technologies for the elaboration of point clouds [3]. In this regard, laser-scanning [4] and photogrammetric techniques [5] are new ways of making surveys that meet the digital requirements and are little by little expanding their field of application. The point cloud derived from the digital survey represents a digital copy of the building in the form of a 3D model. The laser-scanner technique has been used to acquire Palazzo Penne's point cloud and from it, bi-dimensional drawings have been obtained, including sections, plans and elevations. The graphics have been used as reference for the creation of the BIM Model in Edificius, the BIM authoring software. In detail, for each of the plants extracted from the pointcloud, was placed a level. Due to the presence of any mezzanine floors (i.e. loft floors) in the basement of the building and in some areas where there are variations in inter-storey heights, sub-levels were added, in order not to increase the number of levels that would have been difficult to manage. The levels placed at each floor have been considered as boundaries for all the BIM objects. Besides, it can be stated that many difficulties arose while modelling the building as BIM authoring software have been developed for the design of new buildings, so that even the modelling operation is difficult to carry out for an existing one. The reason for that can be identified in the uniqueness and complexity of each element that hardly fit the concept of "parametric object" and even because of the absence of a dedicated BIM library for specific objects. Indeed, modelling Palazzo Penne, significant deficiencies have been identified about specific objects that characterize the historical buildings. Modeling the walls, numerous singularities that characterize the historical building have emerged. For example, some of the walls that make up the building envelope have a variable thickness. In the model, however, no use was made of the functionality that manages the variability of thickness, although present, in order to improve the interoperability with the structural analysis environment. Instead, it was preferred to divide the perimeter walls into several thicknesses that faithfully follow the profile of the wall and assign an average but constant thickness to each of them. Moreover, in some of the walls there were also arches whose opening space, over time, has been closed by a curtain wall. Their shape, however, is clearly distinguishable, as there are still some decorative elements that protrude from the wall thickness. It was therefore decided to take into account this feature inside the model, inserting extrusion elements that approximate the shape of the decorations, choosing from the objects already listed in the of BIM objects software's library. So, although there are not always custom elements that vitalize each real object, they were introduced into the model, taking into account only the geometry, with simple tricks. Indeed, it can be observed that it is not always necessary to model the objects in all the details. In fact, some elements, such as doors, windows and portals have been chosen among the objects already existing in the library that mostly matched the real ones in terms of shape and typological features. In this regard, the procedure implemented in usBIM.platform takes into account an important concept linked to BIM modelling: the model elaboration has to be commensurate with its use; the use and the Level of Detail of the objects modelling (LOD according to ISO 19650-2) are closely linked. Famous, in fact, is the motto “begin with the end in mind” which aim to state this concept. In this regard, the platform tools make possible to digitalize information with alternative solutions so that, some of the data and features of the objects resulting hard and heavy for the model, were added to the model with #tagBIM.

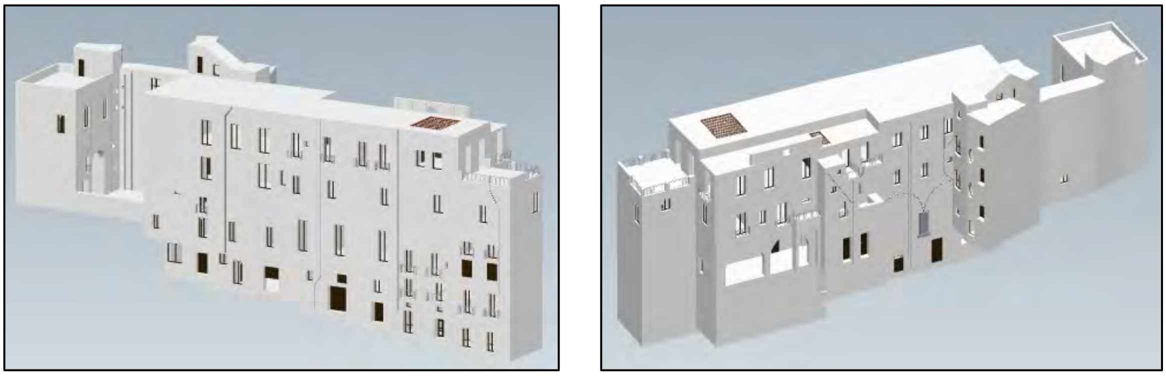


Figure 5.34: BIM model of Palazzo Penne

Once the model is completed (Fig. 5.34), the process progresses with the specialist surveys, so that each of the specialists can perform the investigations of its own competence. Hence, the structural engineer performs investigations for the definition of the mechanical properties of the materials and detect the cracks and the collapses affecting the structure while the architect reports the damages and the degradations. The documentation reporting these operations can be uploaded to the CDE and managed with properly #TagsBIM as showed in par.5.4.1.4. Since many of the information managed during these operations can hardly be integrated directly into the model in the shape of parameters related to the BIM objects, the most important feature of the platform is to aggregate information even if it is disseminated in models and documents of different nature. Thanks to the online viewer usbim.browser directly connected to the platform, report, pointclouds and file even in different format, are linked to the model directly within the CDE. More in detail, the damage datasheets, the degradation datasheets and the mesh model of elements of architectural value (like the front door or the façade ashlars with the coats of arms of d'Angiò and Penne) have been linked directly to the object to which they refer. Thanks to the point cloud, it is even possible to extract the measurements of the objects that were not modelled (Fig. 5.36).

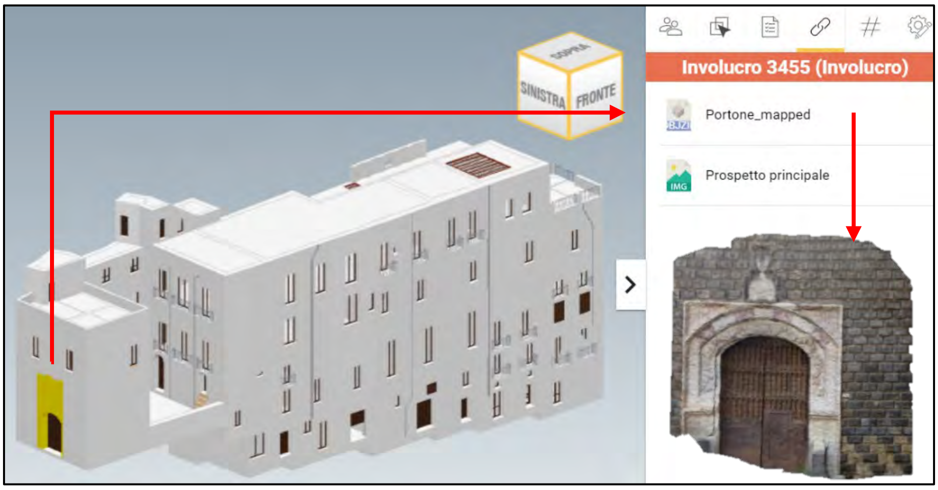


Figure 5.35: Links among documents in the Palazzo Penne's Common Data Environment

Moreover, any pointers were added to the model for referencing such data, favouring a quick and easy navigation and visualization of the files. With reference to the survey activity, the structural engineering has referenced photos of the endoscopy of the walls with its identification number while the architect photos of the degradations inspected, in order to have a visualization of the damage if it has not been modelled directly (Fig. 5.36). This enables optimizing analysis phases and the scheduling of maintenance interventions downstream.

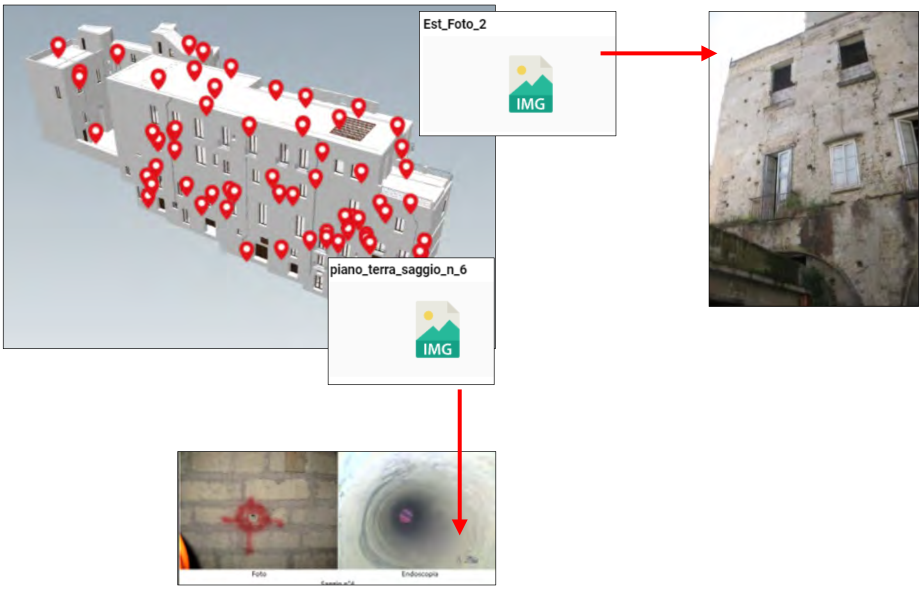


Figure 5.36: Geolocation of the inspections on Palazzo Penne's BIM model

In addition, the #tagBIM have been added even to the objects of the model as it proved to be a particularly useful tool for each user to quickly browse information. More in detail, the information pointed with the #tagBIM pertains the damages inspected, the investigations and the retrofit interventions scheduled. Checking the options offered by the different #tagBIM, all this information can be crossed facilitating the research activities, as shown in Fig. 5.37.

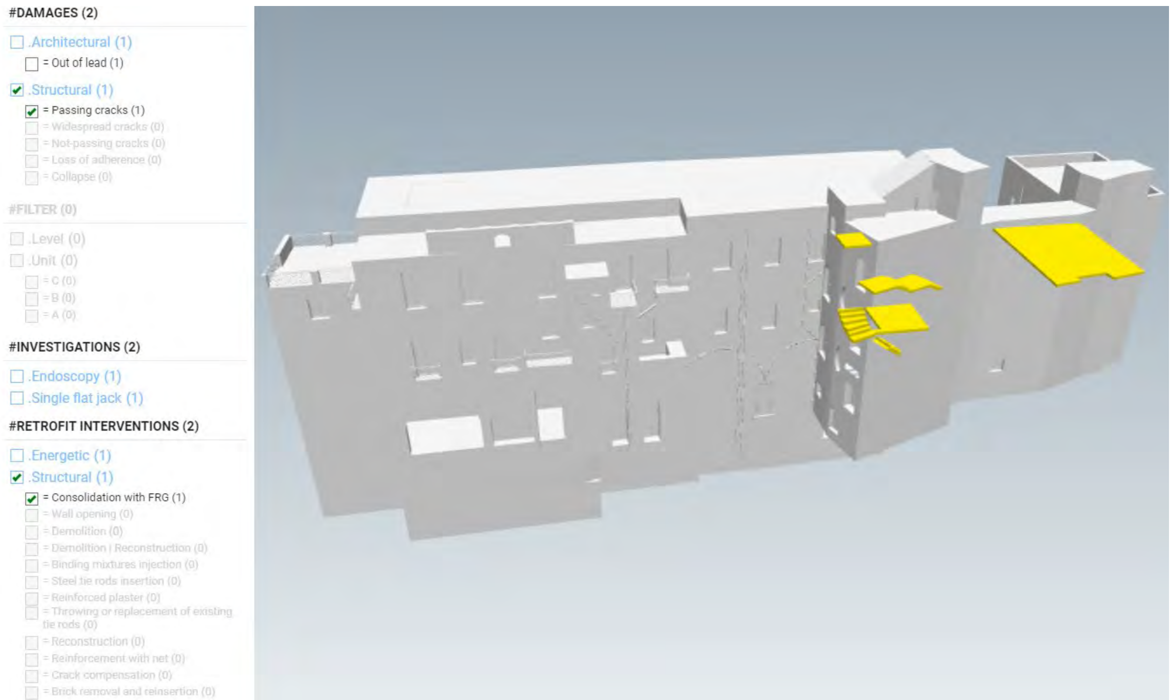


Figure 5.37: #TagBIM of the BIM model's objects of Palazzo Penne

With these tools the information can be "googled" directly from an online browser and find the files and the documents linked to their respective objects.

5.4.2.7 Results

As discussed in Par. 2.5, the current configuration of the IFC standard does not include certain classes of information, which make it not yet fully mature for use in the management of historic buildings. However, it should be noted that very often for the management of historical buildings it is necessary to manage information sources such as photos, documents and drawings in both digital and paper formats. From this point of view, collaborative platforms such as usBIM.platform are a valuable reference point. In particular, thanks to the correlation of all the information set as indicated above, it is possible to make queries both on the documents and directly on the model to extract the information disseminated in the CDE. In Fig. 5.38-5.39 are reported some examples of query paths for the research of the response spectrums of the site and the safety index of the units of Palazzo Penne. The path to follow to get to the information is the following: starting from the #tagBIM of the documents (1), the file in which the information is contained is rapidly searched with its folder path (2); opening the document (3) ad ticking the boxes corresponding to the information (choosing from the ones highlighted with the internal #tagBIM) (4), the place in the document where the information is written, is rapidly reached.

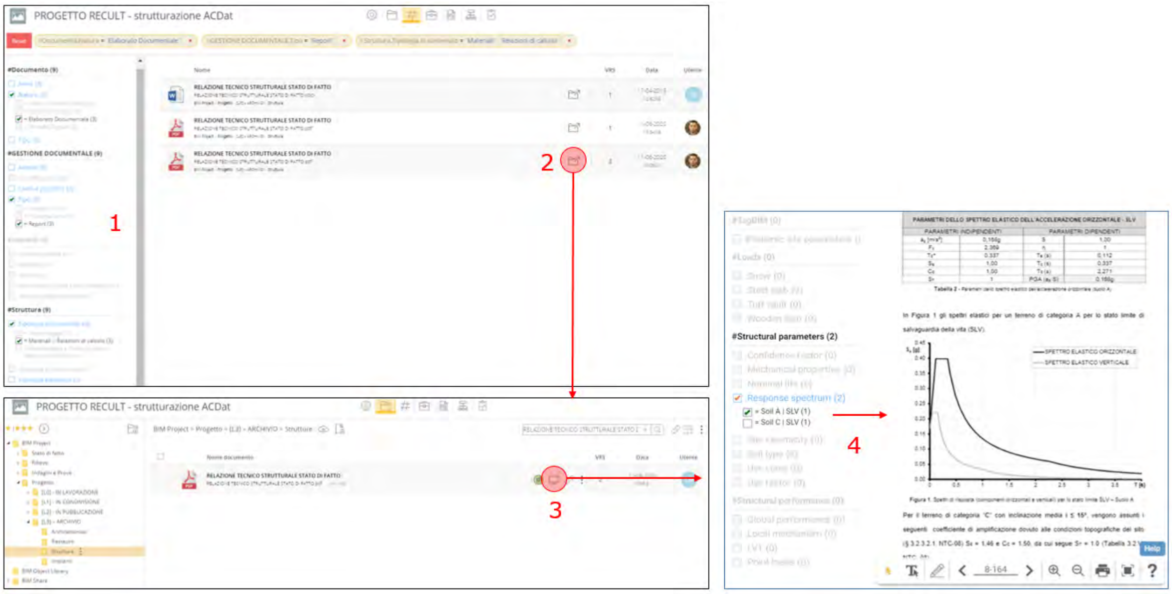


Figure 5.38: Query path for searching for response spectra of Palazzo Penne's site within documents

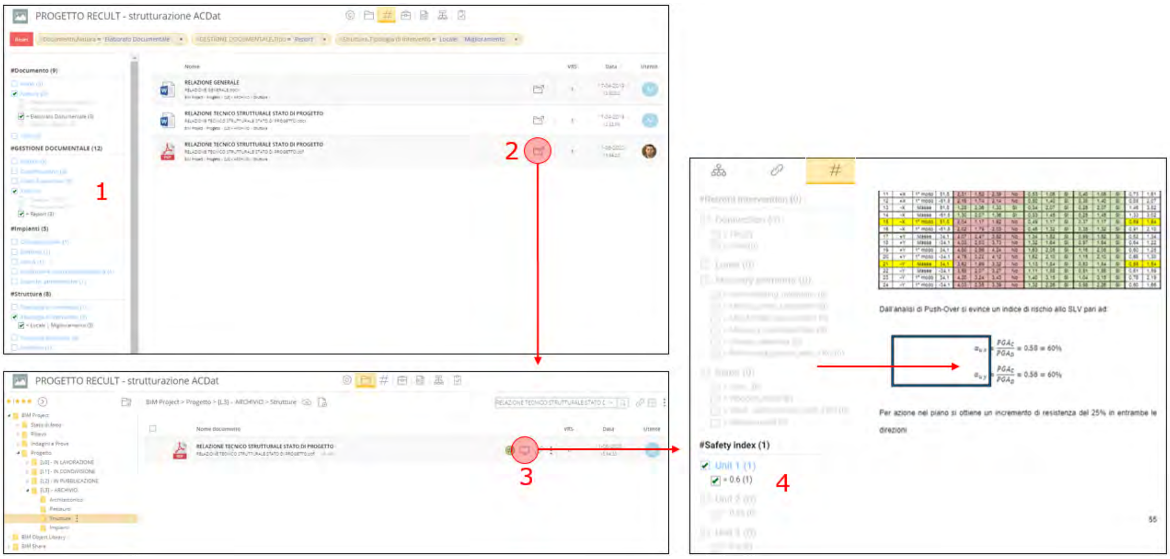


Figure 5.39: Query path for searching for safety index of the Palazzo Penne's units within documents

Similarly, even the BIM model can be used for the research of information. In the example in Fig. 5.40, the path for the research of the endoscopy's results is illustrated: ticking the box of the #tagBIM corresponding to the endoscopy (1), all the elements investigated are with this technique are highlighted so that, clicking on a specific object (2), the report of the investigation is obtained (3).

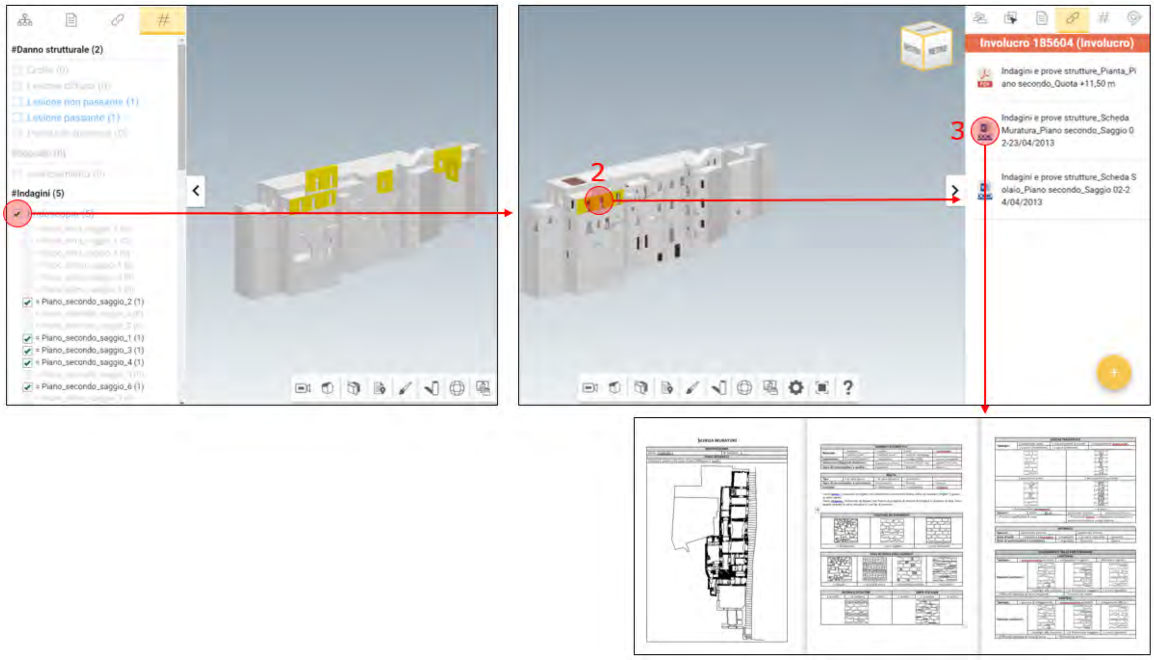


Figure 5.40: Query path for searching for endoscopy's results of Palazzo Penne within the model

5.4.2.8 Discussion

In the steps above, it has been illustrated the potentialities of digital tools and their implementation for the H-BIM management. In particular, the strong point of the methodology explained consists in the fact that all the operations have been performed in a model in IFC format, the standard format introduced by buildingSMART that ensure that the openBIM principals have been taken into account, regardless of the software used for modelling. In the case study of Palazzo Penne, it can be noticed how the model has been used in a completely different way comparing to the common application of new buildings. In this case, in fact, the model, after the uploading in the management platform, has been used as a storage for all the information produced for the renovation. The BIM model, in fact, rather than a mere 3D representation of the building, has become the key access to all the information of the CDE, dealing a huge amount of data previously fragmented in the files. Thanks to pointers and #tagBIM, all the information has been centralized on the BIM model that in this way represents a point of reference for all the team members and constantly support their activities. In fact, as the process goes on, the model is always enriched with new information input in a structured manner, in order to always be traceable. As in the traditional process the use a paper archive represents a significant source of loss of time, thanks to the digital instruments the process is improved, allowing to convey the right information at the right time and to the right people. This purpose is also achieved thanks to the implementation of standardized workflows, which introduce the quality principles in the management of the design of retrofit intervention phase. The BIM methodology, if correctly implemented, can indeed represent an important turning point even for the management of existing building, new frontier of digitization, overcoming the currently widely recognized limits of classical methodologies.

5.5. Industrial development and testing of BIM authoring software and BIM tool for the H-BIM

Thanks to the detailed analysis of the processes carried out through the applications on case studies, specific critical issues of H-BIM have been identified, and therefore required the creation of ad hoc tools for a better management of historical buildings with a digital approach. In detail, the deliverables can be summarized as follows:

- tools for storing information during the knowledge phase of the building;
- object library specific for historical buildings;
- representation of degradation and cracks in two-dimensional views.

5.5.1. UsBIM.data for the creation of digital datasheets

With regard to the first point, in many of the operations carried out during the knowledge processes, information about the building and its current state is collected, often through the use of synthetic sheets.

In traditional processes, these forms are paper-based and often at a later stage they are scanned or even copied in an IT environment, causing inefficiencies within the process.

Thanks to the new application usBIM.data, information can be collected during inspections directly in the shape of data and stored within the platform for immediate use. These forms can be directly associated with the IFC elements of the models to which they refer, and can also be filled in with information that is not expressly codified in the IFC standard but which is nevertheless necessary for carrying out the operations.

With regard to Palazzo Penne, for the collection of information have been defined datasheets for slabs, walls, cracks, collapses and decays. Starting from some forms actually in use in current practice, their content has been expanded with parameters researched in numerous standards. These include:

- Schede AEDES;
- lessico normal 1/88;
- abaco dei degradi;
- Disposizioni concernenti i rilievi di agibilità post sismica conseguenti agli eventi sismici che hanno colpito il territorio delle Regioni Lazio, Marche, Umbria e Abruzzo a partire dal giorno 24 agosto 2016”, Ordinanza n. 10 del 19/12/2016 and s.m.i.;
- Direttiva del Ministro dei beni e delle attività culturali e del turismo - Aggiornamento della direttiva del 12 dicembre 2013 - “Procedure per la gestione delle attività di messa in sicurezza e salvaguardia del patrimonio culturale in caso di emergenze derivanti da calamità naturali”.

Below there are some examples of the datasheets drawn up for the Palazzo Penne case study (Fig. 5.41-5.43). These templates can be completed directly on site through with the aid of tablets or smartphones and are referenced on the BIM model directly on the element, which they refer.

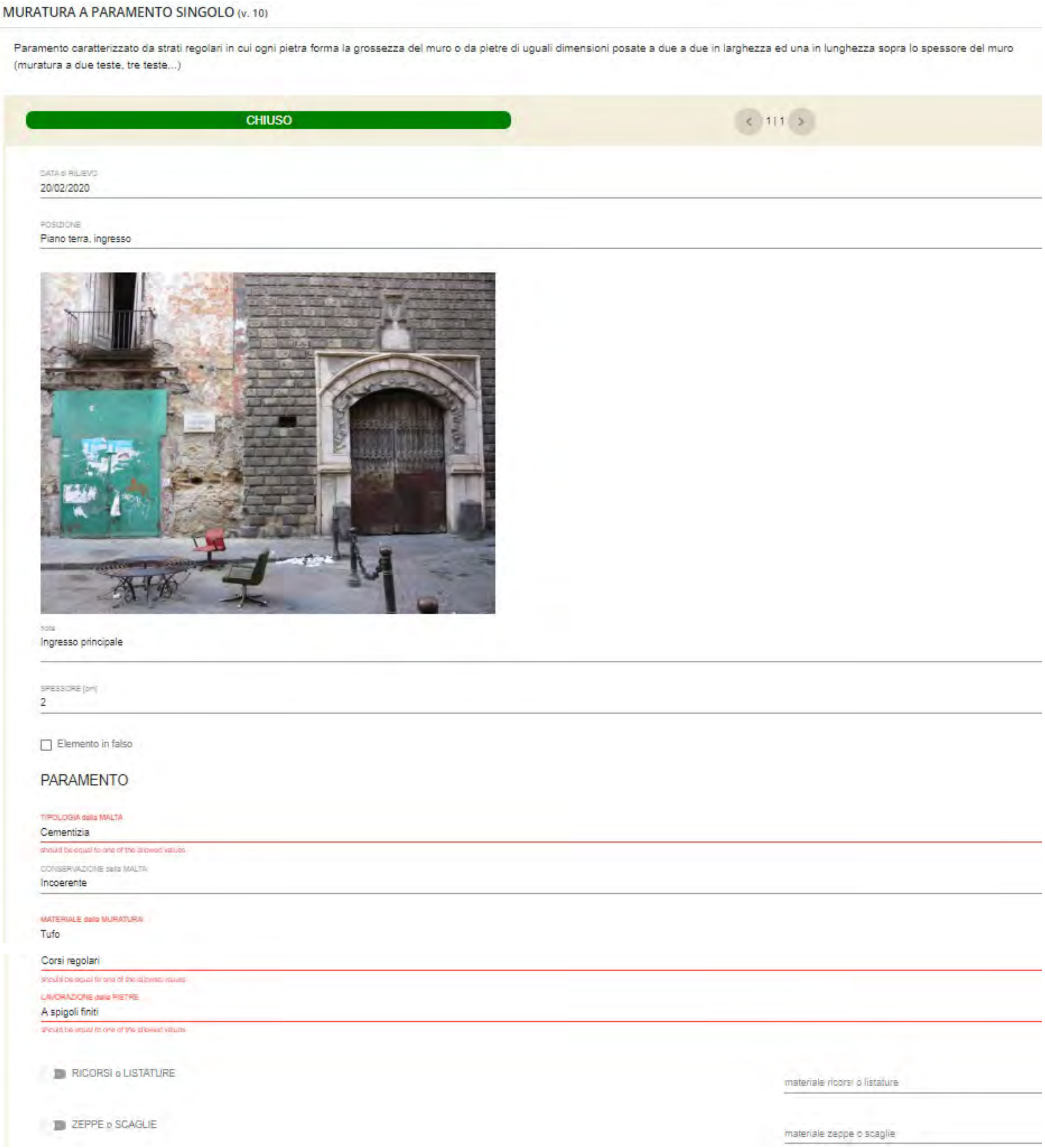


Figure 5.41: Template of a wall datasheet produced with usBIM.data

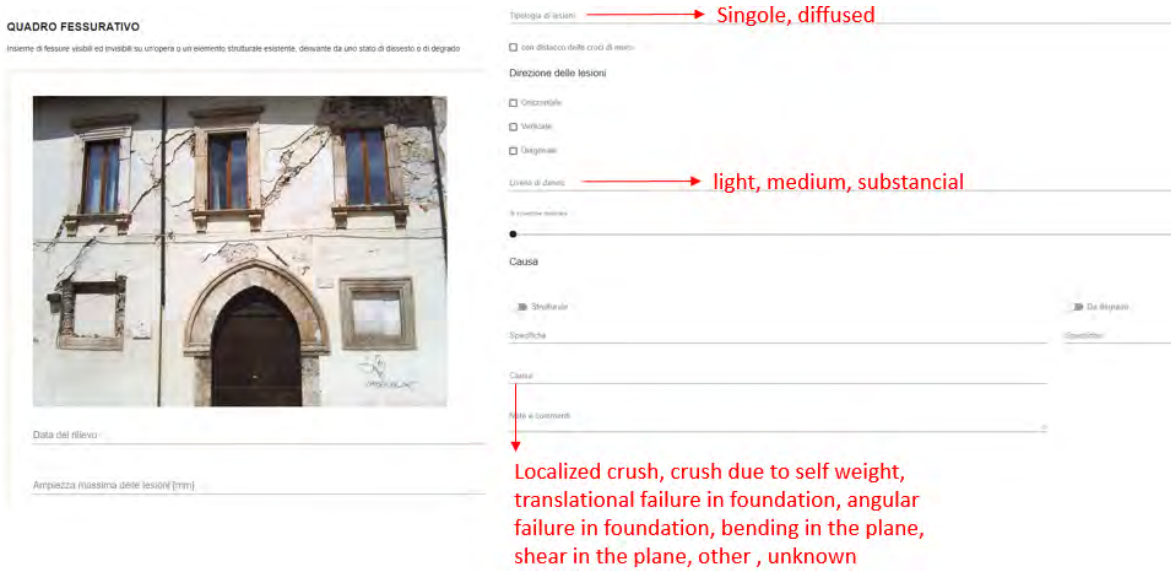


Figure 5.42: Template of a crack pattern datasheet produced with usBIM.data

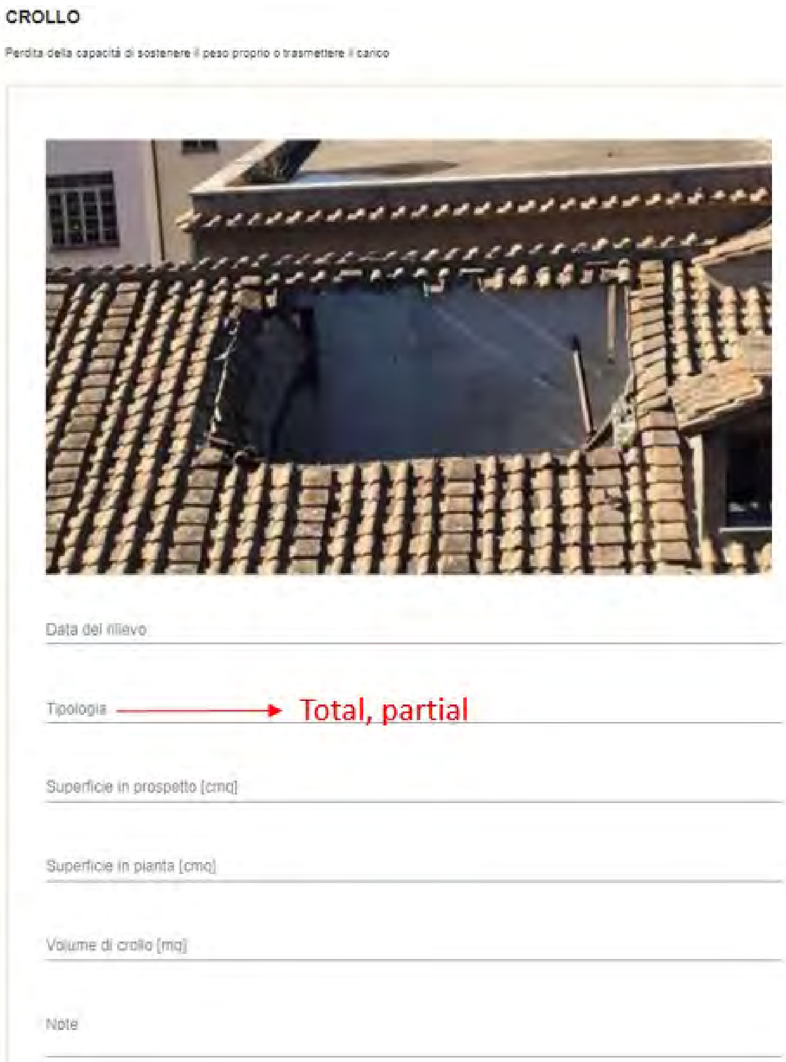


Figure 5.43: Template of a collapse datasheet produced with usBIM.data

The datasheets can be used both in their extended version and in tabular form, and can therefore be converted into .csv format documents. This has a great advantage, as it helps to perform the more extensive assessments of the whole building only with the information collected on the elements. For example, the damaged elements can be counted taking into account even their degree of damage, similarly to what is requested in the AEDES forms filled in following seismic events, for the definition of a global damage state. (Fig. 5.41-5.43)

These datasheets not only help to detect the state of damage at the time of the survey, but can also be implemented for monitoring. In fact, they can be completed several times to monitor the possible progression of the damage, thanks to the management of multiple versions. The information can then be collected without being canceled or overlapped so that there is always a trace of all the operations that are carried out without loss of information. Thanks to their implementation on IFC models, there is no relation with the BIM authoring software used for modeling and therefore the process can be carried out according to the openBIM principles.

5.5.2. H-BIM object library

With reference to the of H-BIM objects library, thanks to the modeling of Palazzo Penne, have been identified some of the objects often recurring in historical buildings for which there are currently no "ready-to-use" BIM objects and which, instead, should contain BIM authoring software for parametric modeling. In detail, four categories of objects have been identified:

- Wooden slabs;
- Vaults:
- Cracks;
- Degradation area.

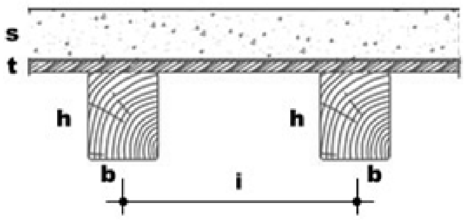
The details of the construction of the "wooden slab" and "crack" objects are discussed below.

5.5.2.1 Wooden slabs

With reference to the "wooden slab" object, it was built by assembling several BIM objects already coded in the IFC standard, i.e. the floor and the beams placed below. In particular, it consists of a wooden planking and a reinforced concrete slab, (the last one may or may not be present); the stratigraphy may be modified according to specific requirements. With reference to the beams placed below, they are not modeled individually but as a system of beams associated with the floor area. The slab has been parametrized taking into account the shape of the beam cross-section (circular or rectangular) with the respective dimensions, the direction of warp and the spacing between the beams or, alternatively, the total number, and, at last, length of the beams penetrating the walls (beam offset). Instead, when the slab is double warped, the second order of beams is not parameterized but must be modelled in the classic way. The tables below (Tab. 5.16-5.19) show the standard configurations.

Table 5.16: Parametrization of the wooden slab with rectangular beams and a reinforced concrete layer

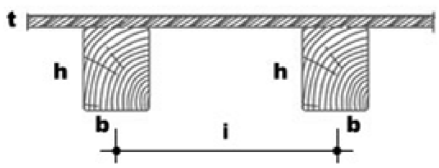
Wooden slab with rectangular beams and a reinforced concrete layer



TYPE OF WOOD: (e.g. chestnut, fir, beech, etc.)				
Parameter		**Value**		
Concrete layer thickness	s		…	cm
Plank thickness	t		…	cm
Slab height	H		…	cm
Beams height	h		…	cm
Beam width	b		…	cm
Spacing between beams	i		…	cm
Number of beams	n		…	nr
Beams offset	o		…	cm
NOTES:				

Table 5.17: Parametrization of the wooden slab with rectangular beams

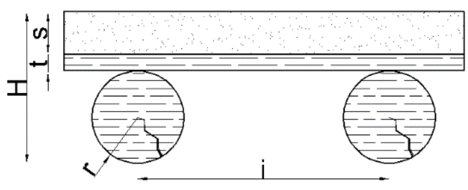
Wooden slab with rectangular beams



TYPE OF WOOD: (e.g. chestnut, fir, beech, etc.)				
Parameter		**Value**		
Slab height	t		…	cm
Beams height	H		…	cm
Beam width	h		…	cm
Spacing between beams	b		…	cm
Slab height	i		…	cm
Number of beams	n		…	nr
Beams offset	o		…	cm
NOTES:				

Table 5. 18: Parametrization of the wooden slab with circular beams and a reinforced concrete layer

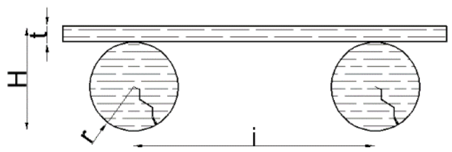
Wooden slab with circular beams and a reinforced concrete layer



TYPE OF WOOD: (e.g. chestnut, fir, beech, etc.)				
Parameter		**Value**		
Concrete layer thickness	s		…	cm
Plank thickness	t		…	cm
Slab height	H		…	cm
Beam radius	r		…	cm
Spacing between beams	i		…	cm
Number of beams	n		…	nr
Beams offset	o		…	cm
NOTES:				

Table 5. 19: Parametrization of the wooden slab with circular beams

Wooden slab with circular beams



TYPE OF WOOD: (e.g. chestnut, fir, beech, etc.)				
Parameter		**Value**		
Plank thickness	t		…	cm
Slab height	H		…	cm
Beam radius	r		…	cm
Spacing between beams	i		…	cm
Number of beams	n		…	nr
Beams offset	o		…	cm
NOTES:				

5.5.2.2 Cracks

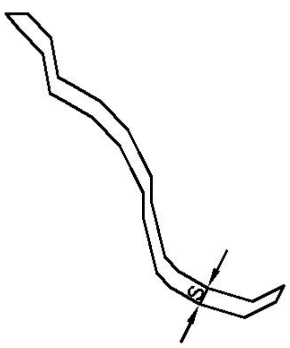
Then there are some BIM objects introduced with the aim of digitizing the damages in masonry buildings, divided into two categories of BIM objects, i.e. the cracks, which are mainly the object of study of the structural engineer and the area of decay, mainly the object of study of the architect.

With reference to the cracks, three different typology of cracks have been identified: single cracks, diffused cracks and cracks due to the detachment of the walls.

Each crack can be placed on walls or on slabs and is characterized by its own parameters, including the width and the direction, evaluated as the angle that the connection between the first and the last edge forms with the horizontal direction. Regarding the parameter of the depth, it may be taken into account through its measurement, which could be difficult to detect, or by defining only whether or not it is passing through the element; when it is passing through it is in fact relevant from a structural point of view and aggravates the state of damage. Lastly, it is also necessary to identify the phenomenon that caused it, which may be due to structural phenomena or degradation. All the parameters are summarized in Tab. 5.20.

Table 5.20: Parametrization of single cracks

Crack



Parameter		**Value**		
Width	s		…	cm
Direction	d	- Horizontal - Vertical - Diagonal		
Profondità	p	- Passing - Not-passing		
Cause	c	- Bending - Shear - Compression - Tension - Not-structural - Unknown		
NOTES:				

It was then assumed that lesions could be introduced into BIM models with three levels of accuracy in the representation, in order to find the right compromise according to specific needs:

- *L0: no 3D representation in the model* - The crack is not represented graphically but there is a marker, for example a #tagBIM, to identify whether the damage is present or not;

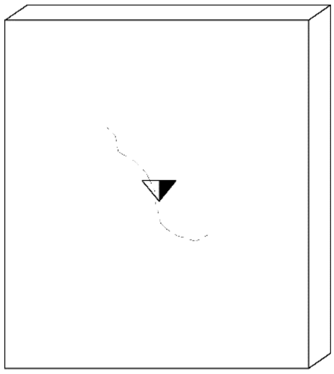


Figure 5.44: Representation of the cracks with an L0 level

- *L1: schematic representation* - the crack is represented in a schematic way, using the symbology indicated in Tab. 5.21 to be reported in the two-dimensional views (plans, elevations and sections);

Table 5. 21: Schematic representation of the cracks with an L1 level

TYPOLOGY	**HORIZONTAL**	**VERTICAL**	**DIAGONAL**	**DIFFUSED**	**CROSS**	**SLAB**
PASSING	P	P	P		P	P
NOT-PASSING						

- *L2: detailed representation* - the crack is represented in a realistic way, reproducing its exact outline.

The objects "area of decay" and "crack" have then been introduced into the model of Palazzo Penne to be tested on the main facade and on one of the facades adjacent to the courtyard. In order to facilitate the modeling operation, the orthophotos have been scaled and overlapped to the respective facades and, using the new BIM objects, the cracks have been faithfully traced with the highest level of accuracy in the representation (L2), as shown in Fig. 5.45-5.46.

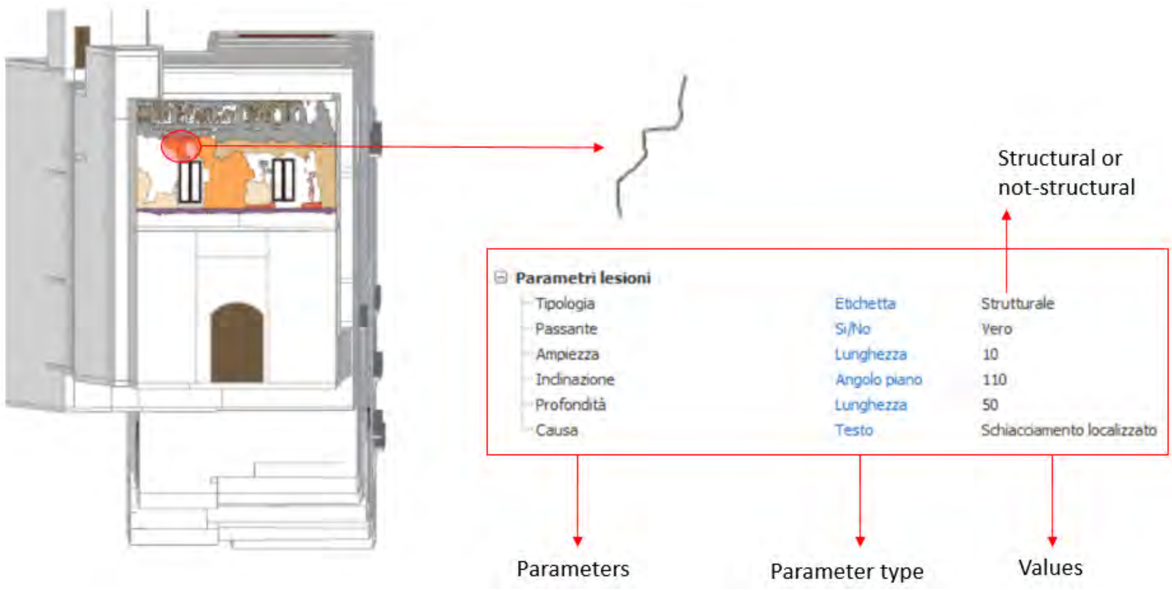


Figure 5.45: Model of the cracks and of the areas of decay of the main facade of Palazzo Penne

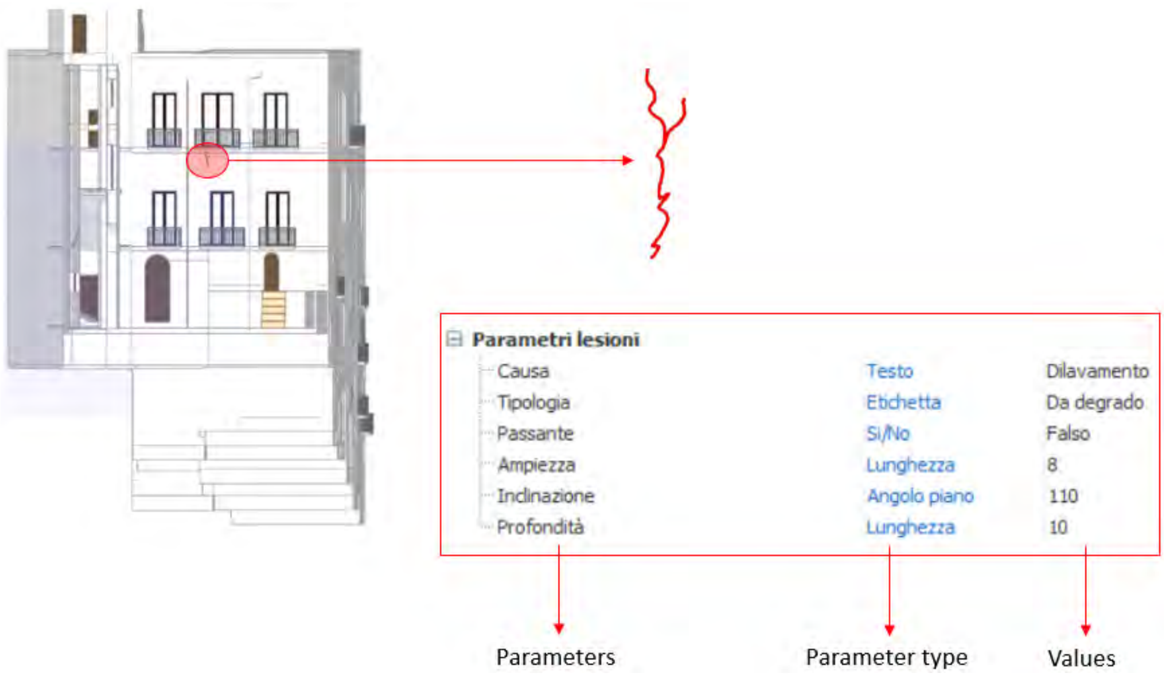


Figure 5.46: Model of the cracks on the facade adjacent to the courtyard of Palazzo Penne

5.5.3. Representation of cracks in two-dimensional views

A further development pertains procedures for the automatic extraction from the BIM model of the building plans showing the damage distribution. For this procedure it has been hypothesized that in the two-dimensional views the lesions can be associated with labels containing text inscriptions consistent with a damage coding system or alternatively images with a symbology reported in a legend. The labels are to be intended as real BIM objects, so that all the properties and parameters illustrated in the previous paragraphs are connected to them in an intelligent way. Tab. 5.47-5.49 shows the proposals made for this purpose for the three categories of cracks previously identified.

Table 5.22: Hypothesis of labels for the displaying individual cracks in the plan view

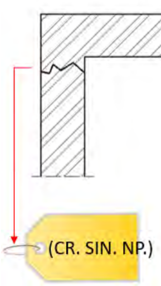
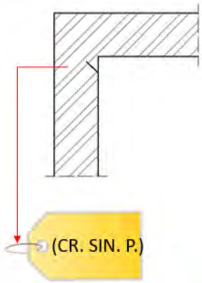
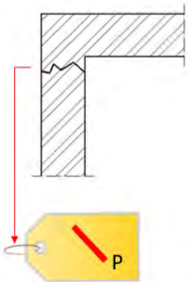
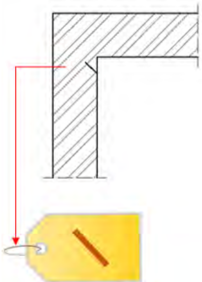
Single crack	**Passing**	**Not-passing**
Hypothesis 1: Label with text		
Hypothesis 2: Label with images		

Table 5.48: Hypothesis of labels for the displaying diffused cracks in the plan view

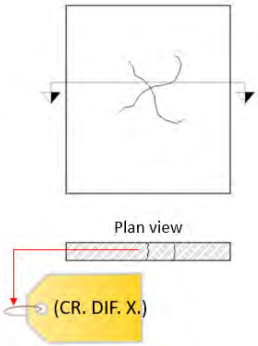
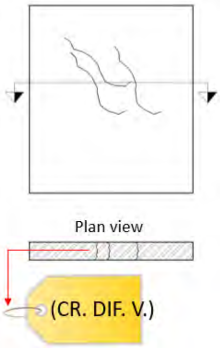
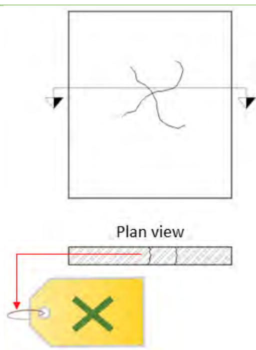
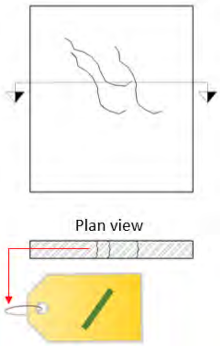
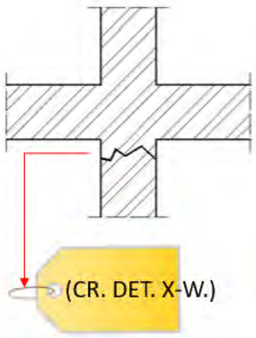
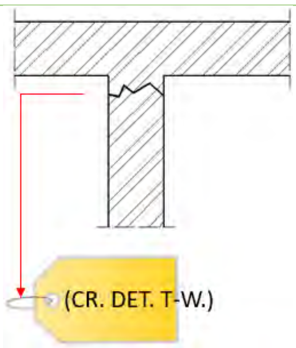
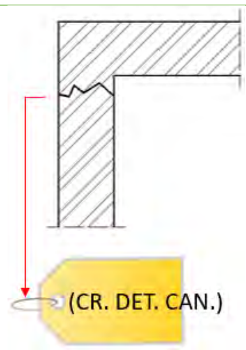
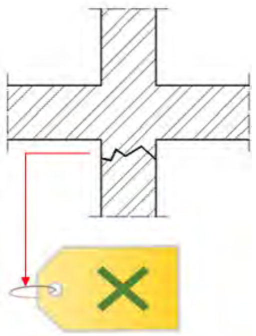
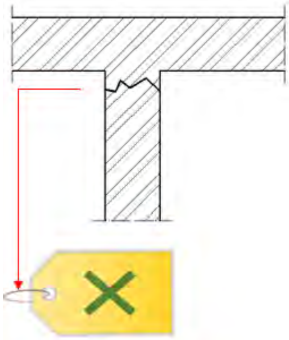
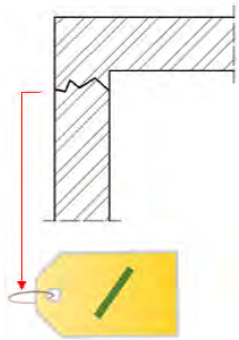
Diffused crack	**X-shape**	**Variable trend**
Hypothesis 1: Label with text		
Hypothesis 2: Label with images		

Table 5.49: Hypothesis of labels for the displaying detachment cracks in the plan view

Detachment crack	**X-shape walls cross**	**T-shape walls cross**	**Cantonal walls**
Hypothesis 1: Label with text			
Hypothesis 2: Label with images			

The industrial developments pertaining the H-BIM library discussed in this chapter have reached such maturity that they have been introduced in an H-BIM toolbar in the BIM3 version of the Edificius software, released from February 2021.

Figure 5.50: H-BIM toolbar introduced in Edificius BIM3 software [6]

Conclusions

The Common Data Environment always provides a good support for the management of existing buildings, as it helps to manage the large amount of information that often characterizes them. Through 4 theoretical case studies have been realized the folder structures and the workflows that take place within them for CDE with different objectives. Then, further CDEs were developed for real case studies. In particular, the existing buildings have been divided into two categories, namely ordinary buildings and historical buildings, characterized by a different degree of importance.

For each of the two cases, a #tagBIM system was developed to manage archives of digital documents and the damages suffered were digitized using two different strategies: in the first case, a model #tagBIM system was introduced which allowed the information to be entered in an expeditious manner; in the second case, it was considered useful to reach a greater level of detail so the damages were modeled in their shape.

In carrying out these experimentations, several software functionalities have been developed thanks to the collaboration with ACCA software; in detail, have been developed applications for the creation of digital damage datasheets, a library of BIM objects characteristic for existing buildings (including cracks, areas of decay, vaults and wooden floors), and have been identified specifications for the representation in elevation of cracks and areas of decay.

Thanks to these software applications, the implementation of the BIM methodology will be more suitable also for existing buildings, and especially for the historical ones.

References

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[6] https://www.acca.it/edificius-bim-3#hbim

Chapter 6:

HERITAGE-BIM (H-BIM) - INTEGRATED WORKFLOW AND DIGITAL TOOLS FOR THE VIRTUALISATION OF THE AS-BUILT STATE OF THE SAN PIETRO IN VINCULIS CHURCH

* Any of the research outcomes reported in this section were published in the following conference papers:

- Lanzara, E., Scandurra, S., Musella, C., Pulcrano, M., Palomba, D., Asprone, D. and di Luggo, A.- Parametric Modelling of vaults and shared implementation of the data in HBIM system- *Proceedings of the conference 3D Modelling&BIM*. Digital Twin. Roma, April 14, 2021
- Lanzara, E., Scandurra, S., Musella, D., Palomba, D. di Luggo, A., Asprone, D. - Documentation of structural damage and material decay phenomena in H-BIM systems – *Proceedings of XXVIIIth CIPA Symposium*. Beijing 28 August-1 September 2021 (under publication process)

**Any of the research outcomes reported in this section were part of the following industrial research project:
BIM ReCulT - *Il metodo BIM per il Recupero del patrimonio CulTurale* (POR Campania FESR 2014-2020)

***The results of industrial research carried out in this section were awarded at the *Digital&BIM award 2020* in category 7: *Digital technologies for the built process*

Abstract

The digitalization of historic buildings is an important opportunity to implement innovative technologies that enable processes to be put in place to achieve much greater results than those obtained with traditional procedures. In this chapter, a new integrated workflow has been defined which takes into account all the disruptive technologies developed and tested in the previous chapters and the knowledge of all the professionalisms involved in the management of historic buildings. More in detail, as part of the BIM ReCulT project (Il metodo BIM per il Recupero del patrimonio CulTurale), surveyors, architects and structural engineers took turns in working on the creation of the digital twin of the church of San Pietro in Vinculis, and in particular on the definition of its state of damage and the seismic safety index of the building. In the following, the way in which dynamic laser scanners, drones, collaborative platforms, BIM objects and software applications provided valuable support to the team members will be analyzed. The activity described in the following paragraphs was carried out synergistically by DIST, DiARC, Stress s.c.ar.l. and ACCA software groups.

6.1. Historical background of San Pietro in Vinculis Church

The church of San Pietro in Vinculis, built by the architect and sculptor Angelo Antonio Fiore, is a historical and monumental building placed in the historic centre of Naples, in Via Sedile di Porto, near Via Mezzocannone. The year of construction of the church is uncertain, but it is known that it was built in the early 1400s and that it was already active in 1423. It was remodelled in the 16th century by Giovanni Lucio Scoppa, a well-known grammarian of the time and author of several treatises. He died around 1543 and left all his possessions to the monastery of San Pietro in Vincoli to finance the teaching of rhetoric, grammar and poetry to 200 poor boys. In 1588, the church became the seat of the ' Corporazione degli speziali manuali e droghieri', which remained so until 8 March 1826, when, by decree of Francis I of Bourbon, it became the 'Confraternita di San Pietro in vinculis degli speziali manuali, dei droghieri, e cioccolattieri della nostra buona Napoli '.

Figure 6.1: "Congrega di san Pietro in Vinculis", inscription on the main entrance

In 1654, according to a plaque behind the high altar, the church was again restored and modified. Inside the church there are still plastered decorations and valuable marble altars. The dome was painted by Giuseppe Fattorusso, a pupil of Beinaschi, while the frescoes on the vault, with St Peter and St Aspreno, are probably from the school of Solimena. Other works of art may have been stolen or transferred elsewhere by the Archdiocese of Naples, the owner of the church. In ancient times the church was called 'a Melia' or 'a Media', from the uncertain name of a noble family belonging to the Seggio di Porto. They were probably the owners of the large palace behind the church, which still exists and has two entrances, one from vico Melofioccolo and the other from calata Santi Cosmo e Damiano. The locution 'a Melia', according to some scholars, in time became 'Amelia' and later 'Ammennola', later italianized into 'Amendola', the name by which the building is known.

Figure 6.2: Façade of San Pietro in Vinculis Church placed in via Sedile di Porto (NA)

The name 'San Pietro a vincolis', was given to the church in memory of two miracles linked to imprisonment suffered by the saint. Herod, while waiting for the people to judge him, kept Peter in prison, in chains and guarded by two soldiers. During the night, an angel freed him from his chains and, after dressing him, led him out of the prison. Peter was not surprised by the doors opening, convinced that it was all just a vision. However, when the angel disappeared and he found himself alone in a street, he understood that his freedom was due to a miracle from God. Centuries later, Empress Elias Eudocia went on a pilgrimage to Jerusalem, where she received the chains that had bound the saint as a gift from Patriarch Juvenal. His daughter, in turn, gave them to Pope Leo the Great, who brought them close to those used for the same purpose in a prison in Rome. Miraculously, the chains fused together, becoming one and indissoluble. In memory of this miracle, the Basilica of St Peter in Chains was built in Rome, where the fused chain is kept under the altar [1]. The Neapolitan church in Via Sedile di Porto is in very poor condition, as is the aforementioned Palazzo Amendola and other ancient structures in the area, which were spared by the bulldozers of the 'Risanamento' and are dying of neglect. Moreover, it is supposed to possess numerous works of art scattered throughout the building: however, since the church has been abandoned for some time, and is in poor condition, the frescoes and architecture of the interior have been disfigured by neglect, as is already evident from the façade, where, moreover, the frescoes in the lunette have almost completely disappeared. The same applies to the works of art. Due to the successive stratifications that have taken place over time, the church is currently part of an urban aggregate and has buildings both adjacent and above it.

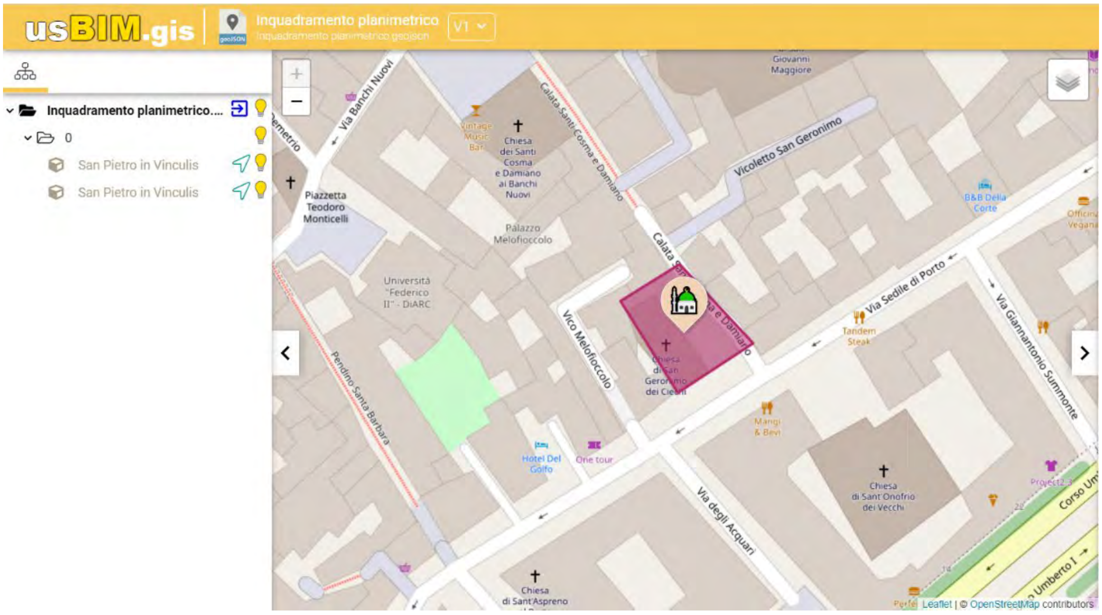
6.2. Structure of the process and organization of the CDE

The entire process has been performed taking advantage of the usBIM integrated system, developed and provided by ACCA software. Before starting to perform any operations, the Common Data

Environment (CDE) was created with the usBIM.platform, for easy and quick sharing of project documents within the team.

Figure 6.3: The Common Data Environment (CDE) for the San Pietro in Vinculis Church

In detail, a first area of documentation was identified, in which some documents obtained following a bibliographic research on the church of San Pietro in Vinculis were included. The starting documentation also includes the planimetric context of the church, drawn up with the usBIM.gis application, using the GIS tool integrated in the usBIM ecosystem in the open .geojson format, and highlighted with a special background and recognition marker (Fig. 6.4).



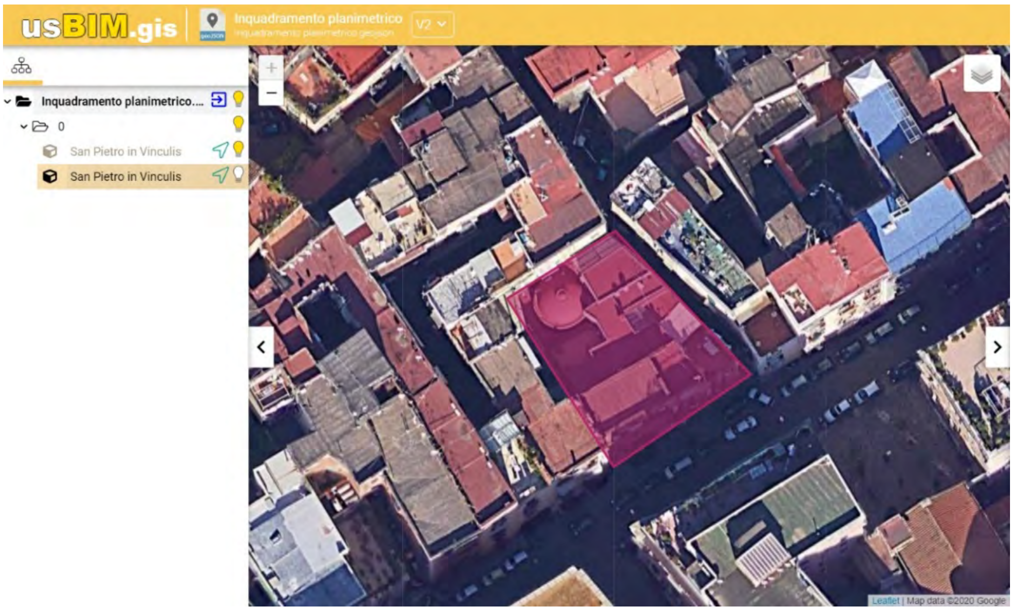


Figure 6.4: Implementation of usBIM.gis for the planimetric context of the church of San Pietro in Vinculis

In the “Geometric survey” working area, point clouds, plans and sections extracted from it, photos acquired with cameras and from drone and 360° photos were uploaded. In the subsequent "Model" and "Specialist surveys" areas all the relevant documents were uploaded, updated as the workflow progressed.

6.3. Survey on-site and assessment of structural instability phenomena

After structuring the CDE for the sharing of information, the first operation consisted in the survey on-site in which all the members of the team took part, each one collecting information relevant to their own discipline. With regard to the structural field, tests were carried out on walls and vaults to expose their structure, useful for the definition of the construction details necessary for the safety assessment of the church (Fig. 6.5).

Figure 6.5: Construction details of the walls and vaults of the church of San Pietro in Vinculis

It was found that the original walls are made of red brick and mortar in a good state of preservation, while some of the more recently added walls are made of yellow tuff with a regular arrangement; there are also openings with a lintel made of metal profiles. The vaults of the side chapel were built with a secondary wooden structure (and not in masonry as the other structural elements of the building) that does not exert a significant pushing action on the perimeter walls. For the acquisition of further details, as well as for a clearer definition of the cracks, the UAV DJI Mavic 2 pro were used, with which photographs were taken of all the walls, the vault and the roof dome (Fig. 6.6).

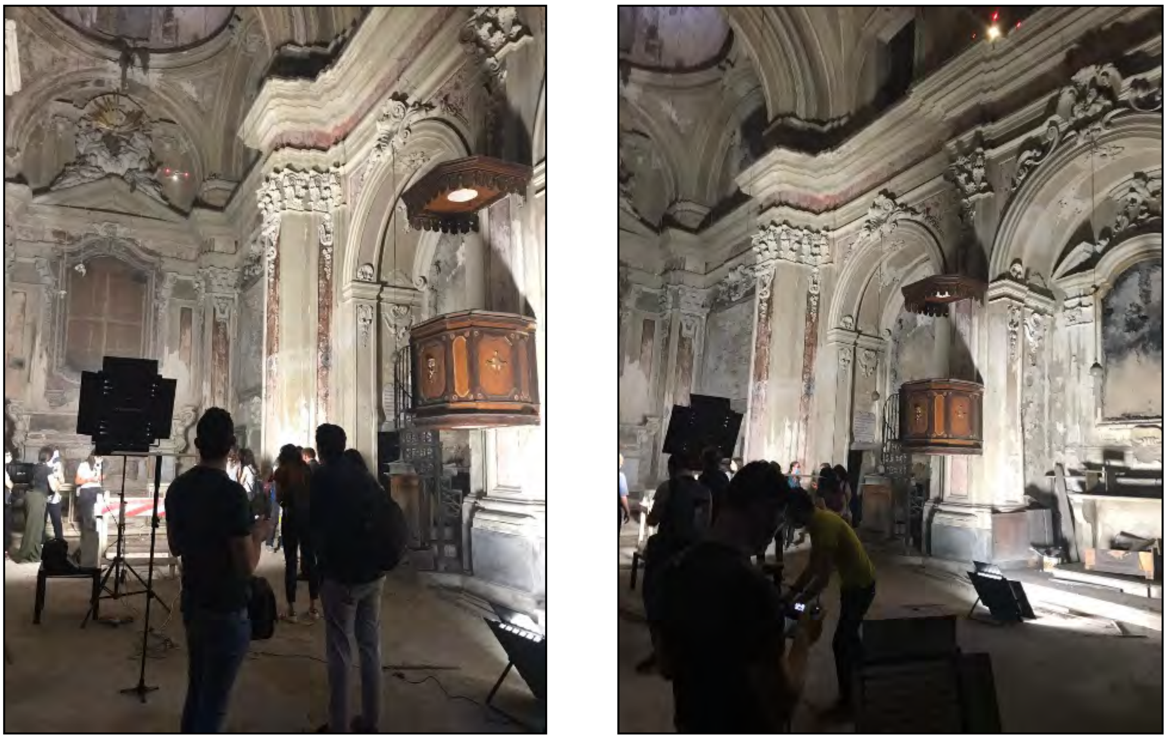


Figure 6.6: Survey of the San Pietro in Vinculis church with UAV DJI Mavic 2 pro

Thanks to an internet connection, access was then made to the usBIM.platform cloud environment and to the BIM model created with LOD C, in order to collect information with the damage analysis sheets specifically prepared (Fig. 6.7). These sheets were then subjected to a subsequent revision and systematisation in order to comply with the Directive of the Minister of Cultural Heritage and Activities and Tourism Update of the Directive of 12 December 2013 "Procedures for the management of activities to secure and safeguard the cultural heritage in the event of emergencies resulting from natural disasters"(trad. *Direttiva del Ministro dei beni e delle attività culturali e del turismo Aggiornamento della direttiva del 12 dicembre 2013 "Procedure per la gestione delle attività di messa in sicurezza e salvaguardia del patrimonio culturale in caso di emergenze derivanti da calamità naturali"*).

Figure 6.7: On-site access to the model with the usBIM.platform

The cracks were then detected on the main façade and on the roofing vault of the main nave. The cracks found in the counter-façade (Fig. 6.8) are due to a vertical sliding mechanism in the plane: the closure of the window compartment with tuff ashlars constituted a considerable load for the underlying spandrel panel which caused it to lower. Subsequently, in order to counteract this lowering, a filler was inserted inside the entrance opening. For this reason, the cracks stopped at the height of the portal compartment [2].

Figure 6.8: Cracks on the main façade of the San Pietro in Vinculis church

Of a greater significance are the cracks in the keystones of the vault, which run the full length of the vault and are most likely due to the load of the floor built above the church. Due to the excessive load exerted by the floor on the vault, the tensile strength of the material of which it is made was exceeded, causing the formation of a cylindrical hinge in the keystone section (Fig. 6.9).

Figure 6.9: Cracks of the keystone section of the vault of the main nave

We then proceeded with the geometric survey, acquiring the point cloud of the entire church using a dynamic GeoSLAM ZEB Horizon laser scanner (Fig. 6.10-6.11). For the geometic survey of the church the technological choice has fallen on the use of a dynamic laser-scanner since it is well suited for rapid damage detection and assessment, which allows in the shortest possible time to acquire a cloud of points with a level of accuracy consistent with the use (even if it could be not suited for every H-BIM application). Unlike common static laser scanners that acquire single scans to be recorded in order to reconstruct the overall cloud, thanks to this new technology the point cloud is acquired directly in its entirety, without the need for further processing, thus saving time and resources. It was not necessary to set up any control points, but it was sufficient to follow a few small precautions during the execution of the operations. The acquisition time was approximately 15 minutes, wearing the equipment with special aids and following a route that allowed both indoor and outdoor environments to be acquired in a single scan, defining a starting point that coincided with the closing point in order to minimise measurement errors and avoid drift.

Technical specification	
Range	100m
FOV	360° x 270°
Protection class	IP 54
Processing	Post
Data logger carrier	Backpack or shoulder strap
Scanner head weight	1.5kg
Datalogger weight (incl. battery)	1.3kg
Colourised point cloud	✓*
Intensity	✓
Referenced imagery	✓*
Scanner points per second	300,000
No. of sensors	16
Relative accuracy	1 - 3 cm**
Raw data file size	100-200MB /min

Figure 6.10: Technical specifications of GeoSLAM ZEB Horizon

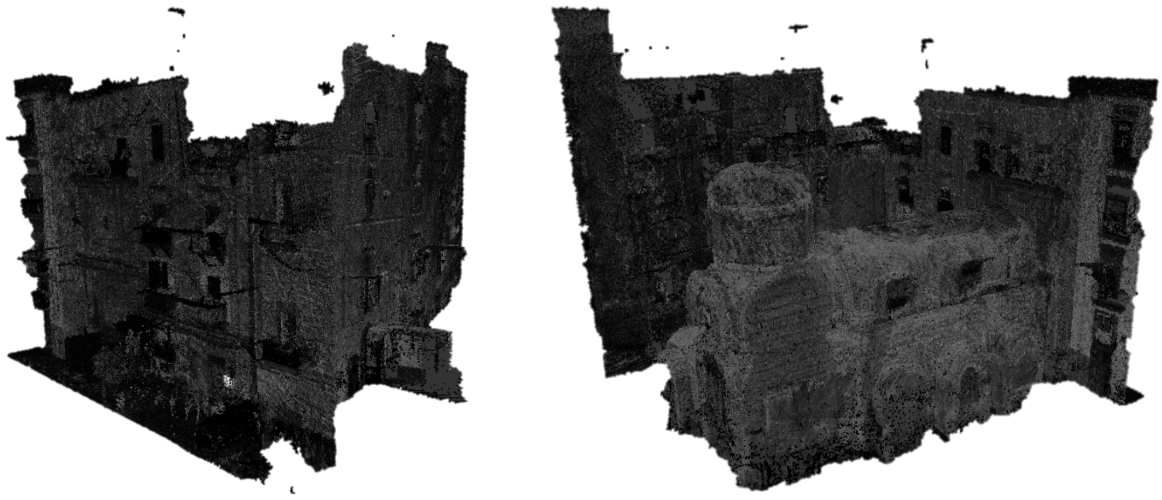


Figure 6.11: Point cloud of the interior and exterior environment of the San Pietro in Vinculis church acquired with SLAM technology

Since all the operations were carried out from the ground floor, the point cloud presented some undetected parts caused by the shadow zones that were inevitably created. For this reason, an aerial photogrammetric survey was carried out by the DiARC group, in particular of the vault of the main nave, the dome and the altar, using a Parrot Anafi Base drone and 21 MP camera and processed with 3D Aerial Zephyr (3D Flow). From the point cloud some significant plans and sections have been extracted, useful to univocally define the geometry of all the elements that make up the building and necessary to elaborate the digital twin of the work. The following are the plan at elevation +2.80 and two significant sections of the chapel and the staircase, the plan at elevation -1.00 m and +10.00 m of the church with relative longitudinal and transversal sections (Fig. 6.12-6.13).

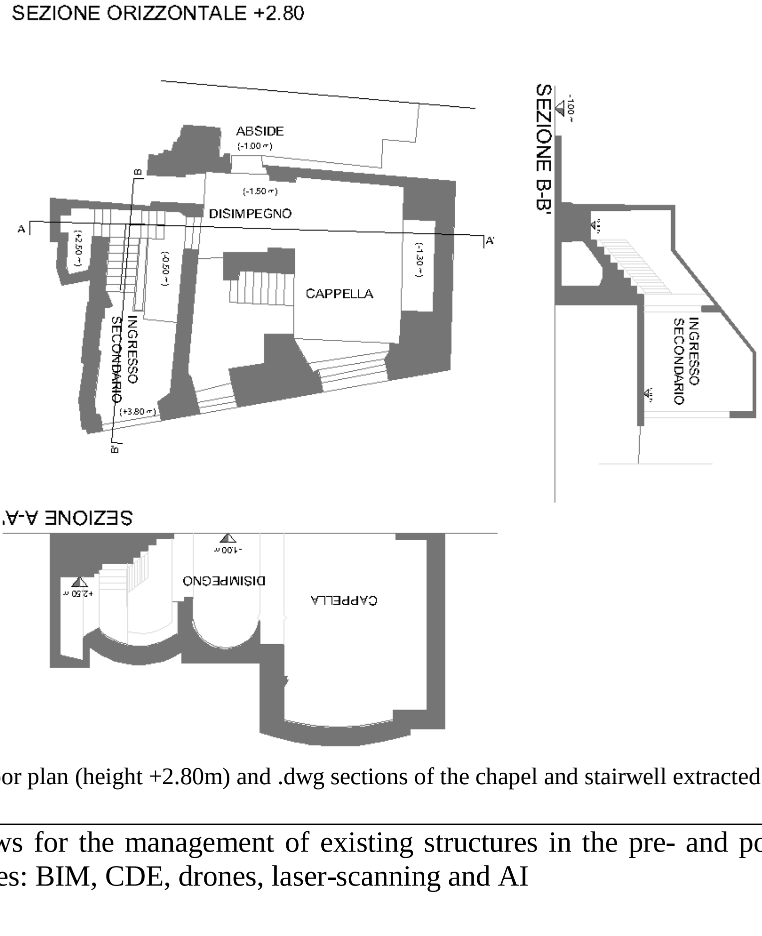


Figure 6.12: Floor plan (height +2.80m) and .dwg sections of the chapel and stairwell extracted from the cloud

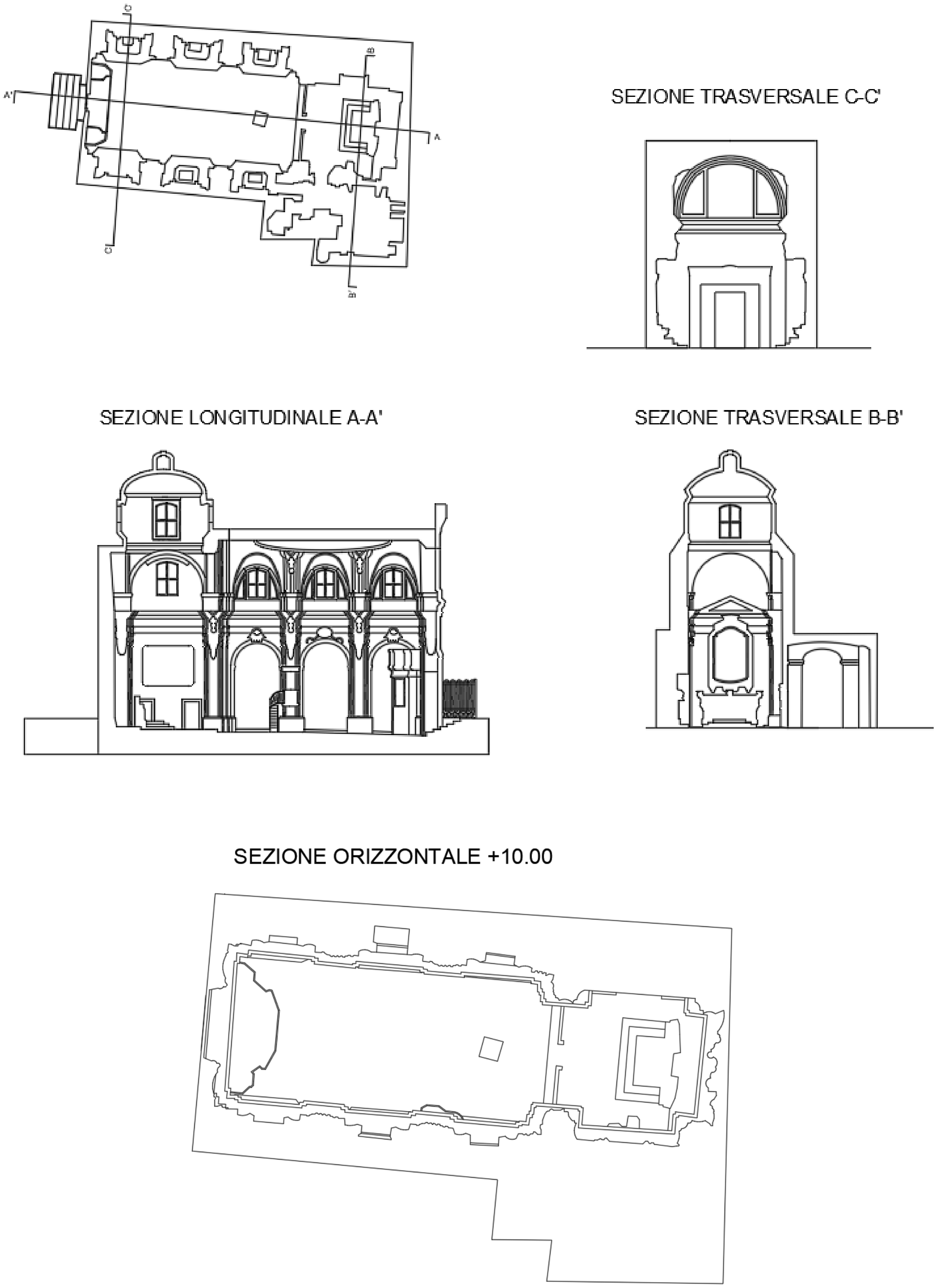


Figure 6. 13: Plans (height -1.00 m and +10.00 m) and .dwg sections of the church extracted from the cloud

In addition to the point cloud, further data sources were acquired. These included 360° photographs of the altar, nave and wooden entrance portal (Fig. 6.14-6.16).

Figure 6.14: Share of the 360° photo of the altar area

Figure 6.15: Share of the 360° photo of the nave area

Figure 6. 16: Share of the 360° photo of the entrance area

Finally, we focused on specific architectural details, taking detailed photogrammetry of the stuccoes of the side altars, capitals, wooden portal, pulpit and altar, from which objects in .obj format have been obtained (Fig. 6.17-6.20).

Figure 6.17: Stuccoes of the side altars in .obj format

Figure 6.18: Capitals in .obj format

Figure 6.19: Wooden portal and pulpit in .obj format

Figure 6.20: Altar in .obj format

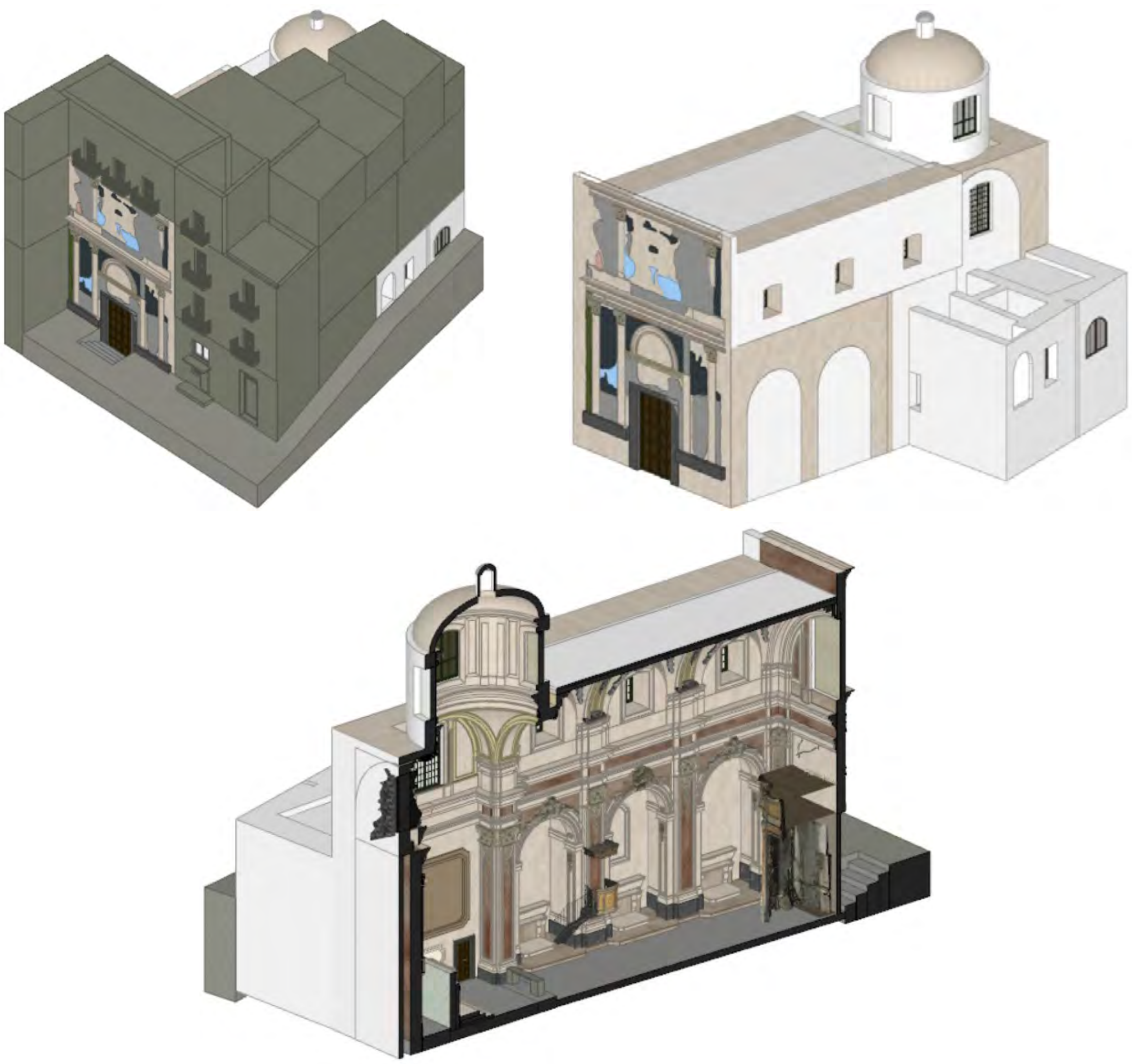
6.4. H-BIM modelling of the San Pietro in Vinculis church

The DiARC team (Emanuela Lanzara, Simona Scandurra, Margherita Pulcrano, Prof.ssa Antonella di Luggo and Prof. Massimiliano Campi) reconstructed the 3D model with all the architectural features of the asset starting from the two-dimensional drawings extracted from the pointcloud.

First of all, a synthetic analysis of semantic decomposition was carried out, through which the entire construction was decomposed into its constituent portions, and the desired level of LOD modelling was defined for each of them. In detail, one of the following modalities was used for the modelling of the elements:

- use of parametric BIM objects encoded within the IFC standard;
- use of parametric BIM objects not currently encoded within the IFC standard but created by ACCA software as considered necessary for H-BIM management are necessary (including vaults and degradations);
- importing objects directly from the point cloud in the .obj format, as they are characterised by uniqueness and therefore cannot be parameterised. These include stuccoes and capitals of the pilasters in the walls of the main nave.

In Fig. 6.21 are shown any perspectives of the completed model with all architectural features are shown.



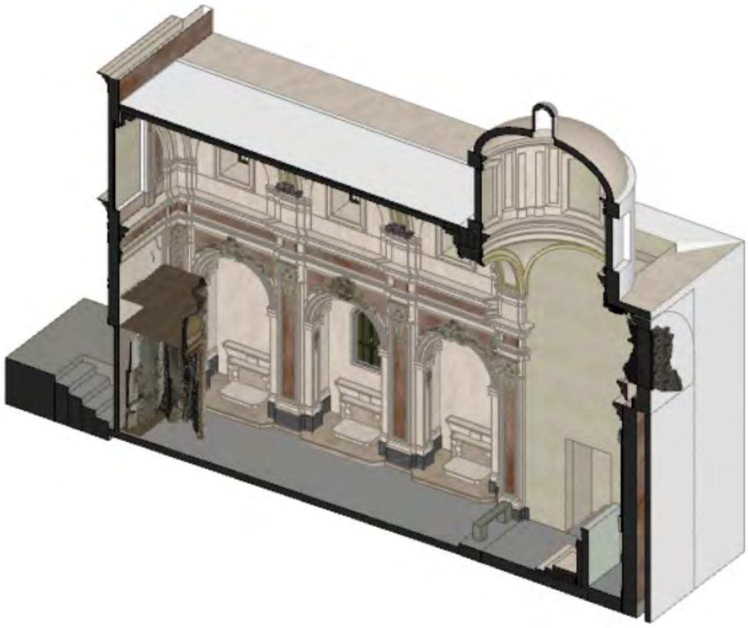


Figure 6.21: Axonometric views and cutaways of the architectural BIM model realized by the DiARC team

The model was then completed with the structural information collected by the DIST team. In detail, for the modelling of the crack pattern, an orthophoto of the main façade in which the course of the cracks was clearly visible was used. Due to the shape of the church, however, it was not possible to take an orthophoto directly on site, but only individual shares of the wall were with the DJI mavic 2 pro UAV, which flew parallel to the wall and taking photos with a regular rhythm. These photos were subsequently stitched together into a single photo with the Image Composite Editor software.

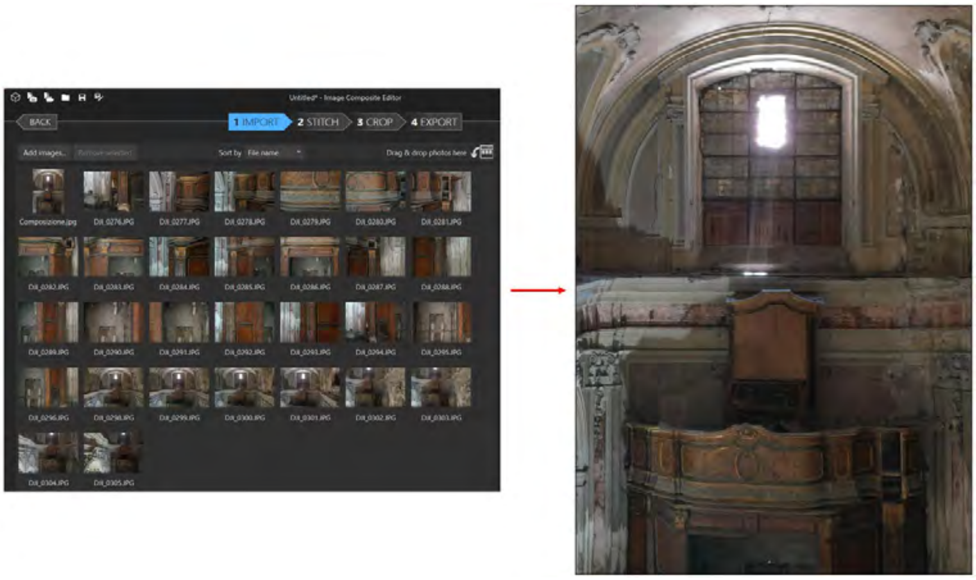


Figure 6.22: Stitching of images on the main façade of the San Pietro in Vinculis church

The crack pattern was then introduced into the BIM model using the 'crack' BIM object avilable into the H-BIM toolbar created by ACCA software. The tool allowed the photo to be uploaded directly into the BIM environment and overlapped the model (Fig. 6.23).

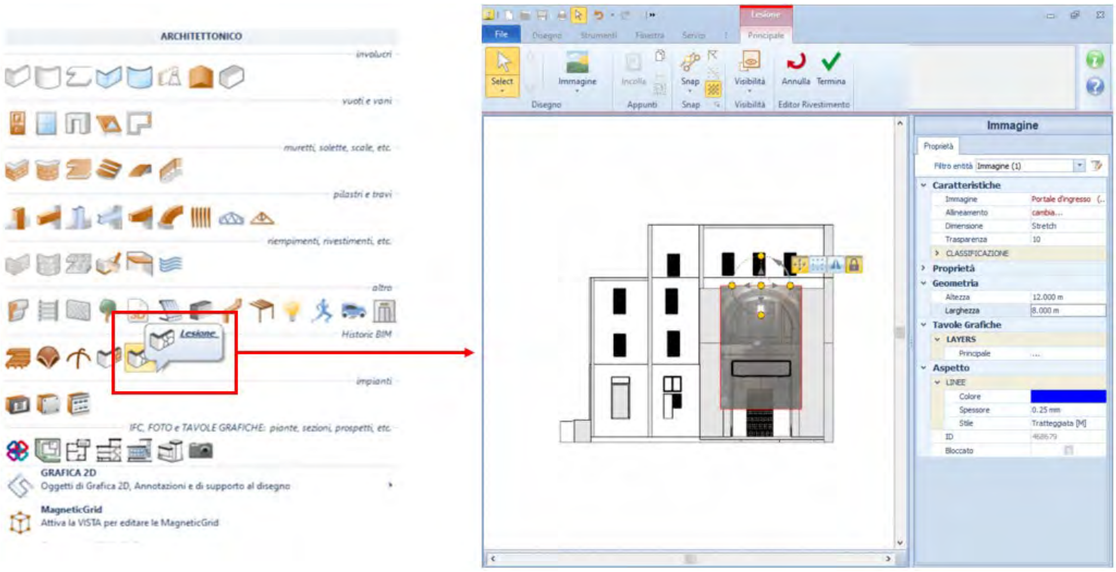


Figure 6.23: Overlapping of the photo to the BIM model of the main façade of the San Pietro in Vinculis church

Assigning a 50% transparency to the photo, both the model and the photo could be seen at the same time so that the best fit was guaranteed. (Fig. 6.24).

Figure 6. 24: Crack modelling

6.5. Seismic vulnerability assessment with implementation of digital mechanism datasheets

After the survey, the BIM modelling and the architectural characterisation of the building, the DIST team performed the last step of the process, consisting in the seismic vulnerability assessment of the asset. The seismic vulnerability assessment of an existing building generally consists of the following steps:

- Identification of the construction;

- Geometrical survey;
- Historical analysis of events and interventions;
- Constructive material survey and definition of the state of conservation;
- Mechanical characterisation of materials;
- Evaluation of geotechnical properties;
- Definition of knowledge level and confidence factor;
- Structural modelling;
- Choice of analysis method (linear static, non-linear static, linear dynamic, non-linear dynamic);
- Definition of the Nominal Life V_N of the structure, of the Use Class C_U and of the Return Period T_R;
- Evaluation of the Safety Index I_S referred to each of the limit states considered.

All these steps, although commonly implemented for ordinary buildings, necessarily require simplification or less detail when applied to historic buildings. In the case of cultural heritage buildings it is objectively difficult to define procedures for verifying safety requirements similar to those applied to ordinary buildings, since the typological variety and constructional singularity (also due to the transformations undergone in the course of the building's history and to its state of preservation) do not allow a univocal and reliable modelling and analysis strategy to be indicated. In these evaluations there are often uncertainties regarding both the modelling criteria and the parameters defining the analytical model. Although it is not always possible to apply the modelling and verification requirements indicated for ordinary buildings to the cultural heritage, it is nevertheless necessary to calculate the seismic loads corresponding to the achievement of the threshold of each limit state, before and after any intervention. The most reliable models should be used for this purpose.

Given the large number of assets that make up this heritage, the assessment tools must be rigorous but sufficiently comfortable to be applied on a large scale; they are based on a scrupulous collection of information through scheduling forms, on the assessment of structural behaviour following knowledge and on the formulation of a preliminary qualitative judgement on the level of seismic risk.

Considering the large number of protected assets, in the case of verifications extended to a territorial scale, these must be understood as an assessment of seismic safety, to be performed with simplified methods, different from those used for the design of an intervention. In any case, it is necessary to quantitatively evaluate the seismic action at SLV and that expected at the site with a prefixed probability of exceedance over a reference period defined on the basis of the features of the building and its use.

For this reason, the Ministry of Cultural Heritage and Activities and Tourism (MIBAC) issued the Guidelines for seismic risk assessment and reduction of cultural heritage aligned with the new Technical Regulations for buildings D.M. 14-01-2008 (trad. *Linee guida per la valutazione e la riduzione del rischio sismico del patrimonio culturale allineate alle nuove Norme Tecniche sulle costruzioni D.M. 14-01-2008*), in which it identified 3 distinct levels of seismic vulnerability assessment.

In detail, level LV1 allows the assessment of seismic action at SLV through simplified methods, based on a limited number of geometric and mechanical parameters or using qualitative data (visual interrogation, observation of construction features, critical and stratigraphic survey).

Two further levels of assessment are then introduced when the seismic vulnerability assessment is aimed at the design of retrofit interventions:

- LV2 (repair or local intervention) - assessments to be adopted for local interventions on limited areas of the building, which do not significantly alter the structural behaviour, for which local analysis methods are suggested; in this case the assessment of the seismic action at SLV for the whole building, however required, is carried out with the LV1 level tools;
- LV3 (intervention for the improvement of the seismic safety index) - design of diffuse interventions in the building, which as far as possible should not modify the structural functioning ascertained through the knowledge pathway; the assessments must concern the whole building, and may use a global structural model, where this can be considered reliable, or the local analysis methods foreseen for level LV2, provided that they are applied in a generalised manner to all the elements of the construction (experience acquired following past seismic events has in fact shown that, for historical masonry buildings, collapse is reached, in most cases, through loss of equilibrium of limited portions of the construction, defined hereafter as macro-elements). The LV3 assessment level can also be used when, without an intervention project, an accurate assessment of the seismic safety of the building is required.

According to the indications of the guidelines, for the San Pietro in Vinculis church reference was made to an LV1 level of assessment since it was aimed at the definition of the state of affairs and not at the design of retrofit interventions.

The systematic analysis of the damage suffered by churches during the main seismic events of the last decades has shown how the seismic behaviour of this type of asset is interpreted through their decomposition into architectural portions characterised by a structural response substantially autonomous with respect to the church as a whole (façade, hall, apse, bell tower, dome, triumphal arch, etc.).

Only in the case of churches with a central plan, which generally have one or more axes of symmetry in constructive homogeneity and good connections between the elements, is it significant to proceed to an overall analysis of the construction (linear or non-linear), evaluating for example the capacity curve an incremental collapse analysis and verifying all the effects due to pushing elements, such as arches, vaults and roofs.

In most cases it is preferable to proceed with local verifications, which generally refer to the different macro-elements, which become the reference unit for structural verification.

Therefore, because of the great variety of types and construction of churches, a simplified mechanical model for assessing seismic safety is preferred, based on a limited number of parameters:

- the maximum ground acceleration corresponding to the different limit states;
- the vulnerability index i_V, obtained through an appropriate assessment of the elements of vulnerability and anti-seismic protection.

The methodology used considers 28 damage mechanisms that can affect the macro-elements of a church and that are listed in the following Tab. 6.1.

Table 6.1: List of damage mechanisms proposed in the new survey methodology

Failure mechanisms		Failure mode	Macro-element
M1	Façade overturning	I	Façade
M2	Mechanisms at the top of the façade	I	
M3	Mechanisms in the façade plane	II	
M4	Prothyrum-narthex	I/II	
M5	Transverse response of the church hall	I	Hall
M6	Shear mechanisms in the side walls	II	
M7	Longitudinal column response (multi-aisled churches)	I	
M8	Vaults of the nave	I/II	
M9	Vaults of the side aisles	I/II	
M10	Overturning of the end walls of the transept	I	Transept
M11	Shear mechanisms in the transept walls	II	
M12	Transept vaults	I/II	
M13	Triumphal arches	II	Triumphal arches
M14	Dome - drum/tiburium	I/II	Dome
M15	Lantern	I/II	
M16	Apse overturning	I	Apse
M17	Shear mechanisms in the presbytery or apse	II	
M18	Presbytery or apse vaults	I/II	
M19	Mechanisms in the roofing elements (hall side walls)	I/II	Roofing
M20	Mechanisms in the roofing elements (transept)	I/II	
M21	Mechanisms in the roofing elements (presbytery or apse)	I/II	
M22	Church drum	I	Chapels and annexes
M23	Shear mechanisms in chapel walls	II	
M24	Chapel vaults	I/II	
M25	Interactions in proximity of irregularities	I/II	
M26	Overhangs (sail, spires, spandrels, statues)	I	Bell tower overhangs
M27	Bell tower	I/II	
M28	Bell chamber	I/II	

The mechanisms that can be activated, however, do not contribute equally to the overall assessment of the seismic vulnerability of the church, although they all do, so a factor quantifying the weight of each mechanism ρ_k was introduced. First of all it is necessary to check if some macro elements are not contemned in the church, so that any mechanisms could not occur in the church after an earthquake, and to these assign ρ_k =0; the others should be given the value k=1, except for mechanisms 4 and 15 where ρ_k =0.5 and some mechanisms (10, 11, 12, 18, 20, 22, 23, 24, 25, 26), where a value 0.5< ρ_k <1 should be chosen, in relation to the importance of the element in the context of the construction. The values of ρ_k for each mechanism are summarized in Tab. 6.2.

Table 6.2: List of ρ_k values for all the damage mechanisms

Failure mechanism		Assigned value	Variability range
M1	Façade overturning	1	
M2	Mechanisms at the top of the façade	1	
M3	Mechanisms in the façade plane	1	
M4	Prothyrum-narthex		0.5÷1
M5	Transverse response of the church hall	1	
M6	Shear mechanisms in the side walls	1	
M7	Longitudinal column response (multi-aisled churches)	1	
M8	Vaults of the nave	1	
M9	Vaults of the side aisles	1	
M10	Overturning of the end walls of the transept		0.5÷1
M11	Shear mechanisms in the transept walls		0.5÷1
M12	Transept vaults		0.5÷1
M13	Triumphal arches	1	
M14	Dome - drum/tiburium	1	
M15	Lantern	0.5	
M16	Apse overturning	1	
M17	Shear mechanisms in the presbytery or apse	1	
M18	Presbytery or apse vaults		0.5÷1
M19	Mechanisms in the roofing elements (hall side walls)	1	
M20	Mechanisms in the roofing elements (transept)		0.5÷1
M21	Mechanisms in the roofing elements (presbytery or apse)	1	
M22	Church drum		0.5÷1
M23	Shear mechanisms in chapel walls		0.5÷1
M24	Chapel vaults		0.5÷1
M25	Interactions in proximity of irregularities		0.5÷1
M26	Overhangs (sail, spires, spandrels, statues)	0.8	
M27	Bell tower	1	
M28	Bell chamber	1	

At each mechanism corresponds a dedicated datasheet in which the possible elements of anti-seismic protection and vulnerability indicators are suggested; other elements can be added to these lists if they emerge, following specific knowledge of the construction, as significant for the evaluation of the seismic behavior of the church. As a way of example, Fig. 6.25 shows the datasheet relating to mechanism M1 - façade overturning.

1 – RIBALTAMENTO DELLA FACCIATA				
Presenza del macroelemento in relazione al meccanismo: Si ❑ No ❑				
Vulnerabilità	Si	No	*Presidi antisismici*[1]	
	❑	❑	Presenza di catene longitudinali[2]	❑ ❑ ❑
	❑	❑	Presenza di efficaci elementi di contrasto (contrafforti, corpi addossati, altri edifici)[3]	❑ ❑ ❑
	❑	❑	Ammorsamento di buona qualità tra la facciata ed i muri della navata[4]	❑ ❑ ❑
	❑	❑	....	❑ ❑ ❑
	Si	No	*Indicatori di vulnerabilità*[5]	
	❑	❑	Presenza di elementi spingenti (puntoni di copertura, volte, archi)[6]	❑ ❑ ❑
	❑	❑	Presenza di grandi aperture nelle pareti laterali in vicinanza del cantonale[7]	❑ ❑ ❑
	❑	❑	....	❑ ❑ ❑
Danno	attuale[8]		Distacco della facciata dalle pareti o evidenti fuori piombo[10]	❑ ❑ ❑ ❑ ❑
	pregresso[9]		Distacco della facciata dalle pareti o evidenti fuori piombo[10]	❑ ❑ ❑ ❑ ❑

Figure 6.25: Datasheet related to the mechanism M1- façade overturning

From the analysis of the datasheet M1, it can be seen that the first line shows the name of the mechanism or macro-element whose vulnerability is to be assessed, with a box next to it in which to mark whether the macro-element is present in the church being considered, useful for defining with certainty whether the mechanism has been considered or not and thus eliminating one of the main sources of ambiguity that emerged from a previous version of the same sheet. In the next line, instead, the anti-seismic devices that can counteract the activation of the above-mentioned kinematic mechanism and a series of vulnerability indicators that can instead increase the propensity to damage are reported. For each of them, the surveyor highlights the presence or absence (Yes - No), and in the right column expresses a judgement on the effectiveness of the construction detail, modulating his judgement on three different levels (0: ineffective; 1: modest; 2: good; 3: completely effective).

The last box is referred to the survey of the damage, whose assessment must be carried out in relation to 5 levels of damage in accordance with the EMS98 methodology (Gruntal et al., 1998; Lagomarsino and Podestà, 1999, Tab. 6.3). In particular, a distinction is made between current damage, corresponding to that observed at the time of the inspection, and past damage, i.e. due to phenomena that occurred before the seismic event under investigation.

Table 6.3: Damage level of the EMS macroseismic scale for churches

Level	Description of the structural damage
0	Undamaged
1	Minor or negligible damage: minor or moderate damage in some mechanisms
2	Medium damage: moderate damage in many mechanisms, with one or two mechanisms activated at medium level
3	Severe damage: many mechanisms activated at medium level, with some mechanisms at severe level
4	Very serious damage: serious damage in many mechanisms, with possible collapse of some elements of the church
5	Collapse: more than 2/3 have a level of damage corresponding to the collapse

With reference to the vulnerability assessment, it is necessary to detect those typological and constructive details that play a fundamental role in the seismic response of the building; in particular, vulnerability and anti-seismic protection indicators are considered. The seismic behavior of the whole building is represented, on a statistical basis, by a vulnerability index, variable between 0 and 1, which is defined as a weighted average of the behavior of the different parts of the church:

$$i_V = \frac{1}{6}\frac{\sum_{k=1}^{28} \rho_k (v_{ki} - v_{kp})}{\sum_{k=1}^{28} \rho_k} + \frac{1}{2}$$

Where, for the k-th mechanism:

v_{ki} is the score obtained from the vulnerability indicators;

v_{kp} is the score obtained by the anti-seismic indicators;

Both indices can be calculated with reference to Table 6.4.

Table 6.4: Vulnerability score assessment for each damage mechanism

Assessment of effectiveness	Number of vulnerability indicators or anti-seismic indicators	v_k value
3	minimum 1	3
2	minimum 2	
2	1	2
1	minimum 2	
1	1	1
0	-	0

Thanks to the experience of the numerous surveys carried out on churches damaged during seismic events, it was possible to introduce an additional parameter that quantifies the degree of damage suffered by each macro-element, in relation to the different possible damage mechanisms. The damage index i_d is variable between 0 and 1 and is evaluated as the normalized average of local damages:

$$i_d = \frac{1}{5}\frac{\sum_{k=1}^{28} \rho_k d_k}{\sum_{k=1}^{28} \rho_k}$$

where d_k is the level of damage suffered by the k-th mechanism (from 0 to 5).

With all the parameters defined can be calculated the global safety index of the building in a simple way. In fact, the datasheets for the survey of damage and vulnerability of churches have been used in seismic emergencies since 1995; the considerable amount of data collected (over 4000 churches) has allowed, through statistical processing, to establish a relationship between the seismic action and damage, according to the vulnerability index of the church. It is evident that an estimate made in this way has a purely statistical value, but this approach can be considered correct if aimed at a territorial analysis, in order to establish priority lists and better plan more in-depth evaluations and address prevention interventions. Moreover, the use of a unitary model for assessments of this nature allows a more objective relative comparison in terms of seismic risk.

From the statistical analysis of the damages suffered, the probabilistic distributions associated with different seismic intensities (damage probability matrices) were evaluated, as the vulnerability index varied. Through an appropriate correlation between the intensity and the peak ground acceleration, it was possible to define a direct correlation between the seismic input associated to the different limit states and the detected vulnerability. This allows to calculate, for each church, the values of the ground acceleration corresponding to the damage limit state (SLD) and to the life-saving limit state (SLV) through the following relations:

$$a_{SLD}S = 0.0025 \times 1.8^{2.75-3.44i_v}$$
$$a_{SLV}S = 0.0025 \times 1.8^{5.1-3.44i_v}$$

It is therefore possible to define an acceleration factor, defined by the ratio between the ground acceleration leading at the SLV and the acceleration corresponding to the reference return period, both referring to subsoil category A:

$$f_{a,SLV} = \frac{a_{SLV}}{a_{g,SLV}}$$

The illustrated procedure was implemented using digital tools, which considerably simplified its application. Through the use of #tagBIM, macro-elements have been introduced directly into the architectural BIM model, which allow to identify among all the objects of the model those that are part of each mechanism.

Figure 6.26: Implementation of the #tagBIM into the H-BIM model

Thanks to the usBIM.data application, each of the elements making up the macro-element has been assigned the corresponding mechanism datasheets. As a way of example, the model for the M1-facade overturning mechanism is shown in Fig. 6.27.

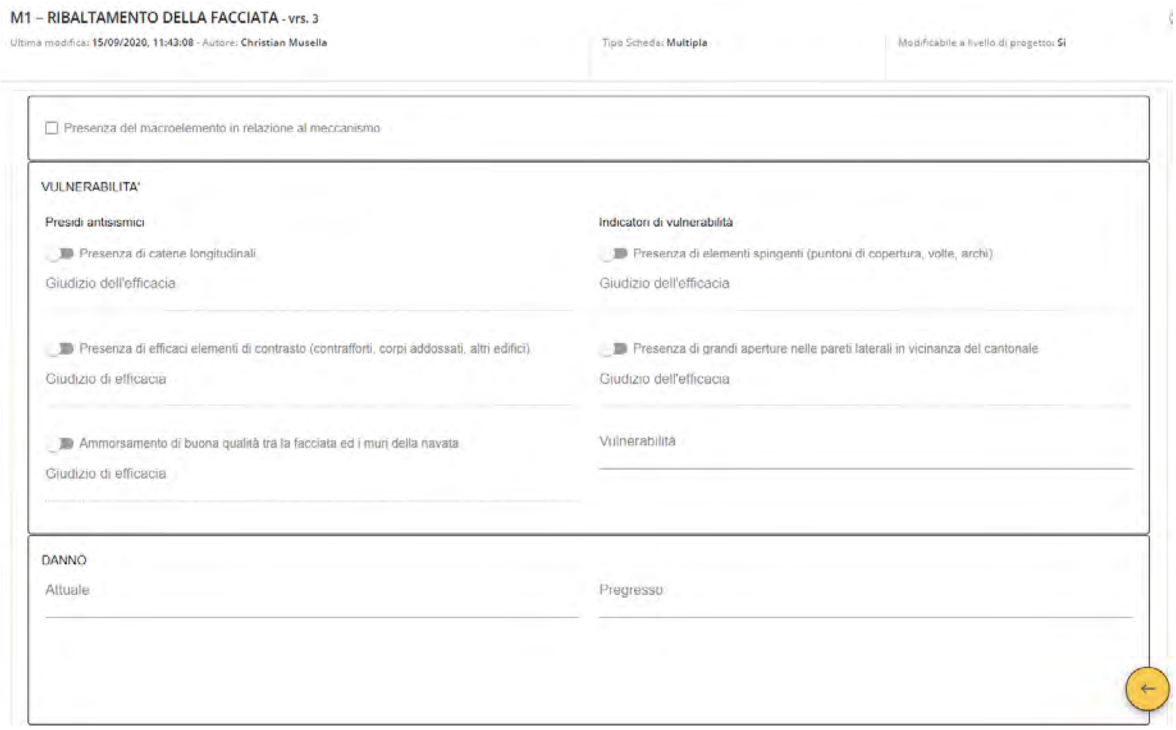


Figure 6.27: Digital datasheet related to the mechanism M1- façade overturning

These datasheets are to be filled in on site as traditional paper sheets. For the calculation of the parameters, an additional sheet has been elaborated and is unique for all mechanisms (Fig. 6.28).

Figure 6.28: Digital parameter datasheet

The use of a single tab for the collection of parameters makes it possible, on the one hand, to comfortably introduce the information into the model and, on the other, to systematically extract it in a single Excel table (Tab. 6.5).

Table 6.5: Table of the parameters extracted from the H-BIM model

Macro-element	Mechanism	ρ_k	d	V_I	V_P
FACADE	M1 - Façade overturning	1	0	1	0
	M3 - Mechanisms in the façade plane	1	1	2	2
HALL	M5 - Transverse response of the church hall	1	4	3	3
	M6 - Shear mechanisms in the side walls	1	0	3	3
	M8 - Vaults of the nave	1	0	3	0
TRIUMPHALL ARCHES	M13 - Triumphal arches	1	1	0	2
DOME	M14 - Dome - drum/tiburium	1	1	1	0
	M15 - Lantern	0.5	0	0	2
CHAPEL AND ANNEXES	M22 - Church drum	1	1	0	2
	M23 - Shear mechanisms in chapel walls	1	1	2	2
	M24 - Chapel vaults	1	2	0	0

For the sake of brevity, the details of all the mechanism and parameter datasheets for each of the mechanisms that can be activated in the church of San Pietro in Vinculis have been reported in Annex B. Thanks to the relations illustrated previously, finally, the acceleration factor f_a is obtained, assuming that both the stratigraphic and topographic factors have unit values (S_S = S_T=1) and that therefore S=1 as well.

Table 6.6: Calculation of the acceleration factor

DAMAGE INDEX (I_D)	VULNERABILITY INDEX (I_V)	a_{SLV} (g)	a_{SLD} (g)	$a_{g, SLV}$ (g)	f_a
0.21	0.5	0.18	0.05	0.26	0.70

Following the seismic vulnerability analysis, further descriptive sheets were added to the model, reporting the considerations made by the team of structural engineers regarding the evolution of the structural instability, useful for defining a suitable intervention strategy (Fig. 6.29).

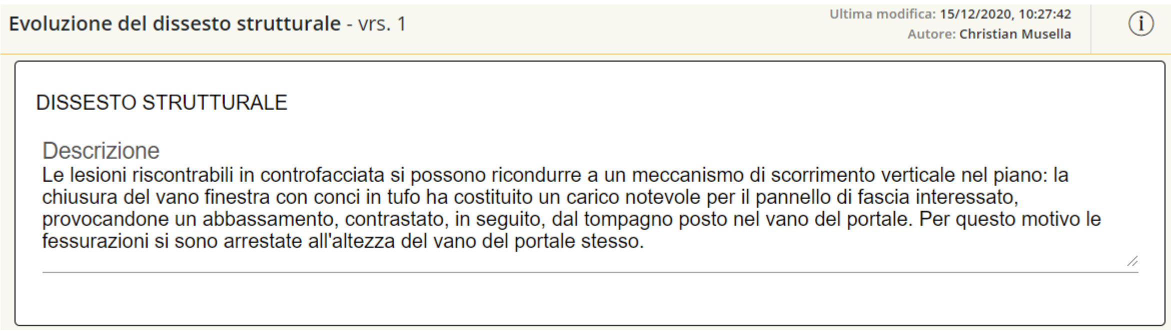


Figure 6.29: Datasheet for the structural instability of the main façade of the San Pietro in Vinculis church

Conclusions

The digital management of historic buildings involves the use of numerous technologies, which must be appropriately combined in order to manage optimised information flows based on the exchange of information between all actors in the process, and aimed at reducing the time and resources used. The experimentation carried out on the church of San Pietro in Vinculis used the Common Data Environment (CDE), drones, laser scanners and BIM models. Among these, the CDE was structured to manage all the documents and files produced in the process, and to communicate this information effectively. Both drones and laser scanners were used for the survey. In detail, the dynamic laser-scanner was used to perform a quick geometric survey of the entire church (operation time about 10 minutes) with an approximation in the measurements of less than 3 cm, while drones were used to perform detailed aero-photogrammetric acquisitions of specific elements, which were then combined to obtain a complete and sufficiently detailed point cloud. This information was the reference to proceed with H-BIM modelling. Bi-dimensional plants and sections were extracted from the point cloud in CAD format and introduced into the BIM authoring software as references for modelling. In order to create a digital twin of the asset as faithful, part of the elements, those most similar to the logic of parameterization, were modelled with BIM objects, while those with unique characteristics, such as stucco, capitals and altar, were imported into the BIM model as mesh objects. The resulting H-BIM model made it possible to implement typical structural engineering processes. Once the crack patterns affecting the various macro-elements into which the church can be broken down had been modelled (thanks to the BIM objects developed as explained in detail in chapter 5), the mechanism datasheets for all the mechanisms that can be activated in the church were filled, in accordance with the MIBACT guidelines. The usBIM.data application developed by ACCA software was used for this purpose, allowing the creation of forms for each datasheet, which was then filled in with the information gathered during the in-situ surveys. With these datasheets, the data was collected directly on the BIM model, which were then processed to calculate the vulnerability and damage parameters associated with each mechanism, and finally to obtain the acceleration ratio on a statistical basis, calculated as the ratio between the acceleration inducing the attainment of the Safeguard Limit State (SLV) and the demand values established according to the NTC2018 standard.

Finally, it can be stated that digital technologies are a valuable support for the implementation of processes involving numerous actors through the implementation of well-structured workflows.

References

[1] https://www.napolitan.it/2016/01/04/36189/degrado-della-chiesa-di-san-pietro-in-vinculis/

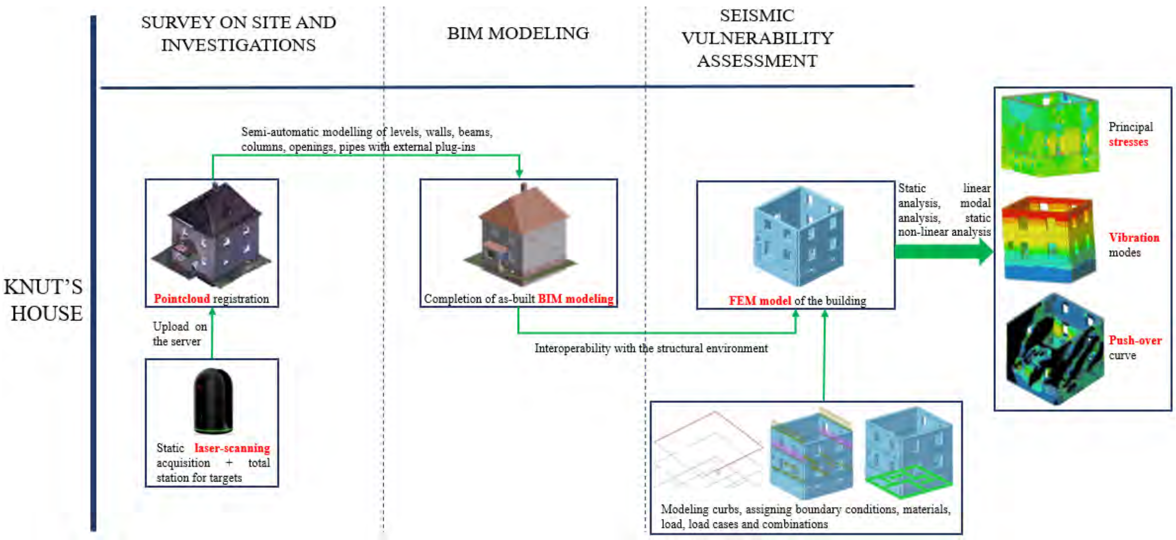
[2] Casapulla C.(2016). La valutazione della sicurezza sismica delle chiese a scala territoriale – Book chapter: Il Patrimonio architettonico ecclesiastico di Napoli: Forme e spazi ritrovati. Publisher: Artstudio Paparo

CONCLUSIONS

The main topic of this thesis was the study of the application of the BIM methodology to existing buildings. The BIM methodology, if correctly implemented, guarantees the reduction of inefficiencies in the construction industry, thanks to the use of digital tools and techniques which lead to an optimization of productive, management and documentation processes. Among the most complex processes are those related to structural engineering, due to the need to relate the structural BIM model to the analytical model. Indeed, interoperability between different software is a crucial point for the implementation of workflows. For this reason, it is always desirable that information exchange processes are based on openBIM standards.

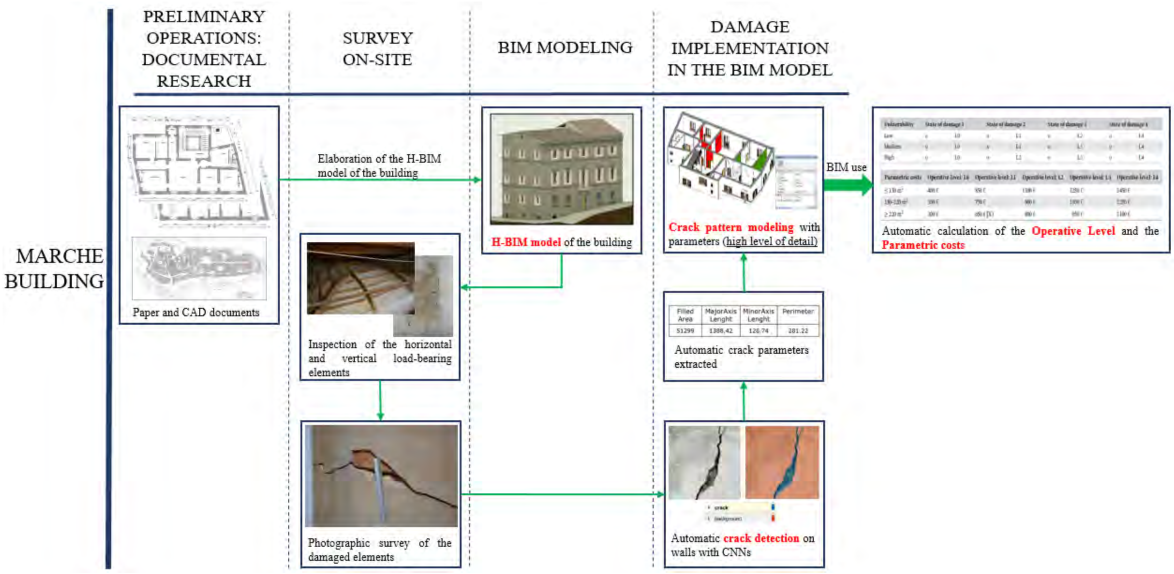
The approach used consisted in defining processes for the management of the structures in the pre- and post-earthquake phases based on the openBIM standards, and in particular of the Information Delivery Manual (IDM) - process standard - and of the Industry Foundation Classes (IFC) - product standard - not bound to specific software applications. According to the IDM standard, process maps were developed, in which were summarized all the operations that are carried out during a project and the party responsible for each of them. This process was then applied to case studies of existing buildings characterized by different peculiarities, including the state of health, which may be damaged or undamaged, the feature of the building, which may be ordinary or historic, and with different starting conditions, with the aim of defining workflows applicable to different types of buildings, as they can hardly be grouped into a single class.

The first workflow implemented is the scan-to-FEM process, which takes into account all the phases that go from the digital survey of masonry structures to the creation of the FEM model and the performance of the structural analysis. The procedure was applied to an ordinary three-dimensional building (Knut’s house), which required the use of a laser-scanner for the geometry acquisition. The BIM model was then obtained semi-automatically from the pointcloud together with the FEM model, in which the walls are modelled with shell-type 2D elements. Several type of analyses were performed to check the FEM model and to make a safety assessment of the structure. In detail, with the static linear analysis was monitored the reliability of the stresses flow acting due to gravity loads; with the modal analysis were monitored the structure vibration modes and periods; with the non-linear static analysis the safety conditions of the structure were assessed. The whole workflow turned out to be faster and more controllable than a traditional one, saving time and resources. In order to verify the extensibility of the method to historic buildings, the process was applied on two of the facades of the Santa Chiara monastery (historical building). The BIM model was then moved into the analytical environment, where the modelling operations continued with the application of constraints, materials, cases and load combinations and where the structural analysis was performed to calculate the stresses and deformations. In any case, the application of the method was less convenient in this case, due to the presence of many walls with irregular cross-section shape and unique decorative objects, which make lower the level of automation.



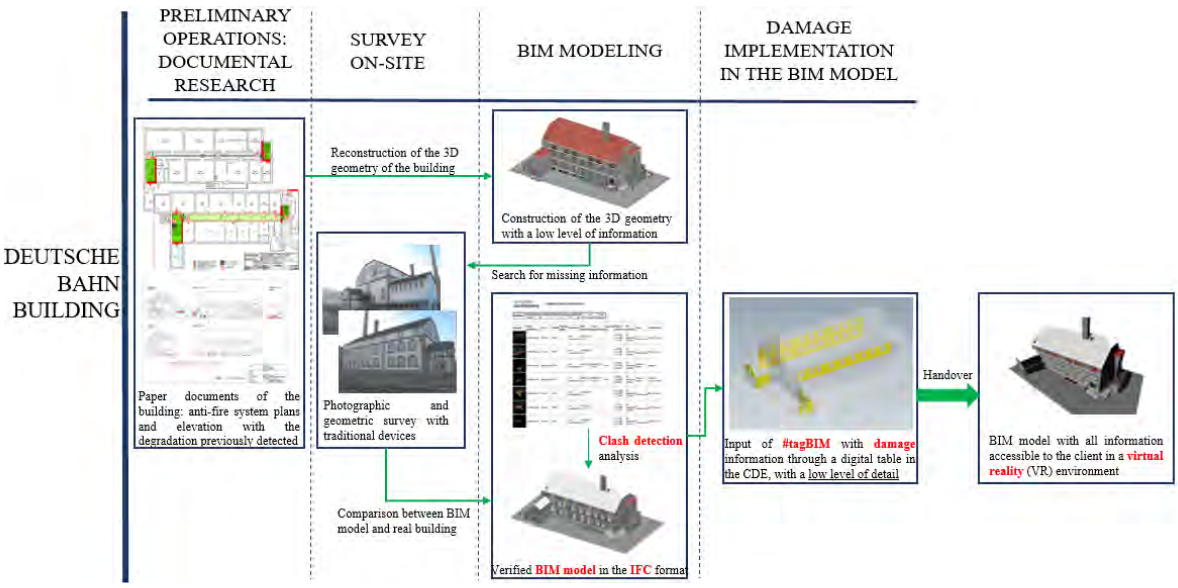
While this process proved to be correctly implementable, greater difficulties were faced with those related to the analysis of damaged structures, typical of the post-earthquake phase, which required more extensive experimentation and the development of ad-hoc software applications.

The first process tested consisted in the evaluation of the Operative Level of a historical masonry building (Marche building), damaged after the seismic event that affected the Marche region in 2016. For the purpose, two Convolutional Neural Networks (CNNs) were developed for the crack detection, one of which was able to isolate cracks from plastered surfaces (that is more suitable for application in indoor environments) and a second one that can isolate cracks from bricks and mortar joints (and therefore is more suitable for application in outdoor environments). Thanks to the use of CNNs, all cracks were automatically detected, and the parameters that characterize them were extracted, including the filled area, the major and minor axis length and the perimeter. These parameters were input parameters for the BIM model. A damage encoding system in a BIM environment was developed, in order to classify all the cracks detected, according to their position within the building and their relevance, the presence of out-of-plumb, detachments, swellings, and also identifying cracked surfaces, thus completing the set of parameters. The cracks were then introduced into the model as BIM objects (classified as "generic models" since the IFC standard does not include yet a class for the digitalization of crack patterns) equipped with all the parameters listed. The model was then used for the information management and to extract tables useful for calculating the Operative Level, which led to the definition of the economic incentives for retrofitting the building and to determine the type of intervention to which these funds can be allocated.



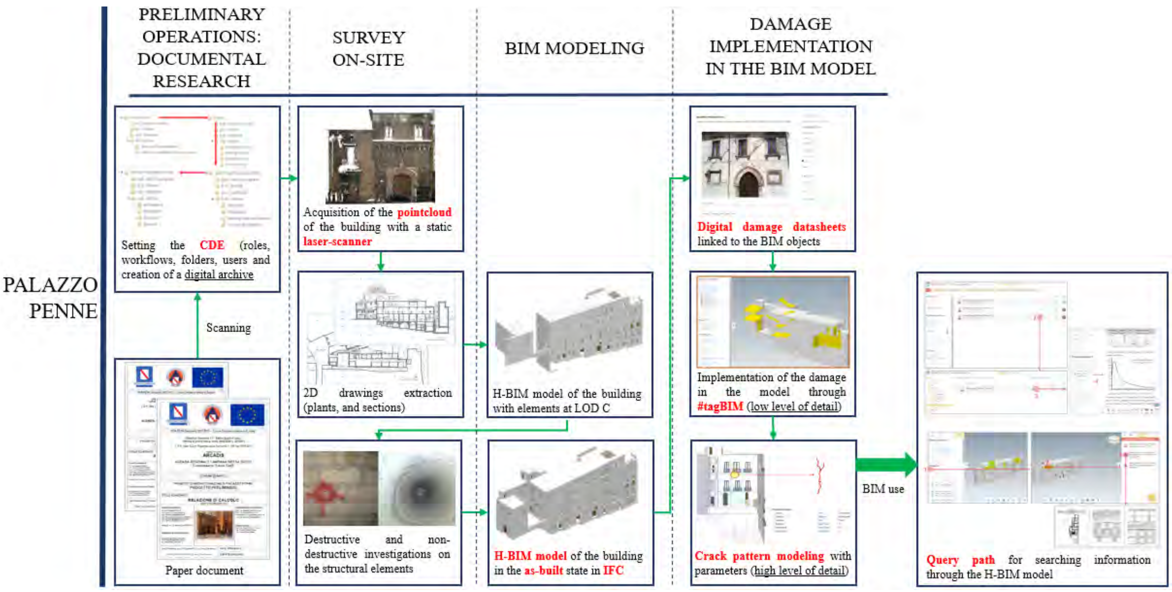
Due to the large amount of information flowed during these processes and the many actors involved in them, the attention was then focused on the benefits that the implementation of a Common Data Environment (CDE) can bring to the management of existing buildings. In particular, applications were carry out both for ordinary buildings and historic ones.

The object of study for ordinary buildings was an office building owned by Deutsche Bahn Immobilien placed in Leipzig (GE), which needed retrofit interventions. A BIM model of the building was obtained starting from paper plans and elevations, which was verified thanks to a clash detection analysis and input into the CDE. Information about the building damages, which was initially also available on paper reports, was then referenced on the model. Starting from the reports, the photos capturing the damage were extracted and inserted as links directly onto the model objects. With the introduction of #tagBIM, a digital damage table was created, so that the damages have been placed on the model objects in a smart way. It follows that even in the absence of damage-specific BIM objects, the information was still digitalized, but with a lower level of detail, with the aim of optimizing the resources deployed in the project.



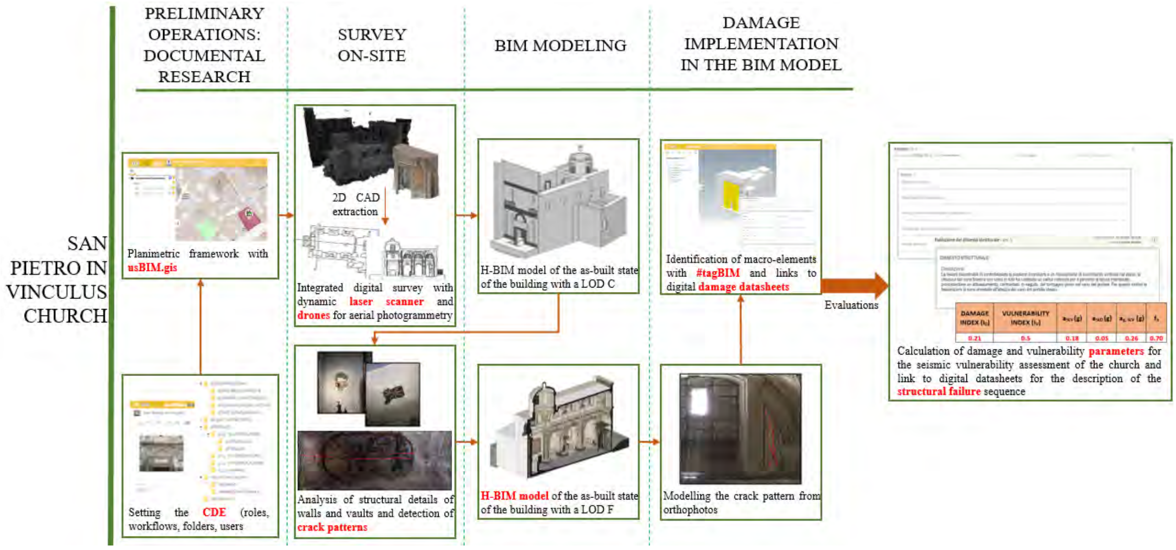
The CDE was then implemented for the information management of Palazzo Penne, a historical building placed in the center of Naples. Structural and architectural retrofit interventions were already designed for Palazzo Penne but in a traditional way, so that starting from those information any digital tools have been tested. Given the large amount of documents, a digital archive was implemented thanks to the #tagBIM; after defining an encoding system, it was applied to all the documents, so that it was possible to make researches by simply ticking boxes on a table list. With reference to the building modelling, starting from the point cloud, and from the two-dimensional elaborations extracted from it, the H-BIM model was created, whose objects reached LOD C. Rather than focusing on the geometric details of the elements, the main focus was the management of information of interest. With the #tagBIM all the information about the damage of the building, the tests performed and the retrofit interventions have been input in the model, while with the markers have been placed the photos capturing the damages. With the links, a direct connection was created between the documents in the archive and the elements of the model. Thanks to all these operations, were created relations between all the files in the CDE, so that query paths were stablished that turned out to be useful for the research of any information. In fact, with the #tagBIM a quick access is guaranteed to the elements of the model and then to the documents relating a specific information. Similarly, within the documents a direct access to information was guaranteed through bookmarks and #tagBIM without need to search in the documents. It follows that better accessibility is also guaranteed to information that could not be included in the H-BIM model, such as the seismic response spectra at the SLD and SLC and the safety index of the construction,

Palazzo Penne was even used for the development and testing of digital applications useful for the implementation of the BIM methodology. In carrying out these experiments, technological deficiencies were identified in the management of damage files (frequently used to manage survey operations) and of the damage itself. Thanks to the collaboration with the firma ACCA software, the usBIM.data application was developed, which allows the creation of digital datasheets and the referencing of information as metadata directly on the objects of the BIM model. It follows that any information can be acquired directly on site and input into the CDE, avoiding the usual time consuming operation, such as the manual compilation and subsequent scanning. In addition, specifications were provided for the creation of BIM "crack" objects, including the definition of the set of parameters, the methods of introducing them into the model and the methods of displaying them in two-dimensional views. It follows that with the Edificius software it is now possible to digitalize the crack pattern, an operation which is currently not allowed by other BIM authoring software, except by forcing such tools.



Thanks to the analysis of these case studies, it was pointed that with the application of the BIM methodology to existing buildings, similarly to the design of new buildings, is still valid the principle which state that workflows must be developed ad-hoc according to the objectives of each project, the uses of the model and the importance of the building, to which are added two further variables relating to the technological component, especially in the survey phase, and the availability of information before starting the process. In fact, it has been observed that thanks to the availability of a wide range of survey methodologies, a careful planning of the operations is always required, which must be optimized according to the conformation of the building, the accessibility of the areas, the expected degree of precision and the available instruments. Moreover, depending on the information available, it may be useful to define methods for their use by all the team members of a project (such as the implementation of digital archive).

Basing on these considerations, the digitization of the San Pietro in Vinculis church was performed, with the aim to maximize the benefits coming from the use of previously tested digital techniques and tools. It is a historic church in an aggregate, which is severely prone to instability and decay. In a preliminary phase, the existing documentation was collected, the CDE was set up and the digital mechanism datasheets were prepared, useful to collect the information of the damage on site. Then, the on-site surveys have been performed, filling the mechanism datasheets for the several macro-elements and gathering the geometric information with the integration of dynamic laser-scanning and drone photogrammetry technologies, necessary to detect the inaccessible parts or to collect higher details of specific objects. The scans were used to reconstruct the H-BIM model of the as-built state of the church, while the orthophotos were used to reconstruct the crack patterns. Filling the mechanism datasheets, the parameters useful for defining the ground acceleration values leading to the drawing of the Damage Limit State (SLD) and the Life-saving Limit State (SLV) were obtained, which led to the definition of the safety index of the construction by means of statistical correlation formulas pertaining the seismic accelerations.



In all the cases examined, the implementation of the digital workflows allowed all operations to be carried out in a fast and controlled manner, avoiding errors, rework and loss of errors, and saving time and resources compared to the use of traditional working methods. In addition, the BIM models turned out to be very useful for the centralization of all the information, and provided valuable support during all phases, including the seismic vulnerability assessment. This ensures that all information is available throughout the building's life cycle, even for design phase of retrofit interventions that could be deemed necessary.

In conclusion, in response to the 3 research questions, regarding the convenience of applying BIM methodology to existing structures (1st question), it can be stated that, despite the difficulties involved, it is still convenient if compared to the traditional methods, as it always guarantees higher quality standards of the processes. However, with reference to the maturity level of its application (2nd question), due to the use of considerable resources necessary for the elaboration of the BIM models of buildings that are often catheterized by a complex geometry, and are far from the logic of standardization, it is advisable to implement low LOD levels to the BIM objects in order to optimize the resources in the modelling phase, and to refer to the BIM models as access keys to the numerous information rather than three-dimensional representations. Finally, with reference to the field of structural engineering processes (3rd question), it was found that BIM methodology can be a useful support for seismic safety and vulnerability assessments carried out with both analytical and empirical methodologies. In fact, regarding the analytical methods, it considerably speed up the realization of FEM models, importing geometry directly from the BIM model thanks to the interoperability of software; with reference to the empirical methods, the digitalization of the crack patterns turned out to be a valid support, as all the information relating to damages can be stored and easily managed.

ANNEX A: MATLAB SCRIPTS FOR SETTING UP CNNs FOR CRACK DETECTION ON PLASTERED AND BRICK-EXPOSED WALLS

CNN for crack detection on plastered walls
Script:

```
%%
inputSize = [256 256 1];
imgLayer = imageInputLayer(inputSize)
filterSize = 8;
numFilters = 32;
conv = convolution2dLayer(filterSize,numFilters,'Padding',1);
relu = reluLayer();
poolSize = 2;
maxPoolDownsample2x = maxPooling2dLayer(poolSize,'Stride',2);

downsamplingLayers = [
	conv
	relu
	maxPoolDownsample2x
	conv
	relu
	maxPoolDownsample2x
	]
filterSize = 9;
transposedConvUpsample2x = transposedConv2dLayer(4,numFilters,'Stride',2,'Cropping',1);

upsamplingLayers = [
	transposedConvUpsample2x
	relu
	transposedConvUpsample2x
	relu
	]

numClasses = 3;
conv1x1 = convolution2dLayer(1,numClasses);

finalLayers = [
	conv1x1
	softmaxLayer()
	pixelClassificationLayer()
	]
%%
net = [
	imgLayer
```

```
        downsamplingLayers
        upsamplingLayers
        finalLayers
        ]
%%
dataSetDir = fullfile(toolboxdir('vision'),'visiondata','crack_prova');
imageDir = fullfile(dataSetDir,'trainingImages');
labelDir = fullfile(dataSetDir,'trainingLabels');

imds = imageDatastore(imageDir);

classNames = ["crack","background"];
labelIDs = [1 2];
pxds = pixelLabelDatastore(labelDir,classNames,labelIDs);

I = read(imds);
C = read(pxds);

I = imresize(I,1);
L = imresize(uint8(C),1);
imshowpair(I,L,'montage')

numFilters = 64;
filterSize = 8;
numClasses = 2;
layers = [
        imageInputLayer([256 256 1])
        convolution2dLayer(filterSize,numFilters,'Padding',1)
        reluLayer()
        maxPooling2dLayer(2,'Stride',2)
        convolution2dLayer(filterSize,numFilters,'Padding',1)
        reluLayer()
        transposedConv2dLayer(4,numFilters,'Stride',2,'Cropping',1);
        convolution2dLayer(1,numClasses);
        softmaxLayer()
        pixelClassificationLayer()
        ]

opts = trainingOptions('sgdm', ...
        'InitialLearnRate',1e-3, ...
        'MaxEpochs',100, ...
        'MiniBatchSize',64);

imageSize = [256 256 1];
lgraph = segnetLayers(imageSize, numClasses, 2);
datasource = pixelLabelImageSource(imds,pxds);

%%
net = trainNetwork(datasource, lgraph, opts);
```

```
%%
testImage = imread('ImageTest.jpg');
imshow(testImage)

%%
C = semanticseg(testImage,net);
B = labeloverlay(testImage,C);
imshow(B)
%%
trainingData = pixelLabelImageDatastore(imds,pxds);
tbl = countEachLabel(trainingData)
totalNumberOfPixels = sum(tbl.PixelCount);
frequency = tbl.PixelCount / totalNumberOfPixels;
classWeights = 1./frequency
layers(end) = pixelClassificationLayer('ClassNames',tbl.Name,'ClassWeights',classWeights);
%%
net = trainNetwork(datasource, lgraph, opts);
%%
C = semanticseg(testImage,net);
B = labeloverlay(testImage,C);
imshow(B)
%%
dataSetDir = fullfile(toolboxdir('vision'), 'visiondata', 'crack_prova');
testImagesDir = fullfile(dataSetDir, 'testImages');
imds = imageDatastore(testImagesDir);
testLabelsDir = fullfile(dataSetDir, 'testLabels');
classNames = ["crack" "background"];
labelIDs = [1 2];
%%
cd(‘percorso file')
save('filename.mat','net')
%%
pxdsTruth = pixelLabelDatastore(testLabelsDir, classNames, labelIDs);
%%
net = load('filename.mat');
net = net.net;
%%
pxdsResults = semanticseg(imds, net, "WriteLocation", tempdir);
metrics = evaluateSemanticSegmentation(pxdsResults, pxdsTruth);
metrics.ClassMetrics
metrics.ConfusionMatrix
normConfMatData = metrics.NormalizedConfusionMatrix.Variables;
figure
h = heatmap(classNames, classNames, 100 * normConfMatData);
h.XLabel = 'Predicted Class';
h.YLabel = 'True Class';
h.Title = 'Normalized Confusion Matrix (%)';
```

```
%%
imageIoU = metrics.ImageMetrics.MeanIoU;
figure
histogram(imageIoU)
title('Image Mean IoU')
%%
[minIoU, worstImageIndex] = min(imageIoU);
minIoU = minIoU(1);
worstImageIndex = worstImageIndex(1);

%%
worstTestImage = readimage(imds, worstImageIndex);
worstTrueLabels = readimage(pxdsTruth, worstImageIndex);
worstPredictedLabels = readimage(pxdsResults, worstImageIndex);
%%
worstTrueLabelImage = im2uint8(worstTrueLabels == classNames(1));
worstPredictedLabelImage = im2uint8(worstPredictedLabels == classNames(1));
%%
worstMontage = cat(4,worstTestImage, worstTrueLabelImage, worstPredictedLabelImage);
worstMontage = imresize(worstMontage, 4, "nearest");
figure
montage(worstMontage, 'Size', [1 3])
title(['Test image vs. Truth vs. Prediction. IoU = ' num2str(minIoU)])

%%
[maxIoU, bestImageIndex] = max(imageIoU);
maxIoU = maxIoU(1);
bestImageIndex = bestImageIndex(1);
%%
bestTestImage = readimage(imds, bestImageIndex);
bestTrueLabels = readimage(pxdsTruth, bestImageIndex);
bestPredictedLabels = readimage(pxdsResults, bestImageIndex);

bestTrueLabelImage = im2uint8(bestTrueLabels == classNames(1));
bestPredictedLabelImage = im2uint8(bestPredictedLabels == classNames(1));

bestMontage = cat(4,bestTestImage, bestTrueLabelImage, bestPredictedLabelImage);
bestMontage = imresize(bestMontage, 4, "nearest");
figure
montage(bestMontage, 'Size', [1 3])
title(['Test image vs. Truth vs. Prediction. IoU = ' num2str(maxIoU)])

%%
evaluationMetrics = ["accuracy" "iou"];

metrics = evaluateSemanticSegmentation(pxdsResults, pxdsTruth, "Metrics",
evaluationMetrics);
metrics.ClassMetrics
```

CNN for crack detection on tuff brick-exposed walls
Script:

```
%%
inputSize = [256 256 1];
imgLayer = imageInputLayer(inputSize)
filterSize = 8;
numFilters = 32;
conv = convolution2dLayer(filterSize,numFilters,'Padding',1);
relu = reluLayer();
poolSize = 2;
maxPoolDownsample2x = maxPooling2dLayer(poolSize,'Stride',2);
downsamplingLayers = [
        conv
        relu
        maxPoolDownsample2x
        conv
        relu
        maxPoolDownsample2x
        ]
filterSize = 9;
transposedConvUpsample2x = transposedConv2dLayer(4,numFilters,'Stride',2,'Cropping',1);

upsamplingLayers = [
        transposedConvUpsample2x
        relu
        transposedConvUpsample2x
        relu
        ]

numClasses = 3;
conv1x1 = convolution2dLayer(1,numClasses);

finalLayers = [
        conv1x1
        softmaxLayer()
        pixelClassificationLayer()
        ]
%%
net = [
imgLayer
downsamplingLayers
upsamplingLayers
finalLayers
]
%%
dataSetDir = fullfile(percorsofile');
imageDir = fullfile(dataSetDir,'trainingImages');
labelDir = fullfile(dataSetDir,'trainingLabels');
```

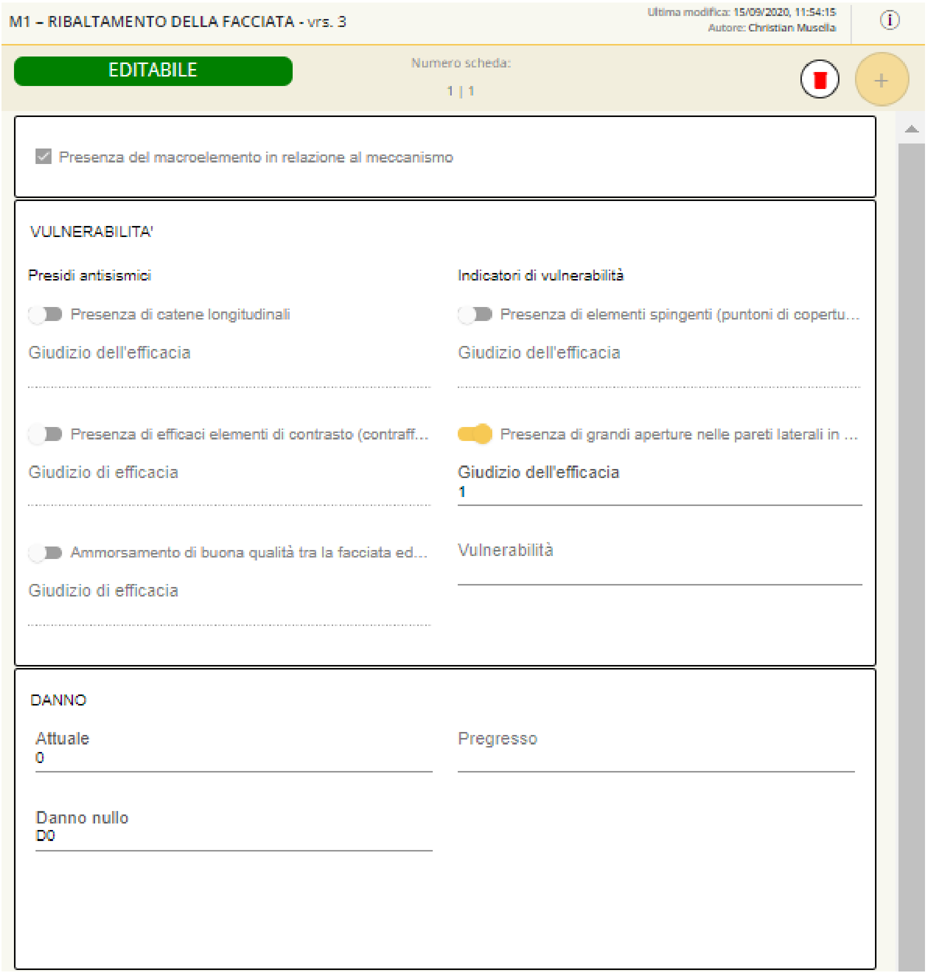
```
imds = imageDatastore(imageDir);

classNames = ["crack","tufo","calce"];
labelIDs = [1 2 3];
pxds = pixelLabelDatastore(labelDir,classNames,labelIDs);

I = read(imds);
C = read(pxds);

I = imresize(I,1);
L = imresize(uint8(C),1);
imshowpair(I,L,'montage')

numFilters = 64;
filterSize = 8;
numClasses = 3;
layers = [
        imageInputLayer([256 256 1])
        convolution2dLayer(filterSize,numFilters,'Padding',1)
        reluLayer()
        maxPooling2dLayer(2,'Stride',2)
        convolution2dLayer(filterSize,numFilters,'Padding',1)
        reluLayer()
        transposedConv2dLayer(4,numFilters,'Stride',2,'Cropping',1);
        convolution2dLayer(1,numClasses);
        softmaxLayer()
        pixelClassificationLayer()
        ]

initialLearningRate = 0.05;
maxEpochs = 50;
minibatchSize = 16;
l2reg = 0.0001;

opts = trainingOptions('sgdm',...
        'InitialLearnRate', initialLearningRate, ...
        'Momentum',0.9,...
        'L2Regularization',l2reg,...
        'MaxEpochs',maxEpochs,...
        'MiniBatchSize',minibatchSize,...
        'VerboseFrequency',20,...
        'LearnRateSchedule','piecewise',...
        'Shuffle','every-epoch',...
        'Plots','training-progress',...
        'GradientThresholdMethod','l2norm',...
        'GradientThreshold',0.05);
        imageSize = [256 256 1];
        lgraph = segnetLayers(imageSize, numClasses, 2);
        datasource = pixelLabelImageSource(imds,pxds);
```

```
%%
net = trainNetwork(datasource, lgraph, opts);

%%
testImage = imread('ImageTest2.png');
imshow(testImage)

%%
C = semanticseg(testImage,net);
B = labeloverlay(testImage,C);
imshow(B)
%%
trainingData = pixelLabelImageDatastore(imds,pxds);
tbl = countEachLabel(trainingData)
totalNumberOfPixels = sum(tbl.PixelCount);
frequency = tbl.PixelCount / totalNumberOfPixels;
classWeights = 1./frequency
layers(end) = pixelClassificationLayer('ClassNames',tbl.Name,'ClassWeights',classWeights);
initialLearningRate = 0.05;
maxEpochs = 150;
minibatchSize = 16;
l2reg = 0.0001;

opts = trainingOptions('sgdm',...
        'InitialLearnRate', initialLearningRate, ...
        'Momentum',0.9,...
        'L2Regularization',l2reg,...
        'MaxEpochs',maxEpochs,...
        'MiniBatchSize',minibatchSize,...
        'VerboseFrequency',20,...
        'LearnRateSchedule','piecewise',...
        'Shuffle','every-epoch',...
        'Plots','training-progress',...
        'GradientThresholdMethod','l2norm',...
        'GradientThreshold',0.05);

%%
net = trainNetwork(datasource, lgraph, opts);
%%
C = semanticseg(testImage,net);
B = labeloverlay(testImage,C);
imshow(B)
%%
dataSetDir = fullfile(percorsofile);
testImagesDir = fullfile(dataSetDir, 'testImages');
imds = imageDatastore(testImagesDir);
testLabelsDir = fullfile(dataSetDir, 'testLabels');

classNames = ["crack","tufo","calce"];
```

```
labelIDs = [1 2 3];

save('fileName.mat','net')
%%
pxdsTruth = pixelLabelDatastore(testLabelsDir, classNames, labelIDs);
%%
net = load('fileName.mat');
net = net.net;
%%
pxdsResults = semanticseg(imds, net, "WriteLocation", tempdir);
metrics = evaluateSemanticSegmentation(pxdsResults, pxdsTruth);
metrics.ClassMetrics
metrics.ConfusionMatrix
%%
figure
normConfMatData = metrics.NormalizedConfusionMatrix.Variables;
h = heatmap(classNames, classNames, 100 * normConfMatData);
h.XLabel = 'Predicted Class';
h.YLabel = 'True Class';
h.Title = 'Normalized Confusion Matrix (%)';

%%
imageIoU = metrics.ImageMetrics.MeanIoU;
figure
histogram(imageIoU)
title('Image Mean IoU')
%%
[minIoU, worstImageIndex] = min(imageIoU);
minIoU = minIoU(1);
worstImageIndex = worstImageIndex(1);
%%
worstTestImage = readimage(imds, worstImageIndex);
worstTrueLabels = readimage(pxdsTruth, worstImageIndex);
worstPredictedLabels = readimage(pxdsResults, worstImageIndex);

%%
worstTrueLabelImage = im2uint8(worstTrueLabels == classNames(1));
worstPredictedLabelImage = im2uint8(worstPredictedLabels == classNames(1));
%%
worstMontage = cat(4,worstTestImage, worstTrueLabelImage, worstPredictedLabelImage);
worstMontage = imresize(worstMontage, 4, "nearest");
figure
montage(worstMontage, 'Size', [1 3])
title(['Test image vs. Truth vs. Prediction. IoU = ' num2str(minIoU)])

%%
[maxIoU, bestImageIndex] = max(imageIoU);
maxIoU = maxIoU(1);
bestImageIndex = bestImageIndex(1);
```

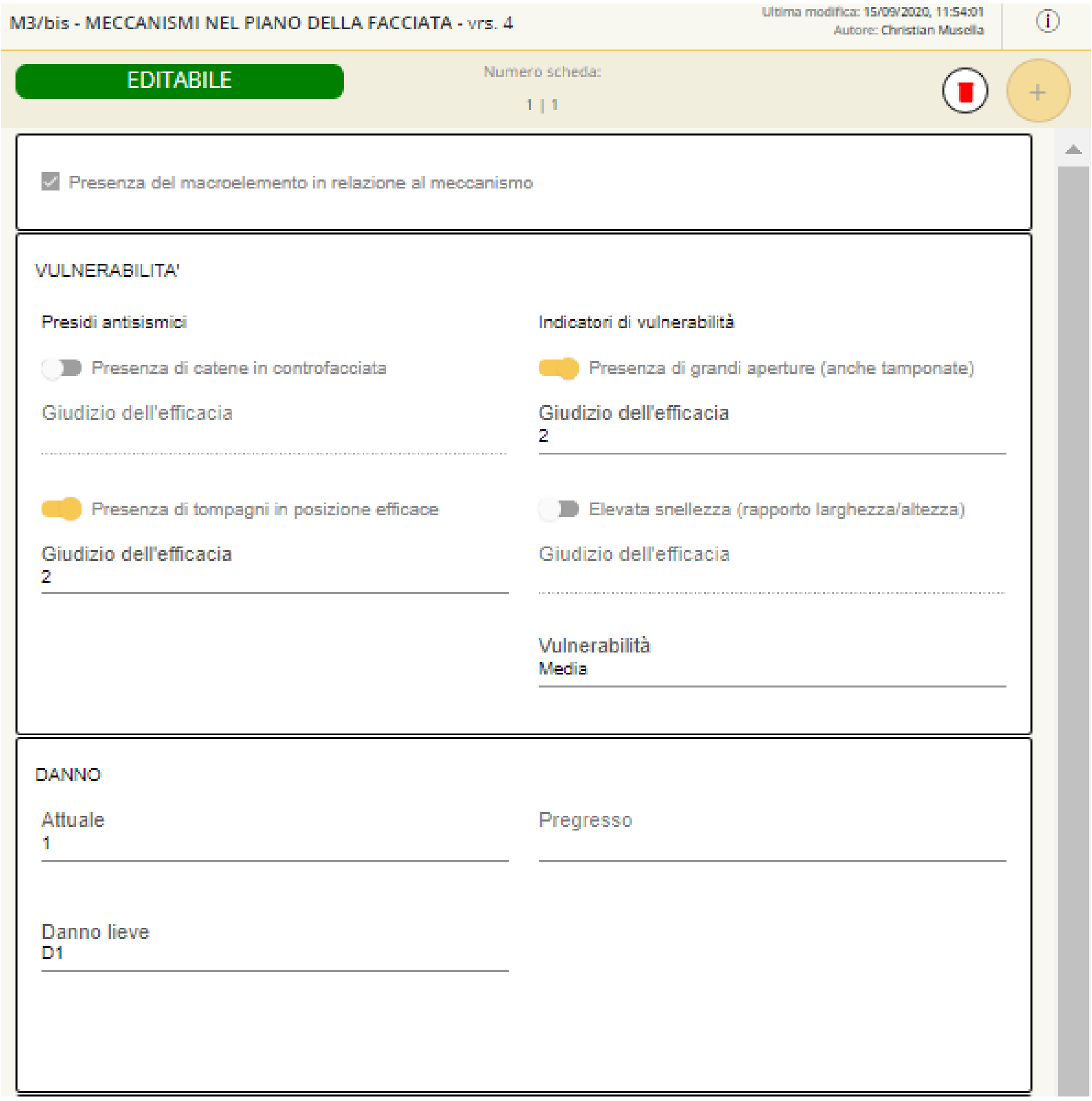
```
%%
bestTestImage = readimage(imds, bestImageIndex);
bestTrueLabels = readimage(pxdsTruth, bestImageIndex);
bestPredictedLabels = readimage(pxdsResults, bestImageIndex);

bestTrueLabelImage = im2uint8(bestTrueLabels == classNames(1));
bestPredictedLabelImage = im2uint8(bestPredictedLabels == classNames(1));

bestMontage = cat(4,bestTestImage, bestTrueLabelImage, bestPredictedLabelImage);
bestMontage = imresize(bestMontage, 4, "nearest");
figure
montage(bestMontage, 'Size', [1 3])
title(['Test image vs. Truth vs. Prediction. IoU = ' num2str(maxIoU)])

%%
evaluationMetrics = ["accuracy" "iou"];

%%
metrics = evaluateSemanticSegmentation(pxdsResults, pxdsTruth, "Metrics",
evaluationMetrics);
%%
metrics.ClassMetrics
```

ANNEX B: DIGITAL DATASHEETS OF THE MECHANISMS AND OF THE SEISMIC PARAMETERS OF THE SAN PIETRO IN VINCULIS CHURCH



ANNEX B: Digital datasheet of the mechanism M1 – Façade overturning

ANNEX B: Digital datasheet of the parameters related to the mechanism M1 – Façade overturning



M3/bis - MECCANISMI NEL PIANO DELLA FACCIATA - vrs. 4

Ultima modifica: 15/09/2020, 11:54:01
Autore: Christian Musella

EDITABILE

Numero scheda:
1 | 1

Presenza del macroelemento in relazione al meccanismo

VULNERABILITA'

Presidi antisismici

Presenza di catene in controfacciata

Giudizio dell'efficacia

Presenza di tompagni in posizione efficace

Giudizio dell'efficacia
2

Indicatori di vulnerabilità

Presenza di grandi aperture (anche tamponate)

Giudizio dell'efficacia
2

Elevata snellezza (rapporto larghezza/altezza)

Giudizio dell'efficacia

Vulnerabilità
Media

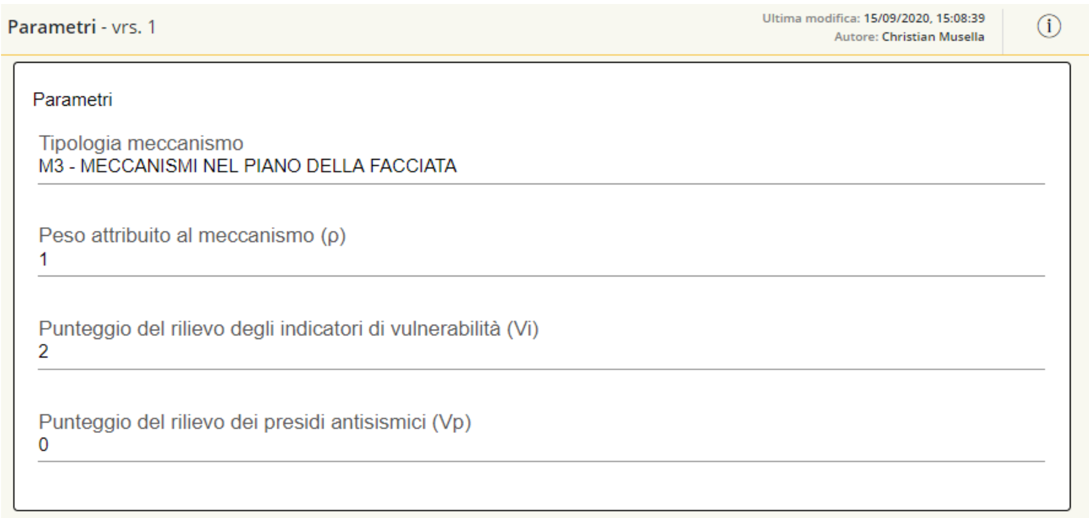
DANNO

Attuale
1

Pregresso

Danno lieve
D1

ANNEX B: Digital datasheet of the mechanism M3bis – Mechanisms in the façade plane



Parametri - vrs. 1

Ultima modifica: 15/09/2020, 15:08:39
Autore: Christian Musella

Parametri

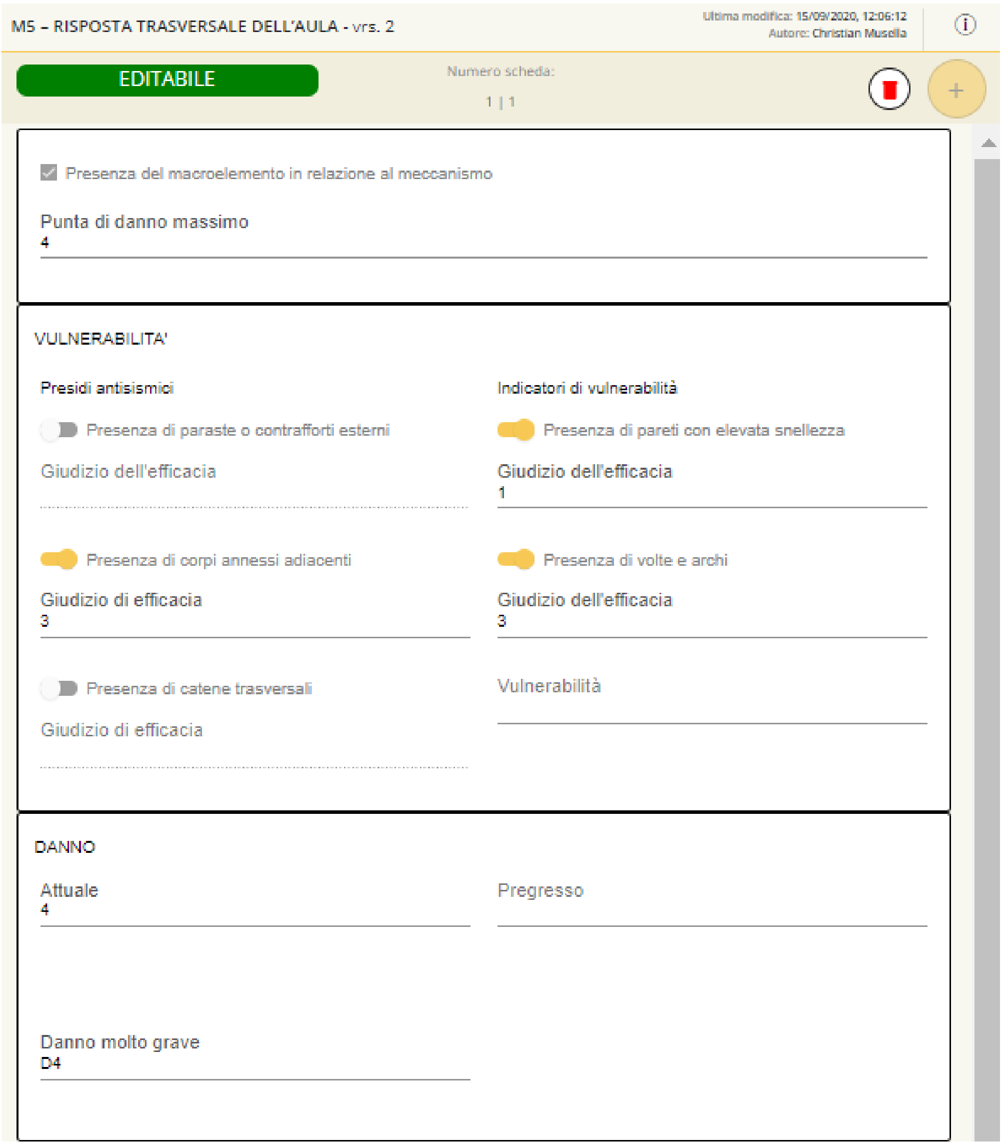
Tipologia meccanismo
M3 - MECCANISMI NEL PIANO DELLA FACCIATA

Peso attribuito al meccanismo (ρ)
1

Punteggio del rilievo degli indicatori di vulnerabilità (Vi)
2

Punteggio del rilievo dei presidi antisismici (Vp)
0

ANNEX B: Digital datasheet of the parameters related to the mechanism M3bis – Mechanisms in the façade plane



M5 – RISPOSTA TRASVERSALE DELL'AULA - vrs. 2

Ultima modifica: 15/09/2020, 12:06:12
Autore: Christian Musella

EDITABILE

Numero scheda:
1 | 1

Presenza del macroelemento in relazione al meccanismo

Punta di danno massimo
4

VULNERABILITA'

Presidi antisismici

Presenza di paraste o contrafforti esterni

Giudizio dell'efficacia

Presenza di corpi annessi adiacenti

Giudizio di efficacia
3

Presenza di catene trasversali

Giudizio di efficacia

Indicatori di vulnerabilità

Presenza di pareti con elevata snellezza

Giudizio dell'efficacia
1

Presenza di volte e archi

Giudizio dell'efficacia
3

Vulnerabilità

DANNO

Attuale
4

Pregresso

Danno molto grave
D4

ANNEX B: Digital datasheet of the mechanism M5 – Transverse response of the church hall

Parametri - vrs. 1

Ultima modifica: 14/12/2020, 21:28:01
Autore: Christian Musella

Parametri

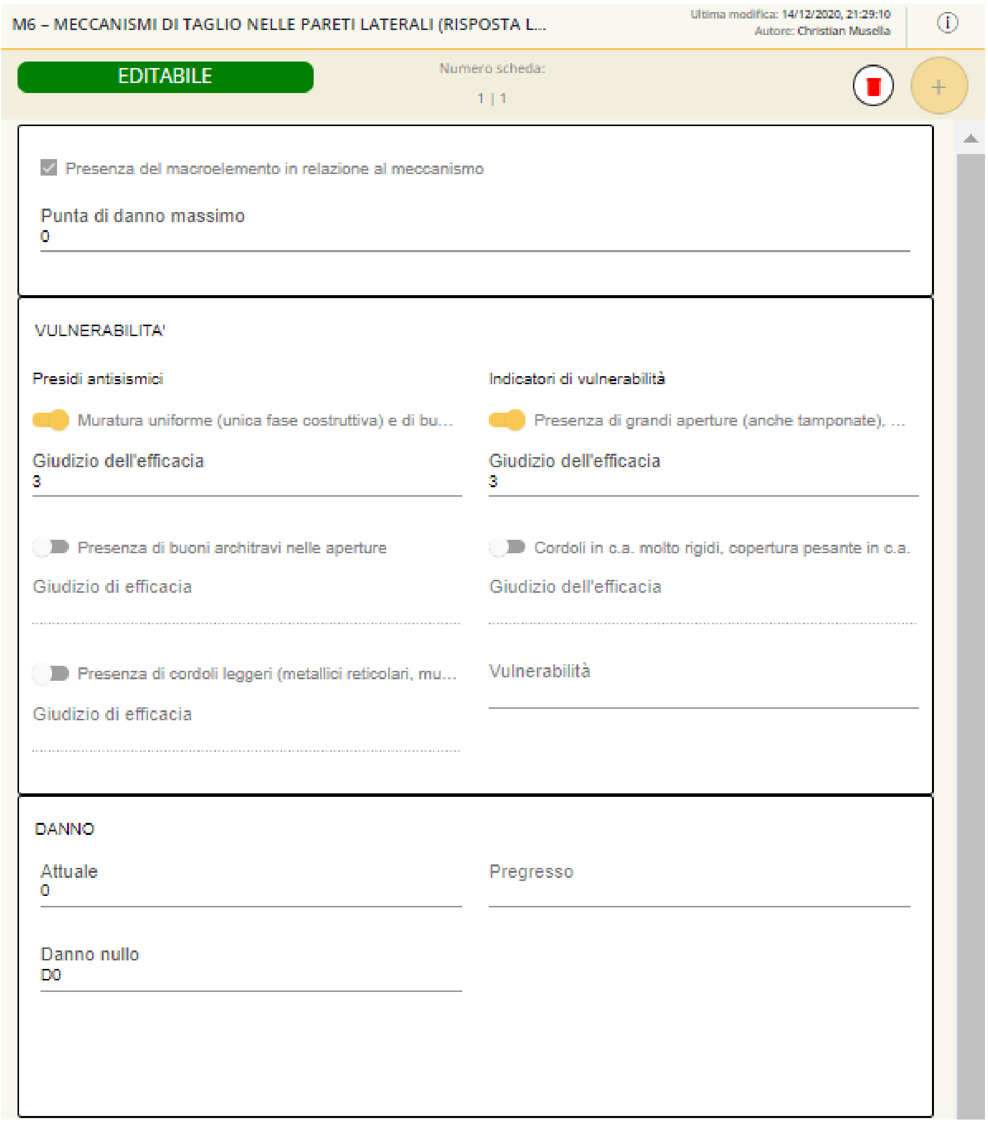
Tipologia meccanismo
M5- RISPOSTA TRASVERSALE DELL'AULA

Peso attribuito al meccanismo (p)
1

Punteggio del rilievo degli indicatori di vulnerabilità (Vi)
3

Punteggio del rilievo dei presidi antisismici (Vp)
3

ANNEX B: Digital datasheet of the parameters related to the mechanism M5 – Transverse response of the church hall



M6 – MECCANISMI DI TAGLIO NELLE PARETI LATERALI (RISPOSTA L...
Ultima modifica: 14/12/2020, 21:29:10
Autore: Christian Musella

EDITABILE

Numero scheda:
1 | 1

Presenza del macroelemento in relazione al meccanismo

Punta di danno massimo
0

VULNERABILITA'

Presidi antisismici

Muratura uniforme (unica fase costruttiva) e di bu...

Giudizio dell'efficacia
3

Presenza di buoni architravi nelle aperture

Giudizio di efficacia

Presenza di cordoli leggeri (metallici reticolari, mu...

Giudizio di efficacia

Indicatori di vulnerabilità

Presenza di grandi aperture (anche tamponate), ...

Giudizio dell'efficacia
3

Cordoli in c.a. molto rigidi, copertura pesante in c.a.

Giudizio dell'efficacia

Vulnerabilità

DANNO

Attuale
0

Pregresso

Danno nullo
D0

ANNEX B: Digital datasheet of the mechanism M6 – Shear mechanisms in the side walls

Parametri - vrs. 1
Ultima modifica: 14/12/2020, 21:28:55
Autore: Christian Musella

Parametri

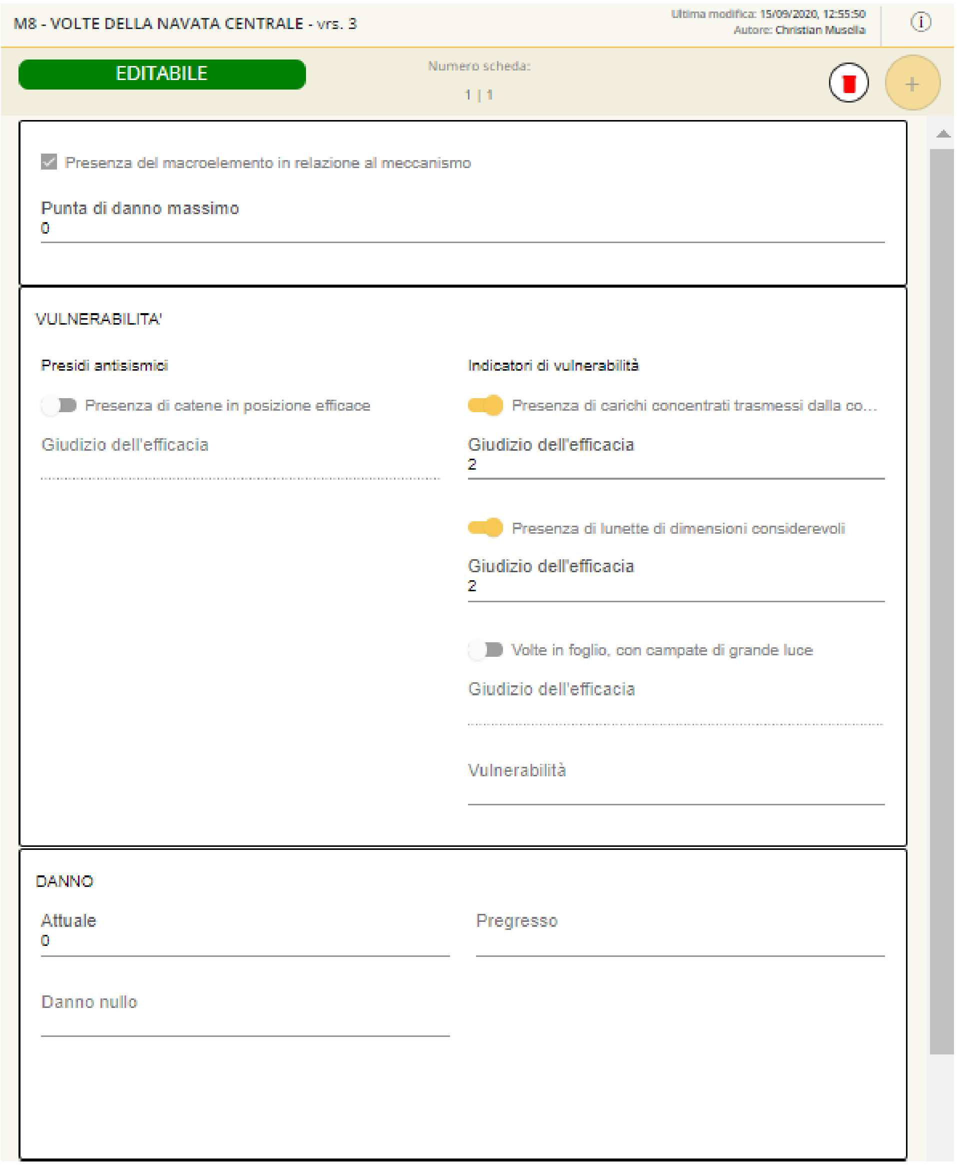
Tipologia meccanismo
M6- MECCANISMI DI TAGLIO DELLE PARETI LATERALI

Peso attribuito al meccanismo (ρ)
1

Punteggio del rilievo degli indicatori di vulnerabilità (Vi)
3

Punteggio del rilievo dei presidi antisismici (Vp)
3

ANNEX B: Digital datasheet of the parameters related to the mechanism M6 – Shear mechanisms in the side walls


M8 - VOLTE DELLA NAVATA CENTRALE - vrs. 3

Ultima modifica: 15/09/2020, 12:55:50
Autore: Christian Musella

EDITABILE

Numero scheda:
1 | 1

Presenza del macroelemento in relazione al meccanismo

Punta di danno massimo
0

VULNERABILITA'

Presidi antisismici

Presenza di catene in posizione efficace

Giudizio dell'efficacia

Indicatori di vulnerabilità

Presenza di carichi concentrati trasmessi dalla co...

Giudizio dell'efficacia
2

Presenza di lunette di dimensioni considerevoli

Giudizio dell'efficacia
2

Volte in foglio, con campate di grande luce

Giudizio dell'efficacia

Vulnerabilità

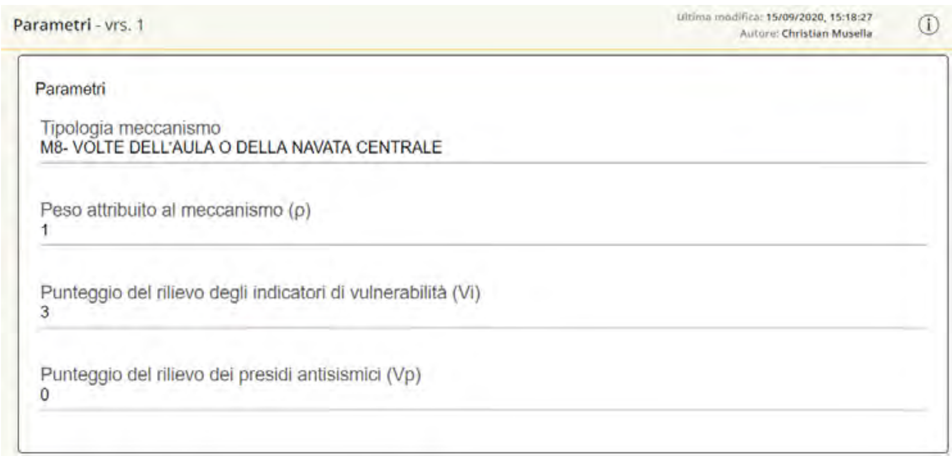
DANNO

Attuale
0

Pregresso

Danno nullo

ANNEX B: Digital datasheet of the mechanism M8 – Vaults of the nave


Parametri - vrs. 1

Ultima modifica: 15/09/2020, 15:18:27
Autore: Christian Musella

Parametri

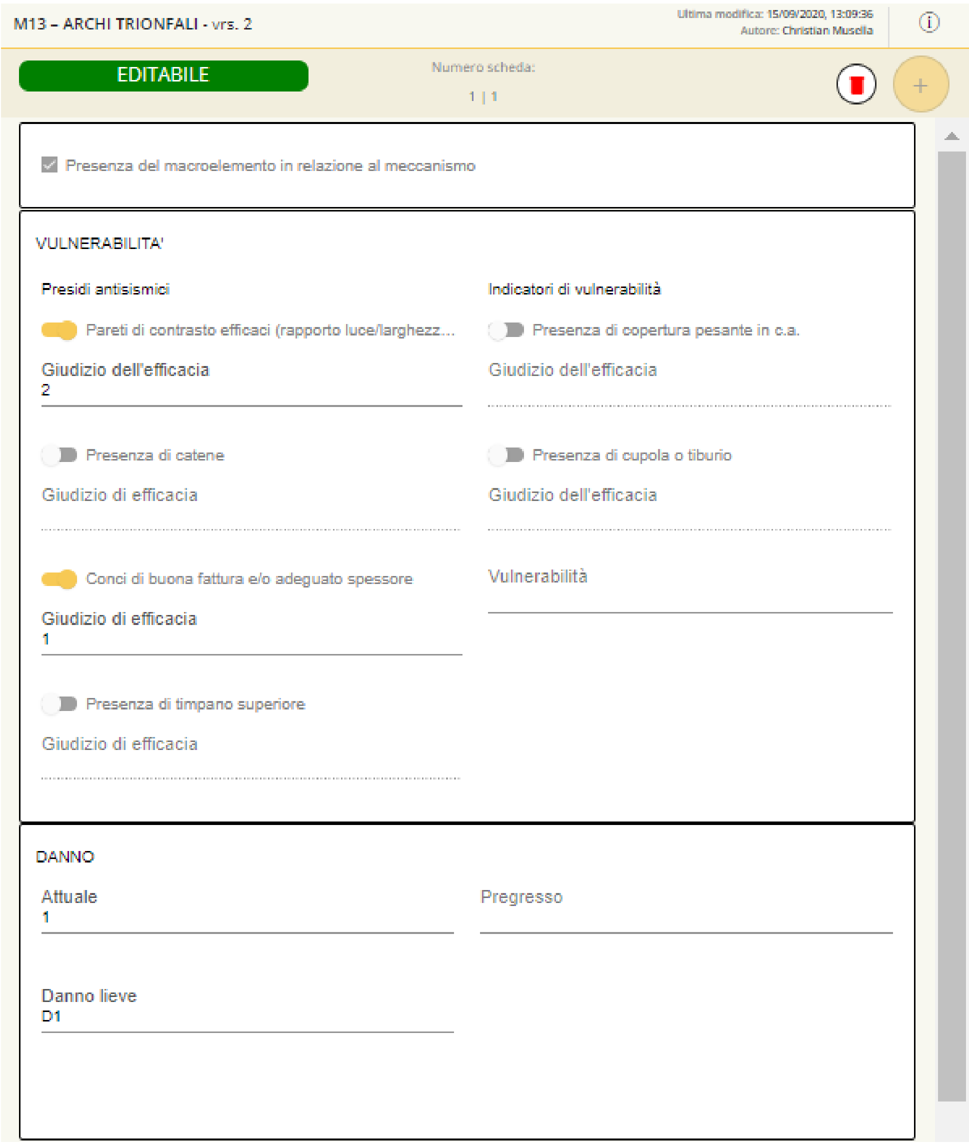
Tipologia meccanismo
M8- VOLTE DELL'AULA O DELLA NAVATA CENTRALE

Peso attribuito al meccanismo (ρ)
1

Punteggio del rilievo degli indicatori di vulnerabilità (Vi)
3

Punteggio del rilievo dei presidi antisismici (Vp)
0

ANNEX B: Digital datasheet of the parameters related to the mechanism M8 – Vaults of the nave


M13 – ARCHI TRIONFALI - vrs. 2

Ultima modifica: 15/09/2020, 13:09:36
Autore: Christian Musella

EDITABILE

Numero scheda:
1 | 1

Presenza del macroelemento in relazione al meccanismo

VULNERABILITA'

Presidi antisismici

Pareti di contrasto efficaci (rapporto luce/larghezz...

Giudizio dell'efficacia
2

Presenza di catene

Giudizio di efficacia

Conci di buona fattura e/o adeguato spessore

Giudizio di efficacia
1

Presenza di timpano superiore

Giudizio di efficacia

Indicatori di vulnerabilità

Presenza di copertura pesante in c.a.

Giudizio dell'efficacia

Presenza di cupola o tiburio

Giudizio dell'efficacia

Vulnerabilità

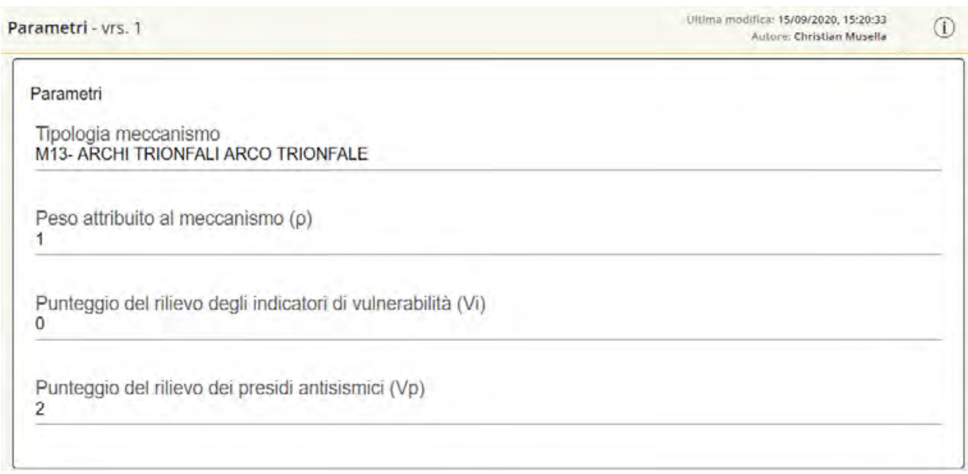
DANNO

Attuale
1

Pregresso

Danno lieve
D1

ANNEX B: Digital datasheet of the mechanism M13 – Triumphal arches


Parametri - vrs. 1

Ultima modifica: 15/09/2020, 15:20:33
Autore: Christian Musella

Parametri

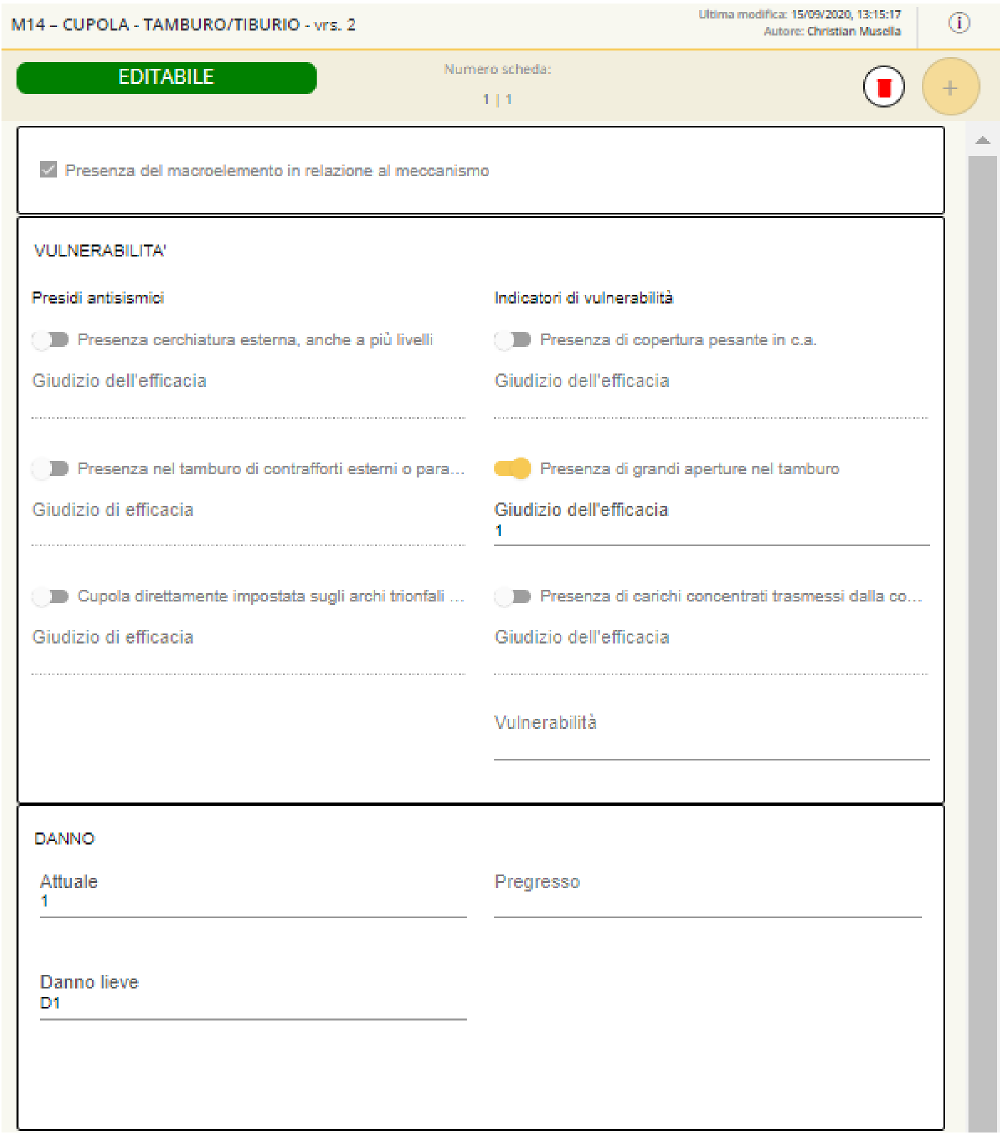
Tipologia meccanismo
M13- ARCHI TRIONFALI ARCO TRIONFALE

Peso attribuito al meccanismo (ρ)
1

Punteggio del rilievo degli indicatori di vulnerabilità (Vi)
0

Punteggio del rilievo dei presidi antisismici (Vp)
2

ANNEX B: Digital datasheet of the parameters related to the mechanism M13 – Triumphal arches


M14 – CUPOLA - TAMBURO/TIBURIO - vrs. 2

Ultima modifica: 15/09/2020, 13:15:17
Autore: Christian Musella

EDITABILE

Numero scheda:
1 | 1

Presenza del macroelemento in relazione al meccanismo

VULNERABILITA'

Presidi antisismici

Presenza cerchiatura esterna, anche a più livelli
Giudizio dell'efficacia

Presenza nel tamburo di contrafforti esterni o para…
Giudizio di efficacia

Cupola direttamente impostata sugli archi trionfali …
Giudizio di efficacia

Indicatori di vulnerabilità

Presenza di copertura pesante in c.a.
Giudizio dell'efficacia

Presenza di grandi aperture nel tamburo
Giudizio dell'efficacia
1

Presenza di carichi concentrati trasmessi dalla co…
Giudizio dell'efficacia

Vulnerabilità

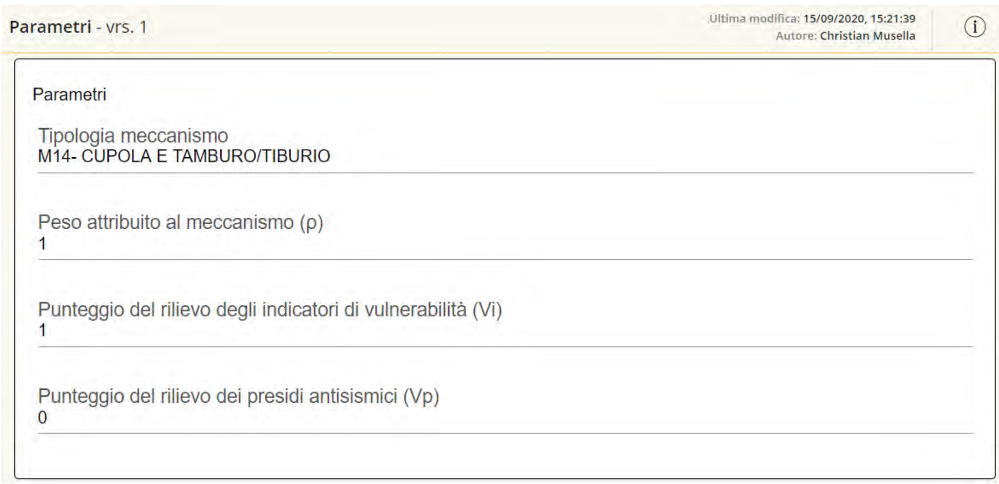
DANNO

Attuale
1

Pregresso

Danno lieve
D1

ANNEX B: Digital datasheet of the mechanism M14 – Dome - drum/tiburium


Parametri - vrs. 1

Ultima modifica: 15/09/2020, 15:21:39
Autore: Christian Musella

Parametri

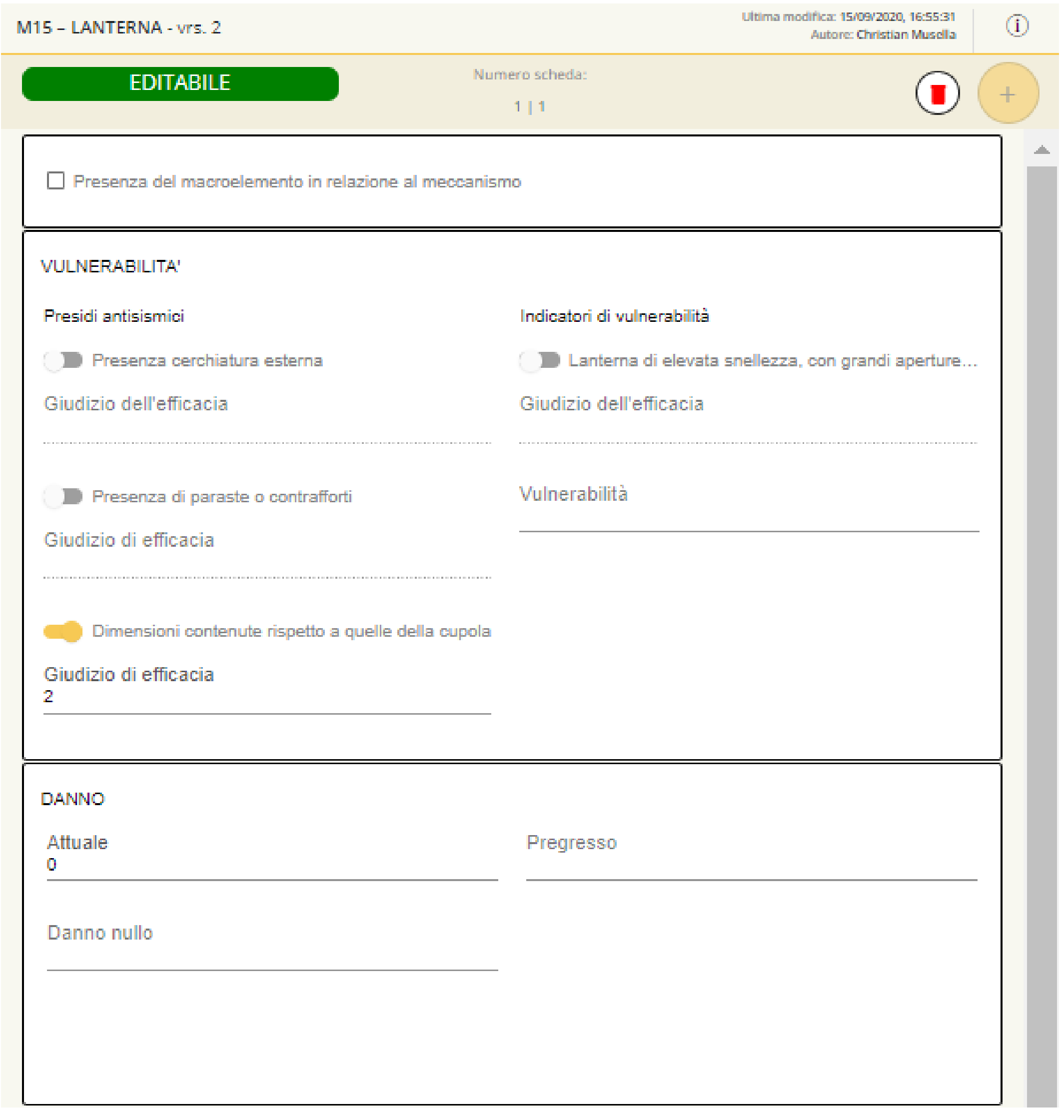
Tipologia meccanismo
M14- CUPOLA E TAMBURO/TIBURIO

Peso attribuito al meccanismo (ρ)
1

Punteggio del rilievo degli indicatori di vulnerabilità (Vi)
1

Punteggio del rilievo dei presidi antisismici (Vp)
0

ANNEX B: Digital datasheet of the parameters related to the mechanism M14 – Dome - drum/tiburium


M15 – LANTERNA - vrs. 2

Ultima modifica: 15/09/2020, 16:55:31
Autore: Christian Musella

EDITABILE

Numero scheda:
1 | 1

Presenza del macroelemento in relazione al meccanismo

VULNERABILITA'

Presidi antisismici

Presenza cerchiatura esterna

Giudizio dell'efficacia

Presenza di paraste o contrafforti

Giudizio di efficacia

Dimensioni contenute rispetto a quelle della cupola

Giudizio di efficacia
2

Indicatori di vulnerabilità

Lanterna di elevata snellezza, con grandi aperture…

Giudizio dell'efficacia

Vulnerabilità

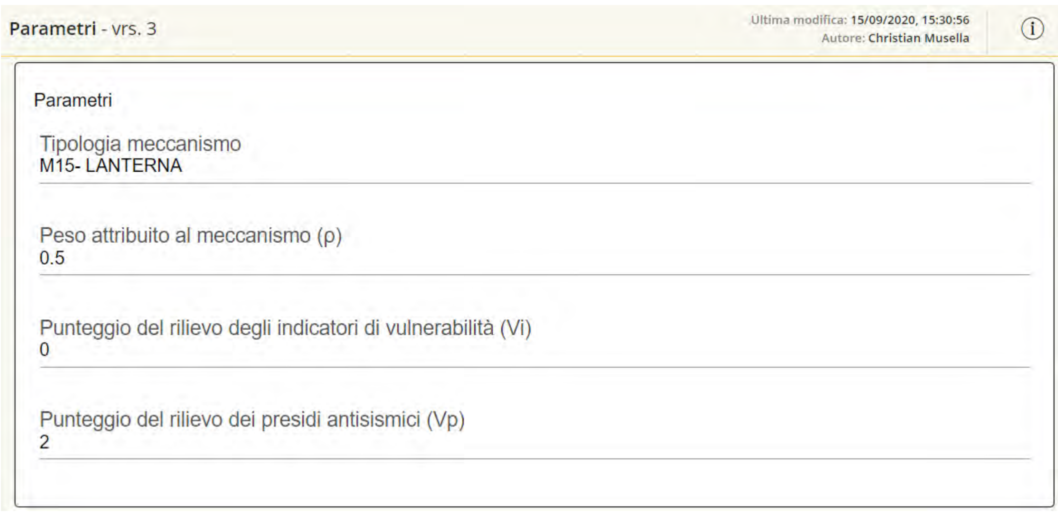
DANNO

Attuale
0

Pregresso

Danno nullo

ANNEX B: Digital datasheet of the mechanism M15 – Lantern


Parametri - vrs. 3

Ultima modifica: 15/09/2020, 15:30:56
Autore: Christian Musella

Parametri

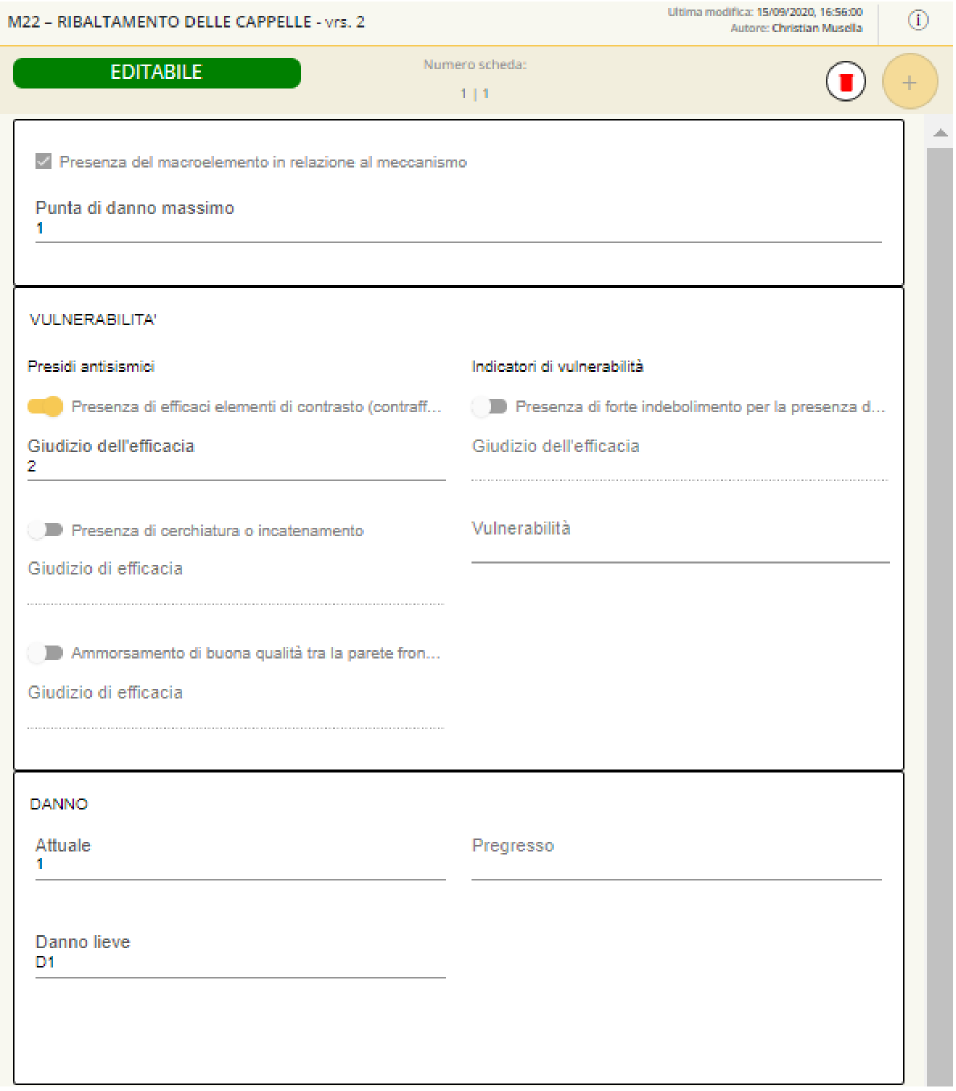
Tipologia meccanismo
M15- LANTERNA

Peso attribuito al meccanismo (ρ)
0.5

Punteggio del rilievo degli indicatori di vulnerabilità (Vi)
0

Punteggio del rilievo dei presidi antisismici (Vp)
2

ANNEX B: Digital datasheet of the parameters related to the mechanism M15 – Lantern

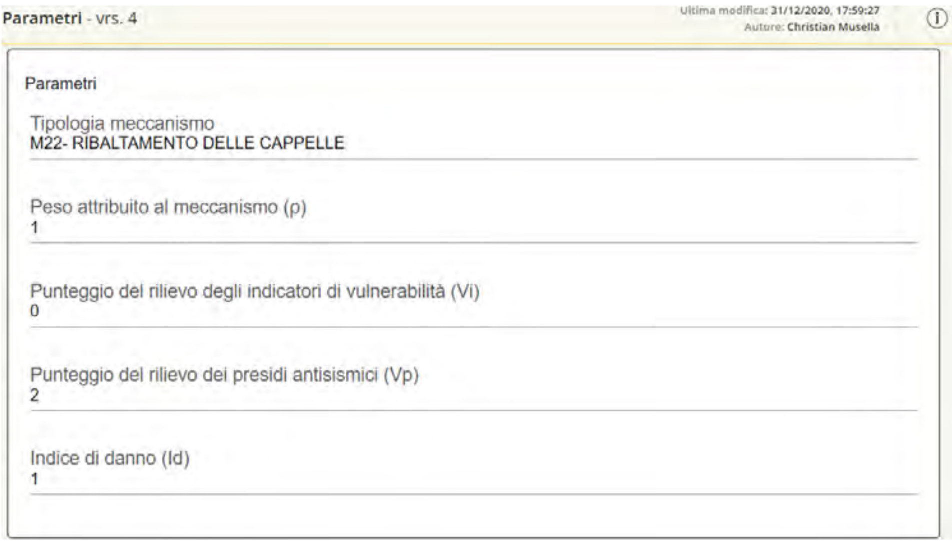

M22 – RIBALTAMENTO DELLE CAPPELLE - vrs. 2
Ultima modifica: 15/09/2020, 16:56:00
Autore: Christian Musella
EDITABILE
Numero scheda:
1 | 1

Presenza del macroelemento in relazione al meccanismo
Punta di danno massimo
1

VULNERABILITA'
Presidi antisismici
Presenza di efficaci elementi di contrasto (contraff...
Giudizio dell'efficacia
2
Presenza di cerchiatura o incatenamento
Giudizio di efficacia
Ammorsamento di buona qualità tra la parete fron...
Giudizio di efficacia
Indicatori di vulnerabilità
Presenza di forte indebolimento per la presenza d...
Giudizio dell'efficacia
Vulnerabilità

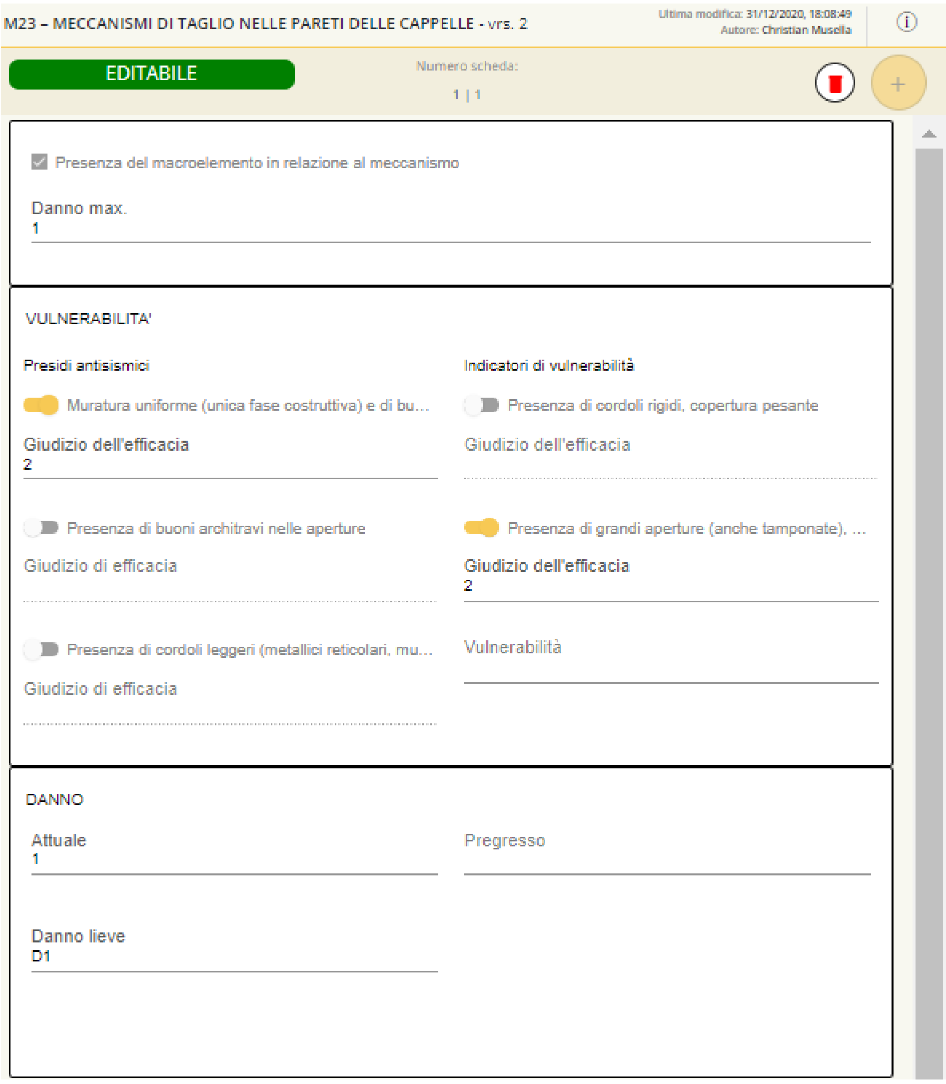
DANNO
Attuale
1
Pregresso
Danno lieve
D1

ANNEX B: Digital datasheet of the mechanism M22 – Church drum


Parametri - vrs. 4
Ultima modifica: 31/12/2020, 17:59:27
Autore: Christian Musella

Parametri
Tipologia meccanismo
M22- RIBALTAMENTO DELLE CAPPELLE
Peso attribuito al meccanismo (p)
1
Punteggio del rilievo degli indicatori di vulnerabilità (Vi)
0
Punteggio del rilievo dei presidi antisismici (Vp)
2
Indice di danno (Id)
1

ANNEX B: Digital datasheet of the parameters related to the mechanism M22 – Church drum


M23 – MECCANISMI DI TAGLIO NELLE PARETI DELLE CAPPELLE - vrs. 2
Ultima modifica: 31/12/2020, 18:08:49
Autore: Christian Musella

EDITABILE

Numero scheda:
1 | 1

Presenza del macroelemento in relazione al meccanismo

Danno max.
1

VULNERABILITA'

Presidi antisismici

Muratura uniforme (unica fase costruttiva) e di bu...

Giudizio dell'efficacia
2

Presenza di buoni architravi nelle aperture

Giudizio di efficacia

Presenza di cordoli leggeri (metallici reticolari, mu...

Giudizio di efficacia

Indicatori di vulnerabilità

Presenza di cordoli rigidi, copertura pesante

Giudizio dell'efficacia

Presenza di grandi aperture (anche tamponate), ...

Giudizio dell'efficacia
2

Vulnerabilità

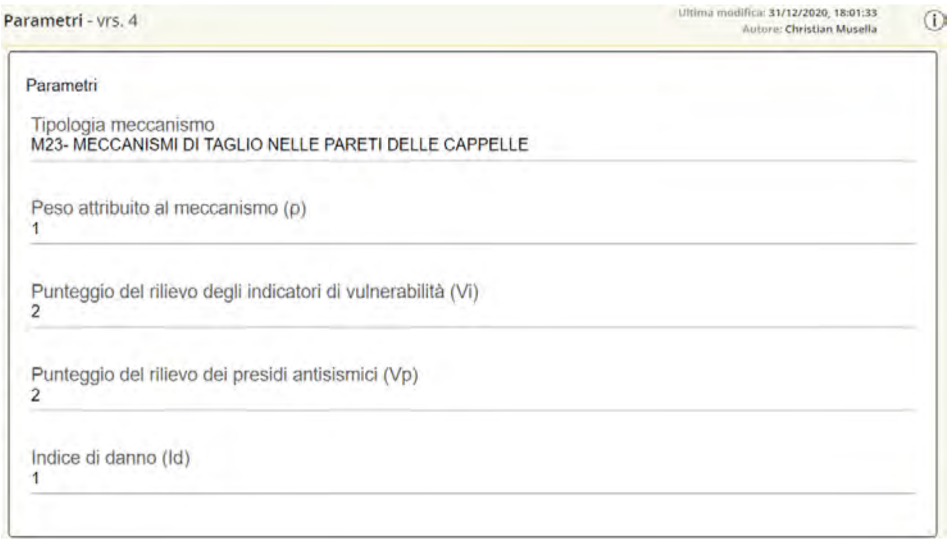
DANNO

Attuale
1

Pregresso

Danno lieve
D1

ANNEX B: Digital datasheet of the mechanism M23 – Shear mechanisms in chapel walls


Parametri - vrs. 4
Ultima modifica: 31/12/2020, 18:01:33
Autore: Christian Musella

Parametri

Tipologia meccanismo
M23- MECCANISMI DI TAGLIO NELLE PARETI DELLE CAPPELLE

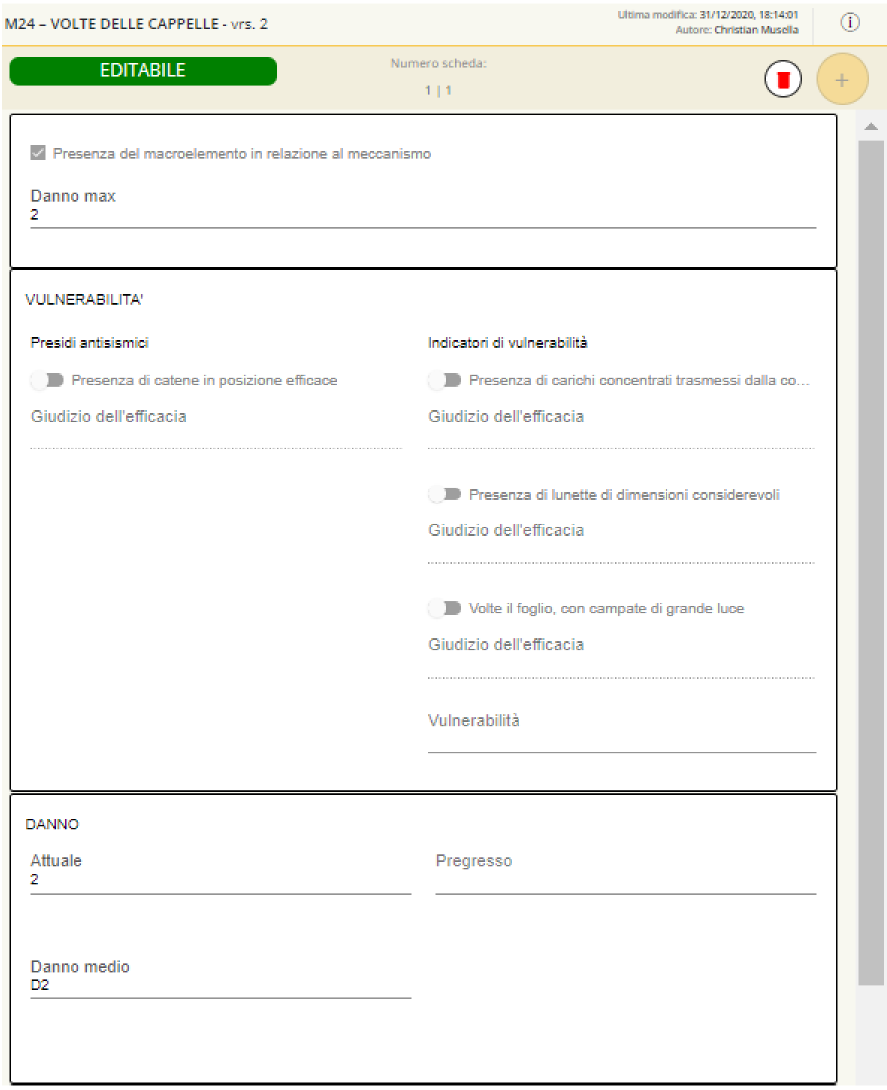
Peso attribuito al meccanismo (p)
1

Punteggio del rilievo degli indicatori di vulnerabilità (Vi)
2

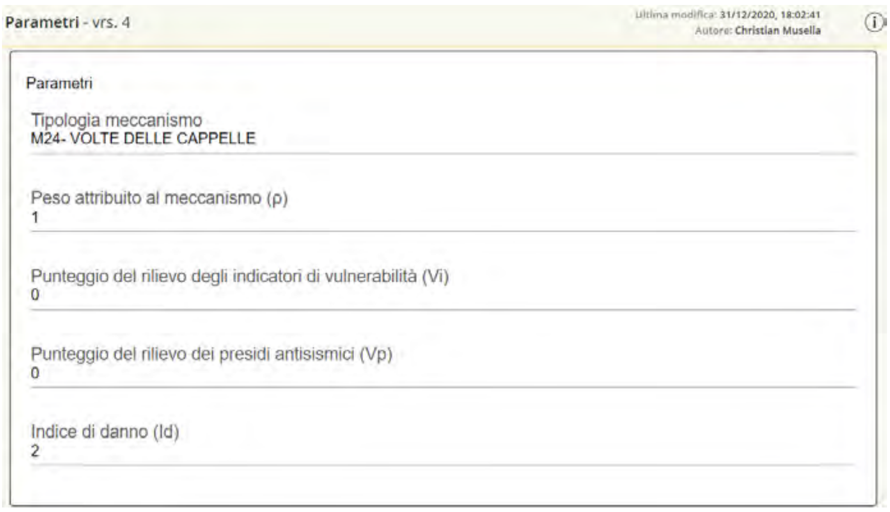
Punteggio del rilievo dei presidi antisismici (Vp)
2

Indice di danno (Id)
1

ANNEX B: Digital datasheet of the parameters related to the mechanism M23 – Shear mechanisms in chapel walls



ANNEX B: Digital datasheet of the mechanism M24 – Chapel vaults



ANNEX B: Digital datasheet of the parameters related to the mechanism M24 – Chapel vaults

ANNEX C: DIGITAL&BIM AWARDS 2020 - HBIM TOOLS. WEB-BASED COLLABORATIVE PLATFORM & HISTORICBIM TOOLBAR

REPORT

E. Lanzara, C. Musella, supervision prof.ssa A. Di Luggo

L'attività è finalizzata alla digitalizzazione degli elementi e dei fenomeni complessi caratterizzanti il patrimonio storico costruito ed è stata sviluppata nell'ambito di un progetto di ricerca industriale in collaborazione tra Università, studi professionali e *Software house*. Il progetto ha previsto la strutturazione, creazione e *beta-testing* di appositi oggetti HBIM *ready to use* e relative schede informative compilabili e di una piattaforma collaborativa *web-based* per la gestione condivisa del processo (*workflow* disciplinari). I prodotti sono stati testati digitalizzando una Chiesa. Sulla base dei dati documentari e *reality-based*, acquisiti mediante Rilievo laser scanner, fotogrammetrico digitale e GEOSLAM, il modello è stato interamente informatizzato in ambiente BIM.

IMPATTO ECONOMICO

I processi BIM tradizionali prevedono che la digitalizzazione dei dati avvenga in tempi diversi dall'acquisizione *in situ*. Gli strumenti presentati ottimizzano tale processo, finalizzato alla tutela e valorizzazione del bene, riducendo il dispendio di risorse, avviando il processo di digitalizzazione in tempo reale (mediante *device*s), rendendo le informazioni (aggiornabili e implementabili) disponibili a tutti i membri del *team* grazie alla capiente piattaforma *web-based*, e usufruendo di appositi oggetti HBIM in fase di modellazione, evitando il dispendio di risorse per la creazione di oggetti "non integrabili". Il progetto consiste nello sviluppo di strumenti ave ti funzione preventiva mediante implementazione di apposite funzionalità per la gestione delle Aree di Degrado e del Danno. Il filtraggio delle proprietà/parametri (quantitativi e qualitativi) in apposite schede sintetiche consente di computare (preventivare) i costi legati alla diagnostica e agli interventi di Restauro e Risanamento.

SOSTENIBILITA'

La sostenibilità **economica** del progetto, verificata digitalizzando il caso studio, è stata discussa all'interno del paragrafo precedente. La sostenibilità, in termini di **orientamento dello sviluppo tecnologico**, è verificata, con riferimento ai grafici allegati, dall'utilizzo di strumenti di modellazione (software di *authoring*) e gestione/condivisione delle informazioni (piattaforma *web-based*) completi e performanti per la digitalizzazione degli elementi e dei fenomeni complessi caratterizzanti il patrimonio storico. Rispetto alla sostenibilità **ambientale** in termini di **valorizzazione delle risorse**, coinvolgendo gli aspetti **culturale**, **sociale** e **territoriale**, è evidente il supporto alle attività di digitalizzazione finalizzate alla valorizzazione e conservazione del patrimonio e alla divulgazione e possibile riutilizzo dei beni, capaci di miglioramento nel breve e lungo termine.

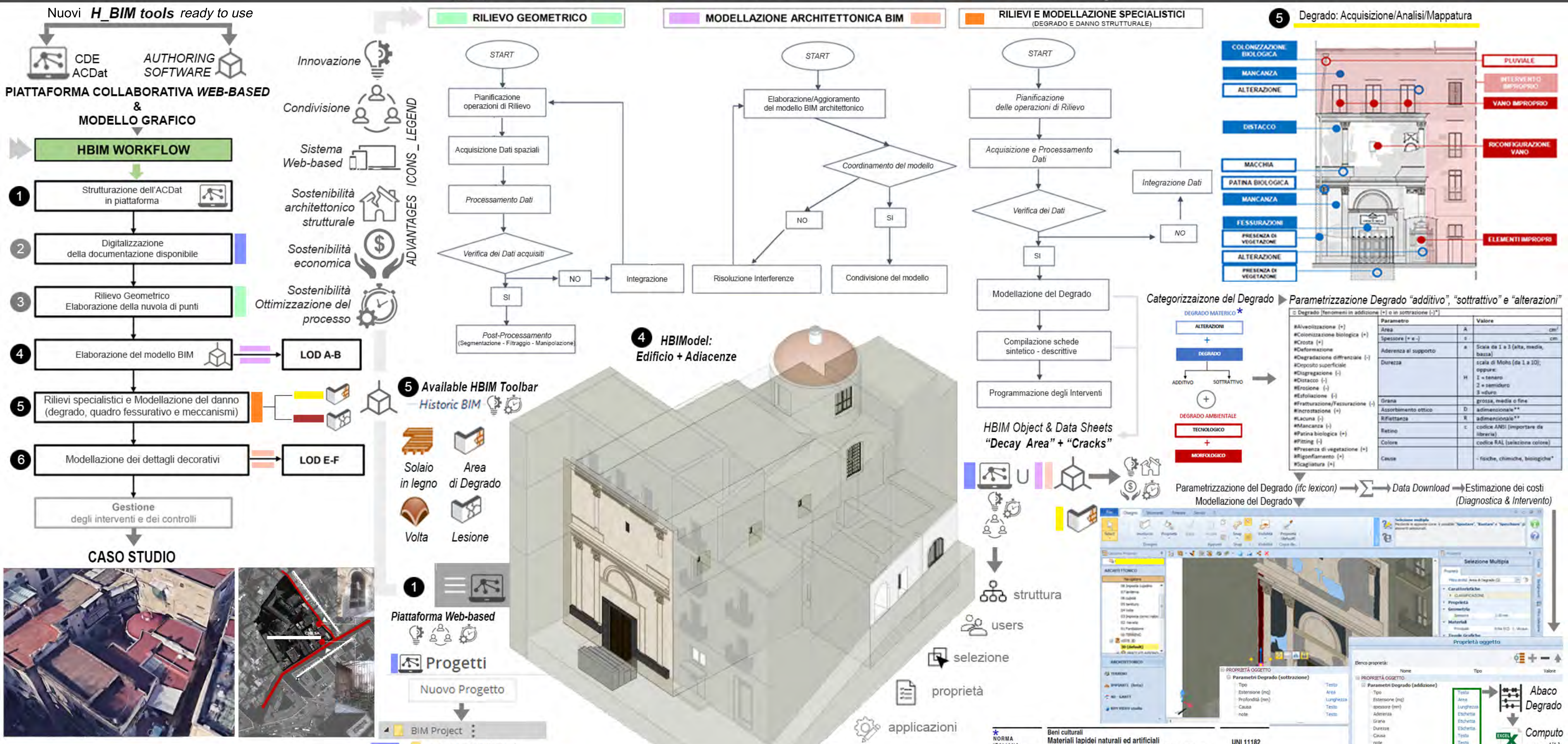
CARATTERE INNOVATIVO

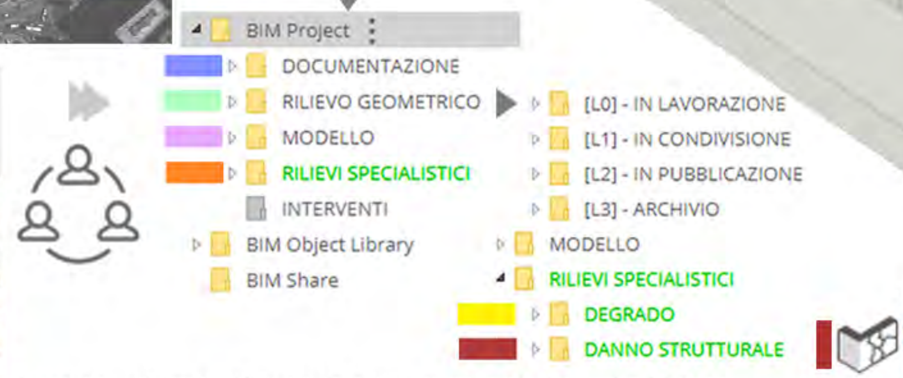
La modellazione dell'organismo complesso Chiesa è stata gestita mediante approccio integrato architetto-ingegnere strutturista, soddisfacendo entrambe le esigenze già in fase interpretativa al fine di evitare successive interferenze. Il rispetto dei *workflow* di lavoro strutturati è supportato dall'utilizzo di schede digitali compilabili *in situ* (piattaforma collaborativa *web-based*), orientate alla gestione e allo scambio di dati direttamente dal formato *ifc*, favorendo processi *open BIM*. I grafici validano l'applicazione di appositi strumenti per la modellazione e documentazione delle volte, del degrado e del danno, raccolti in un'apposita *Toolbar*. L'attività di parametrizzazione delle volte è scaturita nel nuovo oggetto HBIM ***Volta*** (semplice e composta), editabile mediante tagli verticali, orizzontali e fori (circolari a tutto sesto, sesto acuto, ribassati, ovali ed ellittici), consentendo l'adattamento dell'elemento anche ad ambienti irregolari. Il software fornisce anche l'oggetto di completamento ***Costola***. Gli appositi oggetti ***Lesione*** e ***Area di degrado*** consentono la virtualizzazione del quadro di danno e fessurativo, scaturiti dai fenomeni di degrado e da eventi sismici, e del degrado superficiale. In particolare, le schede digitali relative alla documentazione del degrado possono essere "specifiche", riferibili ad uno stesso tipo di degrado (Norma UNI 11182), o "multiple", sintetiche dell'insieme dei fenomeni distribuiti su intere parti/macro-elementi dell'edificio e categorizzati, con riferimento alla norma, in degradazioni (sottrazione e addizione) e alterazioni. Gli strumenti per la digitalizzazione del degrado ambientale sono *in progress*. Per i quadri fessurativi sono state realizzate 28 schede digitali (*Manuale scheda chiese a 28 meccanismi*, Lagomarsino e Podestà, 2005), e una scheda sintetica per raccogliere i parametri numerici necessari per la valutazione della vulnerabilità sismica della Chiesa. La piattaforma fornisce strumenti per individuare (*#tag*), documentare (*link*) e localizzare (*marker*) gli elementi (macro e micro) che caratterizzano il bene. Tali strumenti hanno agevolato la digitalizzazione HBIM del caso studio, verificando e validando le nuove potenzialità del software di *authoring* e della Piattaforma collaborativa *web-based*.

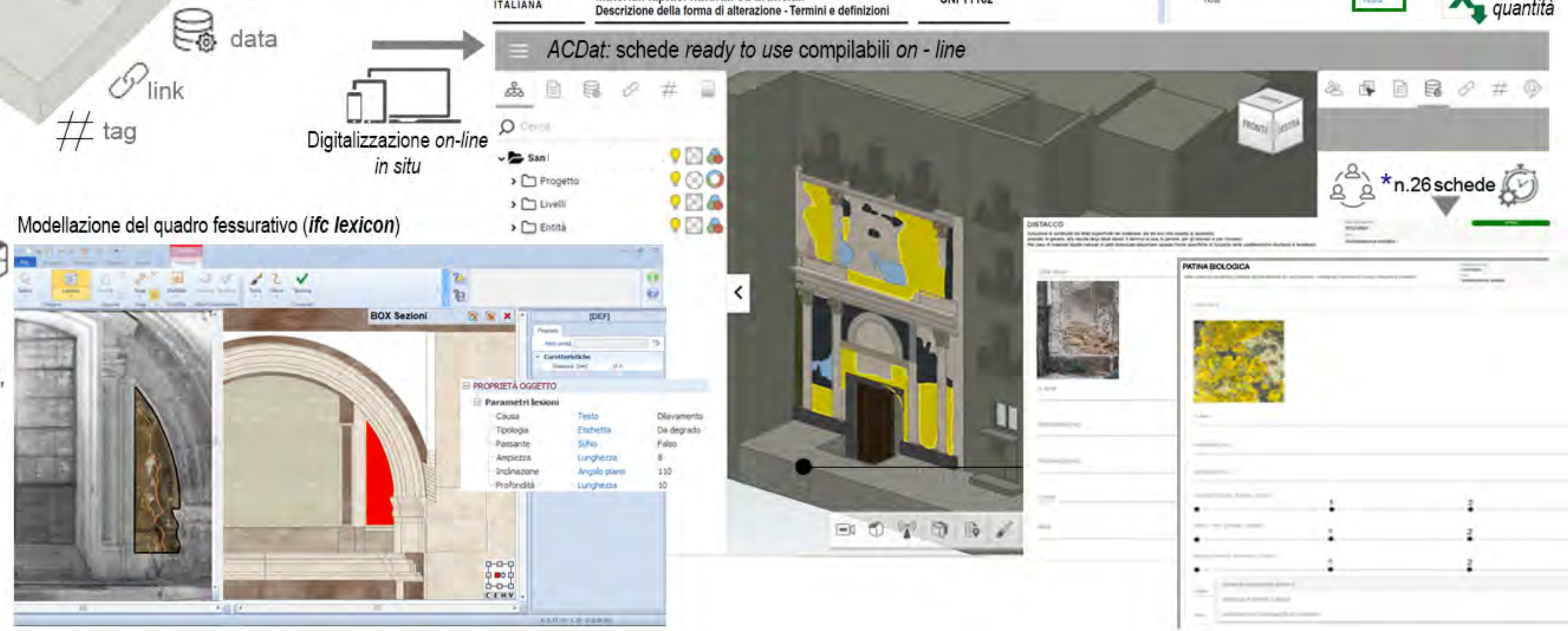
DRAWINGS

E. Lanzara, integration C. Musella, supervision prof.ssa A. Di Luggo

HBIM tools. Piattaforma collaborativa *Web-based* & *HistoricBIM Toolbar.*







Il prodotto graficizzato all'interno delle presenti tre tavole riassuntive è il frutto di un'attività di ricerca sviluppata in collaborazione tra un'Università, Studi professionali e una *Software House* e consiste nella **strutturazione**, **creazione** e ***beta-testing*** di **OGGETTI *HBIM* "dedicati"** o **"*ready to use*" (*TOOLBAR -> SOFTWARE di AUTHORING*)**, per la **digitalizzazione** di elementi e fenomeni complessi (QUALITÀ E CRITICITÀ) caratterizzanti e caratterizzanti il patrimonio storico costruito ed esistente, in particolare relativi a ***Volte, Aree di Degrado* e *Quadro fessurativo***, e di una **PIATTAFORMA COLLABORATIVA *ON-LINE*** implementabile **(CDE -> ACDat)**, per la **gestione integrata e condivisa** (***ontological Workflow***) del processo ***Scan to HBIM***. Gli strumenti oggetto di una ricerca ***in progress*** sono stati testati su un **edificio-Chiesa**, assunta quale caso studio esemplare per le **sperimentazioni teorico - applicative** che guidano e caratterizzano tale attività di ricerca integrata. I grafici e gli stralci riportati nelle tavole sono riferiti agli ***output*** di fatto **inediti**, dunque **innovativi**, rispetto alle attuali soluzioni avanzate sperimentate in ambito *HBIM*.

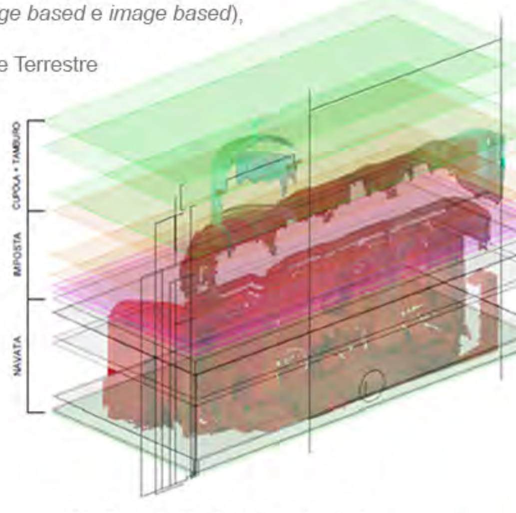
HBIM tools. Piattaforma collaborativa *Web-based* & *HistoricBIM Toolbar.*

Laser Scanner Point Cloud
Faro Focus 3d x-130

La costruzione del **MODELLO GRAFICO** deriva dalla manipolazione (estrazione profili 2D e oggetti 3D) dei dati *reality based* acquisiti attraverso due differenti modalità di rilevamento (*range based* e *image based*), secondo tre tecniche specifiche: rilevamento Laser Scanner, Fotogrammetrico Digitale Terrestre e Fotogrammetrico Digitale UAV e GEOSLAM.

Scomposizione Semantica
MACROELEMENTI
HBIM

SISTEMA DI RIFERIMENTO ALTIMETRICO



le QUOTE della tabella dei LIVELLI sono relative a ZERO EDIFICIO

Descrizione LIVELLO / subLivello	QUOTA [m]	Altezza [m]	delta [m]
Imposta cupolino	20.680	---	---
Volta 136485	---	---	0.000
lanterna	19.480	1.200	---
cupola	17.870	1.610	---
tamburo	13.620	4.250	---
Volte	10.420	3.200	---
Imposta cornici rialzo	9.120	1.300	---
navata	0.000	9.120	---
Fondazione	-0.500	0.500	---
TERRENO [origine]	1.500		

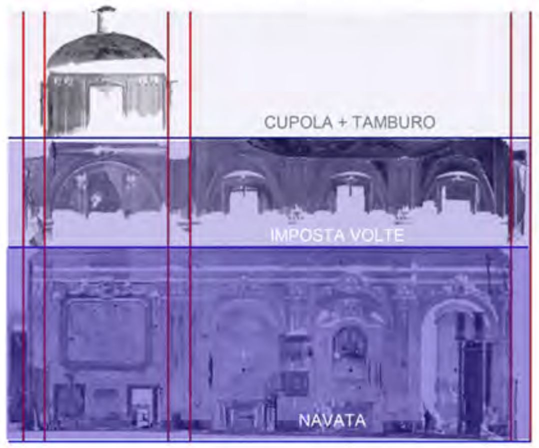
"SCHEDA CHIESE A 28 MECCANISMI"

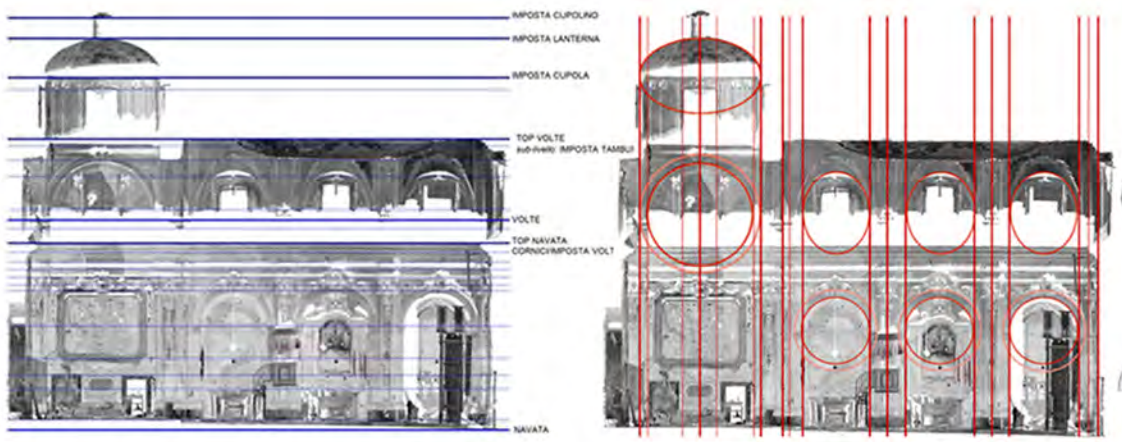
MECCANISMO DI COLLASSO	Modo di danno	Parte della chiesa
1 - RIBALTAMENTO DELLA FACCIATA	I	FACCIATA
2 - MECCANISMI NELLA SOMMITÀ DELLA FACCIATA	I	
3 - MECCANISMI NEL PIANO DELLA FACCIATA	II	
4 - PROTIRO – NARTECE	I o II	
5 - RISPOSTA TRASVERSALE DELL'AULA	I	AULA
6 - MECCANISMI DI TAGLIO NELLE PARETI LATERALI	II	
7 - RISPOSTA LONGITUDINALE DEL COLONNATO (chiese a più navate)	I	
8 - VOLTE DELLA NAVATA CENTRALE	I o II	
9 - VOLTE DELLE NAVATE LATERALI	I o II	
10 - RIBALTAMENTO DELLE PARETI DI ESTREMITÀ DEL TRANSETTO	I	TRANSETTO
11 - MECCANISMI DI TAGLIO NELLE PARETI DEL TRANSETTO	II	
12 - VOLTE DEL TRANSETTO	I o II	
13 - ARCHI TRIONFALI	II	ARCO TRIONFALE
14 - CUPOLA - TAMBURO/TIBURIO	I o II	CUPOLA
15 – LANTERNA	I o II	
16 - RIBALTAMENTO DELL'ABSIDE	I	ABSIDE
17 - MECCANISMI DI TAGLIO NEL PRESBITERIO O NELL'ABSIDE	II	
18 - VOLTE DEL PRESBITERIO O DELL'ABSIDE	I o II	
19 - MECCANISMI NEGLI ELEMENTI DI COPERTURA (pareti laterali aula)	I o II	COPERTURA
20 - MECCANISMI NEGLI ELEMENTI DI COPERTURA (transetto)	I o II	
21 - MECCANISMI NEGLI ELEMENTI DI COPERTURA (abside, presbiterio)	I o II	
22 - RIBALTAMENTO DELLE CAPPELLE	I	CAPPELLE CORPI ANNESSI
23 - MECCANISMI DI TAGLIO NELLE PARETI DELLE CAPPELLE	II	
24 - VOLTE DELLE CAPPELLE	I o II	
25 - INTERAZIONI IN PROSSIMITÀ DI IRREGOLARITÀ	I o II	
26 - AGGETTI (VELA, GUGLIE, PINNACOLI, STATUE)	I	AGGETTI CAMPANILE
27 - TORRE CAMPANARIA	I o II	
28 - CELLA CAMPANARIA	I o II	

(Lagomarsino, I., Podestà, L. 2005)

SCOMPOSIZIONE VERTICALE

SCOMPOSIZIONE ORIZZONTALE





Il ***MODELLO GRAFICO HBIM*** è stato criticamente costruito mediante individuazione dei **MACROELEMENTI** (***SCANSIONE ORIZZONTALE***) caratterizzanti l'edificio storico **CHIESA**.

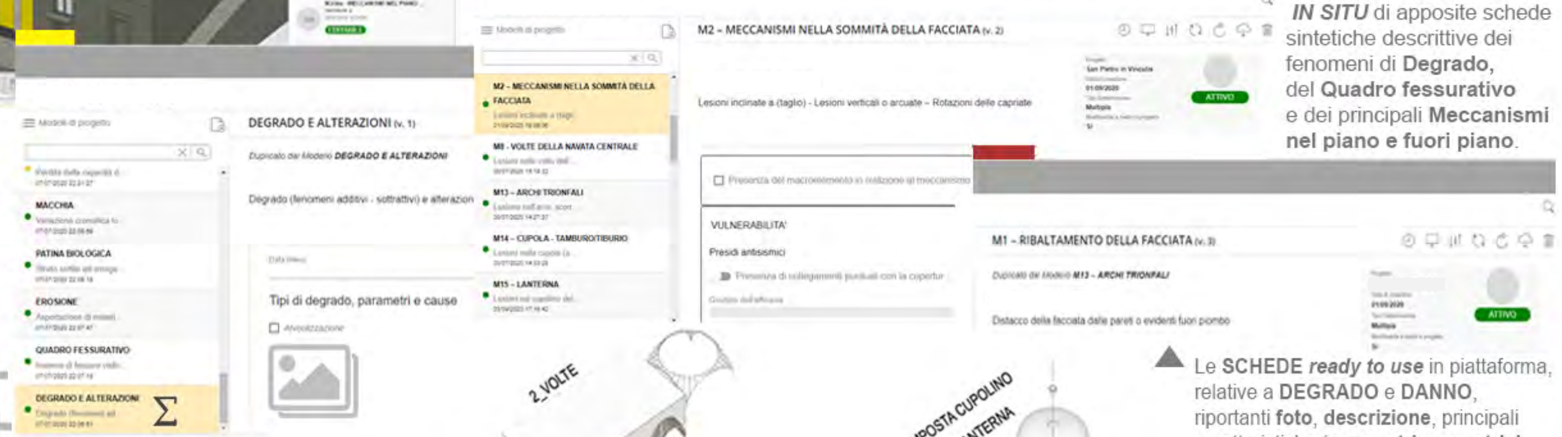
Danno Strutturale & Degrado Materico: SCHEDE ON-LINE

Macroelemento	Meccanismo	Peso del meccanismo (p)	Indice di danno (d)	Punteggio del rilievo degli indicatori di vulnerabilità (V_i)	Punteggio del rilievo dei presidi antisismici (V_p)	p_k	p_k*d_k	$p_k*(V_{ki}-V_{kp})$
FACCIATA	M1 - Ribaltamento della Facciata	1	0	1	0	1	0	1
	M3 - Meccanismi nel piano della facciata	1	1	2	2	1	1	0
AULA	M5 - Risposta trasversale dell'aula	1	4	3	3	1	4	0
	M6 - Meccanismi di taglio pareti laterali	1	0	3	3	1	0	0
	M8 - Volte dell'aula o della navata centrale	1	0	3	0	1	0	3
ARCO TRIONF.	M13 - Archi trionfali	1	1	0	2	1	1	-2
CUPOLA	M14 - Cupola e tamburo/tiburio	1	1	1	0	1	1	1
	M15 - Lanterna	0,5	0	0	2	0,5	0	-1
CAPPELLE	M22 - Ribaltamento delle cappelle	1	1	0	2	1	1	-2
	M23 - Meccanismi di taglio nelle cappelle	1	1	2	2	1	1	0
	M24 - Volte delle cappelle	1	2	0	0	1	2	0
						10,5	11	0

Meccanismi Strutturali

INDICE DI DANNO (i_d)	INDICE DI VULNERABILITA' (i_v)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0,21	0,5	0,18	0,05	0,26	0,70	0,86

La **PIATTAFORMA COLLABORATIVA *web-based*** consente la compilazione ***IN SITU*** di apposite schede sintetiche descrittive dei fenomeni di **Degrado**, del **Quadro fessurativo** e dei principali **Meccanismi nel piano e fuori piano**.

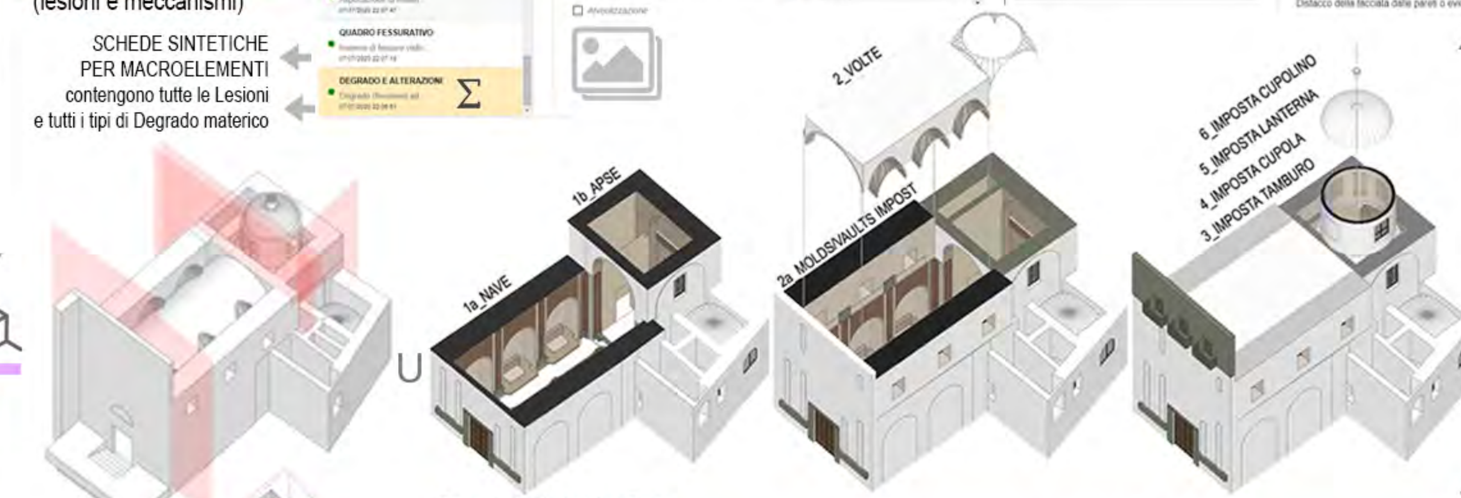


AREE DI DEGRADO

DANNO STRUTTURALE
(lesioni e meccanismi)

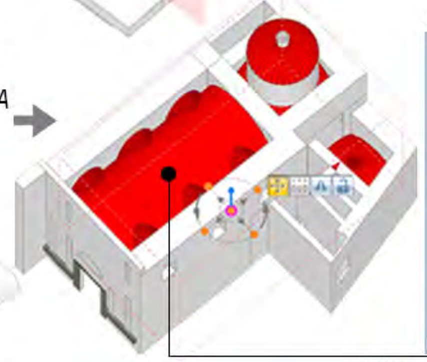
SCHEDE SINTETICHE PER MACROELEMENTI contengono tutte le Lesioni e tutti i tipi di Degrado materico

Le **SCHEDE *ready to use*** in piattaforma, relative a **DEGRADO** e **DANNO**, riportanti **foto**, **descrizione**, principali caratteristiche (**parametri geometrici**, **fisici** e **chimici**) e **principali cause**, sono state strutturate per essere *linkate* separatamente ad ogni area o tracciato specifico o ad un intero macroelemento, consentendo la lettura sintetica dell'intero quadro di danno.

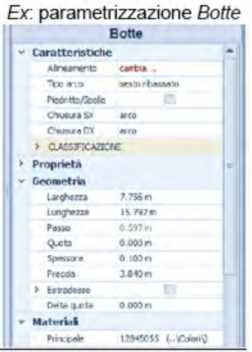


La nuova ***HBIM TOOLBAR*** prevede l'oggetto HBIM *ready to use* ***"VOLTA"***, per la modellazione BIM dedicata a tali elementi, consentendo ampia libertà compositiva per la generazione di volte semplici e composte parametrizzate rispetto alle geometria e alla stratigrafia. *Toolbox* strumento: *Proprietà*, *Caratteristiche*, *Materiali.*

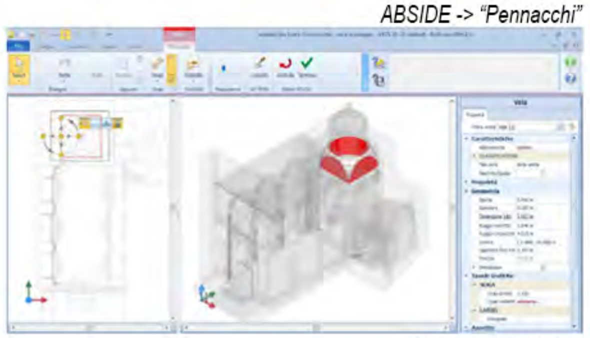
VOLTA



Ex: parametrizzazione Botte

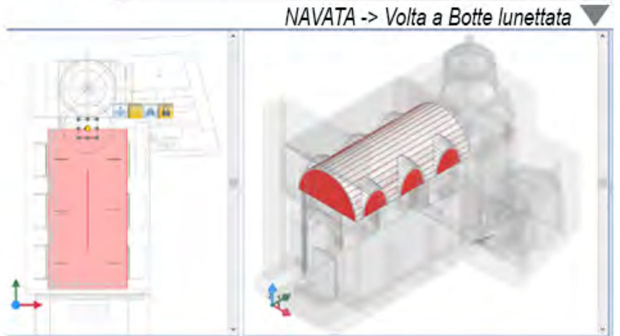


ABSIDE -> "Pennacchi"

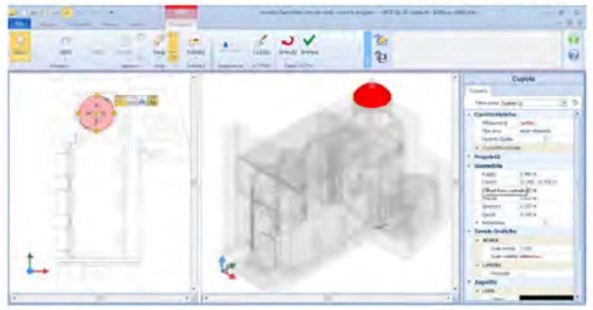


CAPPELLA LATERALE -> Volta a Vela

NAVATA -> Volta a Botte lunettata



ABSIDE -> CUPOLA



Disimpegno corpo scala/ABSIDE/CAPPELLA -> Volta a Crociera

HBIM tools. Piattaforma collaborativa *Web-based* & *HistoricBIM Toolbar.*

Laser Scanner Point Cloud — LOD A/B *MACROELEMENTI* → *HBIM*

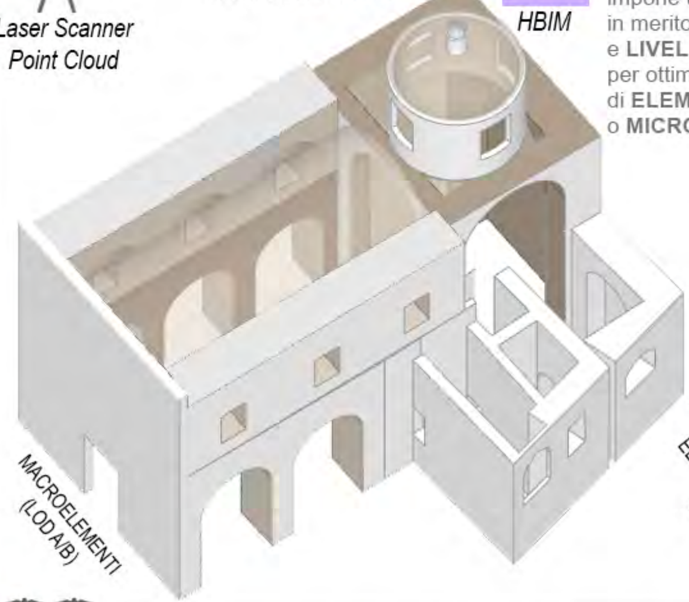
Scomposizione Semantica

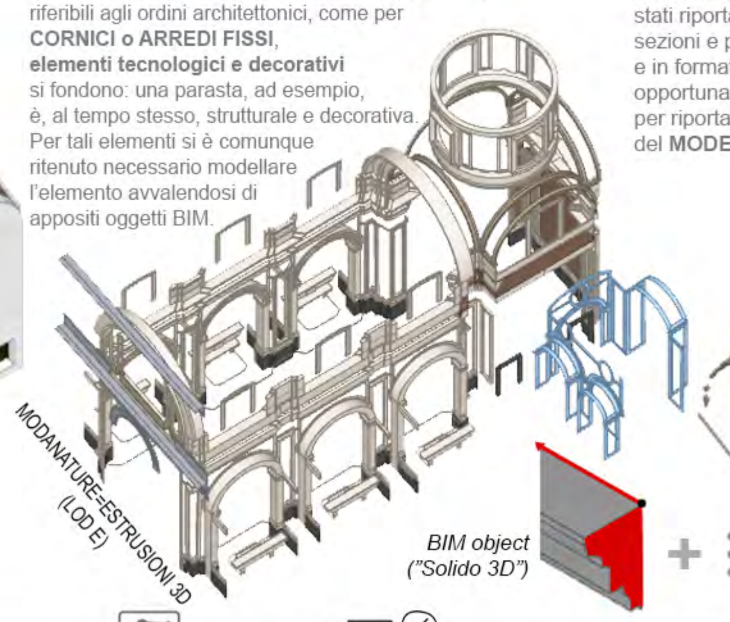
L'attività di modellazione dei **DETTAGLI DECORATIVI** impone una riflessione di carattere **SEMANTICO** in merito ai diversi **LIVELLI DI SVILUPPO (LOD)** e **LIVELLI DI DETTAGLIO/GEOMETRIA (LOG)** per ottimizzare (**LOIN**) la restituzione di **ELEMENTI SECONDARI** o **MICROELEMENTI**.

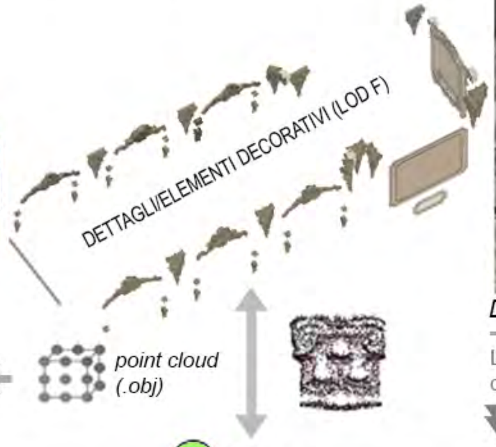
Nel caso di elementi decorativi o di completamento riferibili agli ordini architettonici, come per **CORNICI o ARREDI FISSI**, **elementi tecnologici e decorativi** si fondono: una parasta, ad esempio, è, al tempo stesso, strutturale e decorativa. Per tali elementi si è comunque ritenuto necessario modellare l'elemento avvalendosi di appositi oggetti BIM.

I **DETTAGLI COMPLESSI** (capitelli, stucchi) sono stati riportati in formato .dwg/.dxf per completare sezioni e prospetti (**TAVOLE GRAFICHE 2D**) e in formato **.obj**, estrati dalla **NUVOLA DI PUNTI**, opportunamente manipolati e texturizzati, per riportare i modelli degli stessi elementi all'interno del **MODELLO GRAFICO 3D**.

LOD F *MICROELEMENTI* → *HBIM*







Dettagli: elementi decorativi. Dalla nuvola di punti al modello 3D.

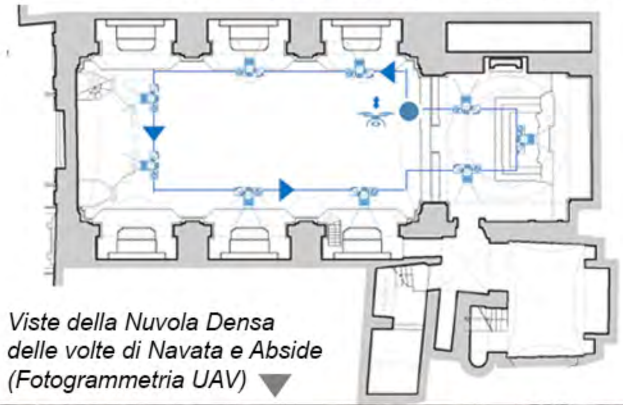
La **PIATTAFORMA *ON-LINE* (CDE)** consente di **ASSOCIARE** dati (**ACDat**) direttamente agli elementi attraverso lo strumento ***LINK***, e di **LOCALIZZARE** e **VISUALIZZARE** le informazioni relative ad uno specifico elemento attraverso lo strumento ***MARKER***.

LINK: DOCUMENTAZIONE - IMPLEMENTAZIONE

UAV Point Cloud

Fotogrammetria UAV_*drone Parrot Anafi Base*
+ Fotocamera da 21 MP
Processamento foto: *3D Aerial Zephyr (3D Flow).*

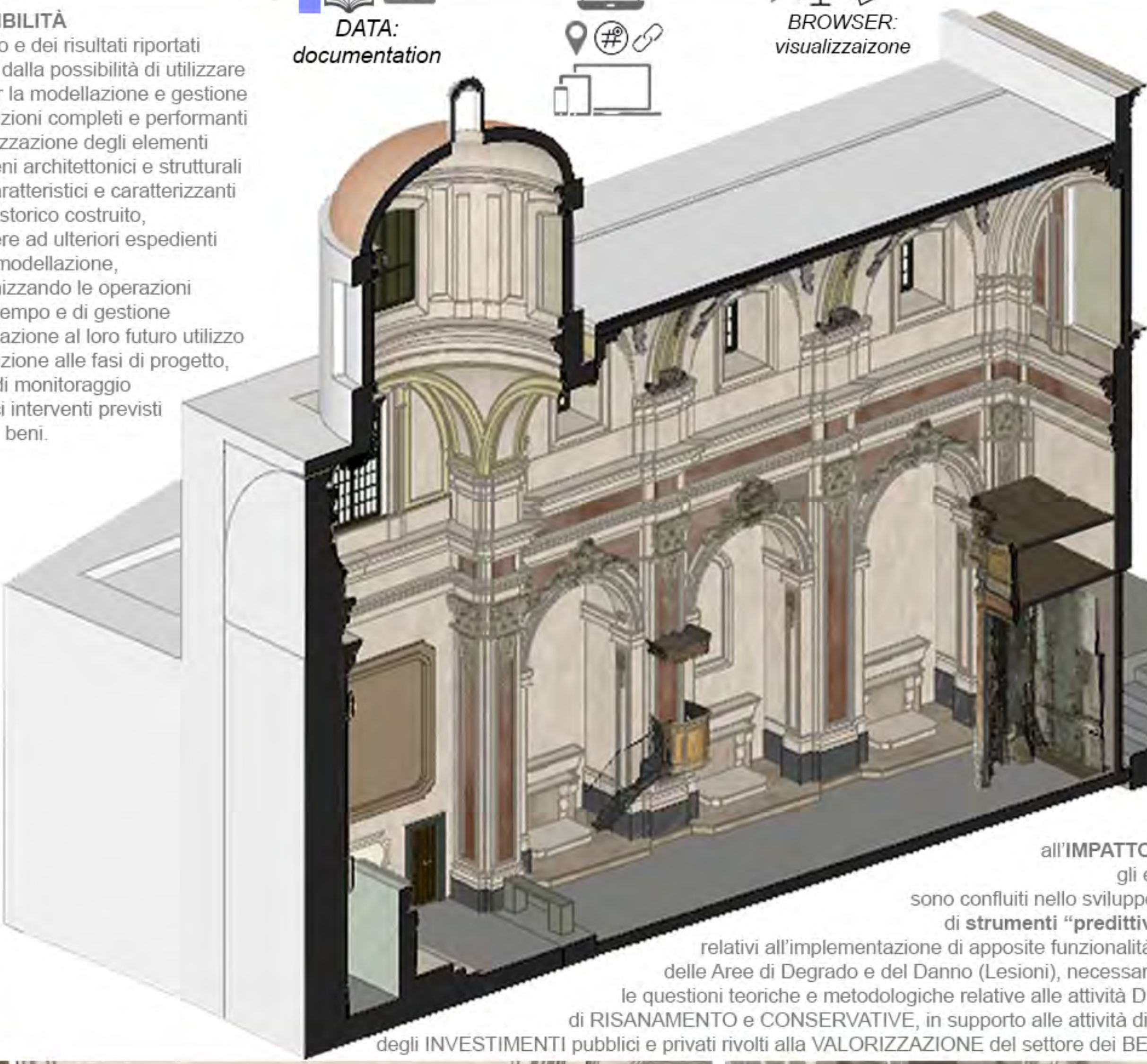
DATA: documentation → *BROWSER: visualizzaizone*



Viste della Nuvola Densa delle volte di Navata e Abside (Fotogrammetria UAV)

Caso studio: spaccato assonometrico e rendering.

La **SOSTENIBILITÀ** dell'approccio e dei risultati riportati è dimostrata dalla possibilità di utilizzare strumenti per la modellazione e gestione delle informazioni completi e performanti per la digitalizzazione degli elementi e dei fenomeni architettonici e strutturali complessi caratteristici e caratterizzanti il patrimonio storico costruito, senza ricorrere ad ulteriori espedienti in termini di modellazione, dunque ottimizzando le operazioni in termini di tempo e di gestione dei dati in relazione al loro futuro utilizzo anche in relazione alle fasi di progetto, esecutiva e di monitoraggio degli specifici interventi previsti rispetto a tali beni.



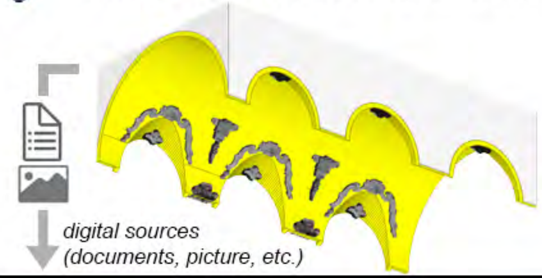
#tag:

SEGMENTAZIONE & SELEZIONE

La **PIATTAFORMA** consente inoltre di "**CATEGORIZZARE**" e "**RICONOSCERE**" gli elementi attraverso i **#tag**, definibili quindi come "*chiavi di ricerca*": il ***tag filter*** consente di individuare solo gli specifici elementi richiamati dal tag#,

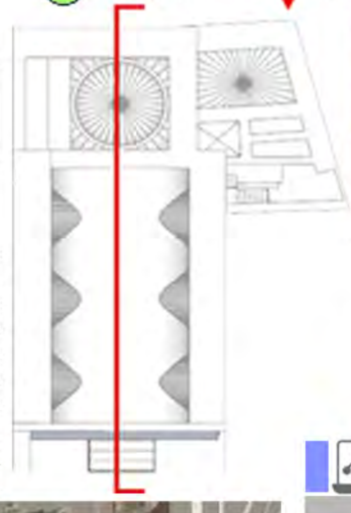
#scomposizione.macroelementi

#scomposizoine.elemento_architettonico
=
- capitello
- stucco
- cornice
- epigrafe



epigrafe **+**

MARKER: LOCALIZZAZIONE - VISUALIZZAZIONE



In riferimento all'**IMPATTO ECONOMICO**, gli esiti del progetto sono confluiti nello sviluppo e applicazione di **strumenti "predittivi"**, in particolare relativi all'implementazione di apposite funzionalità per la gestione delle Aree di Degrado e del Danno (Lesioni), necessarie per affrontare le questioni teoriche e metodologiche relative alle attività DIAGNOSTICHE, di RISANAMENTO e CONSERVATIVE, in supporto alle attività di VALUTAZIONE degli INVESTIMENTI pubblici e privati rivolti alla VALORIZZAZIONE del settore dei BENI CULTURALI.