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InfraBIM methods and tools applied to companies' implementation processes

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

I would like to dedicate this thesis to my loving parents, Tiziana e Marco

And to the love of my life, Mattia

who

suffered with me

laughed with me

loved with me

and

will always be part of me

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Abstract

The impact of digital innovation on markets is increasing over the years, thanks to the fast development of new technologies and tools. The effective use of advanced digital methods and tools within the AECO sector, and specifically the InfraBIM methodology, still faces major challenges in different situations, where the lack of resources in terms of cost and people does not allow to properly approach the implementation of such processes. For this reason, on the one hand the research analysed how to renovate existing processes and workflows towards the implementation of InfraBIM methodology working on standardization, collaboration, and production processes at company level. On the other hand, the research focused on the development and assessment of workflows to identify the most efficient approaches for several InfraBIM uses. Such a framework was built considering specific parameters useful for defining companies' priorities, working on daily procedures for the production of digital information models and related data and documents. According to this approach, the general bias related to the use of new methods and tools are overcome by defining a best practice that could be applied for future implementation processes too.

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List of abbreviations

ACDat	Ambiente di Condivisione Dati
ACDoc	Ambiente di Condivisione Documenti
AECO	Architecture, Engineering, Construction and Operation sector
AGI	Italian Geotechnical Association
AGS	Geotechnical and Geoenvironmental Association
AI	Artificial Intelligence
AIM	Asset Information Model
ANN	Artificial Neural Network
API	Application Programming Interface
AR	Augmented Reality
BAS	Building Automation System
BCF	BIM Collaboration Format
BEP	Building Information Modelling Execution Plan
BIM	Building Information Modelling
BLM	Building Life-cycle Management
BMS	Building Management System
bSDD	Building Smart Data Dictionary
CAD	Computer Aided Design
CBS	Cost Breakdown Structure
CEN	European Committee for Standardization
CDE	Common Data Environment

CI	Capitolato Informativo
CIM	Civil Information Modelling
CMMS	Computerized Maintenance Management System
CPM	Construction Project Management
DESI	Digital Economy and Society Index
DII	Digital Intensity Index
DT	Digital Twin
EIR	Exchange/Employer Information Requirement
EU	European
FEM	Finite Element Method
FM	Facility Management
FSE	Fire Safety Engineering
GIS	Geographic Information System
GML	Geographic Markup Language
ICT/IT	Information and Communication Technology
IDM	Information Delivery
IDP	Integrated Design Process
IFC	Industry Foundation Classes
IFD	International Framework for Dictionaries
InfraBIM	Infra Built Environment Information Model
IoT	Internet of Things
ISO	International Organization for Standardization
IWMS	Integrated Workplace Management System
KPIs	Key performance indicators
LOD	Level of Development/Definition/Detail
LOI	Level of Information
LOG	Level of Geometry
MCDA	Multi-Criteria Decision Approach
MEP	Mechanical, Electrical, Plumbing
ML	Machine Learning

MVD	Model View Definition
VAR	Virtual and Augmented Reality
OBS	Organization Breakdown Structure
oGI	Offerta di Gestione Informativa
OIR	Organizational Information Requirement
O&M	Operation and Maintenance
pGI	Piano di Gestione Informativa
PIM	Project Information Model
PLM	Project Life-cycle Management
PNRR	Piano Nazionale di Ripresa e Resilienza
QMS	Quality Management System
RL	Reinforcement Learning
SHM	Structural Health Monitoring
TBM	Tunnel Boring Machine
TIN	Triangular Irregular Network
UNI	Ente Nazionale Italiano di Unificazione
VAR	Virtual and Augmented Reality
VDC	Virtual Design Construction
VPL	Visual Programming Language
VR	Virtual Reality
WBS	Work Breakdown Structure
WIP	Work In Progress

Chapter 1

Introduction

Nowadays, BIM and InfraBIM are no longer news but solid and, for someone uncomfortable, realities. Nevertheless, BIM and even more InfraBIM still face major challenges for their ordinary application in different situations, where the lack of resources in terms of cost and people does not allow to properly approach the implementation of such processes. However, the possibility to make such methods "current affairs" was given by a combination of factors. This introductory Chapter aims at bringing these factors to light, to better understand the research framework presented in Chapter 2. Furthermore, this section tries to outline what is coming next and what can be considered as lesson learnt in approaching digital innovation in general, getting ready to face and approach further changes. Firstly, the accessibility of enabling technologies without the need for large amounts of capital represented a big push towards digital innovation in different fields, together with the affirmation of new management techniques and tools. However, AECO companies had more difficulties than other sectors in embracing digital innovation, often considering it as a Pandora's box containing all the worst enemies for their professional activities. Anyway, the experience proved that an efficient combination of enabling technologies and innovation management enabled the overcoming of bias that contrasted the use of new methods and tools. These concepts are of paramount importance because it means that no matter the type of innovation, a best practice on how to approach innovation in general can be drawn based on previous experience of adopting new technologies and implementing new processes. Within this context, the focus shifted on how to highlight the human factor thanks to digital innovation, which represents a crucial aspect to consider nowadays, what can be called the "Machine Age". To conclude, the Chapter aims at analysing the new opportunities that digital innovation, enabling technologies and innovation management bring to the Architecture, Engineering, Construction and Operation (AECO) sector, for example working on digital twins rather than stand-alone digital models and integrating Artificial Intelligence (AI) to optimize design processes.

1.1 The Pandora's box of digital innovation

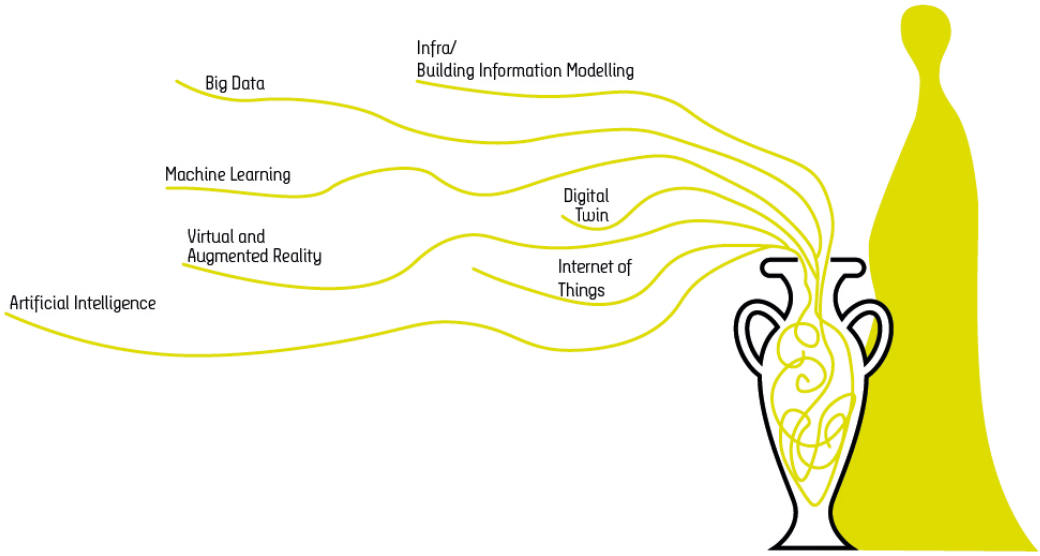


Fig. 1: Pandora's box of digital innovation

The impact of digital innovation on markets is increasing over the years, thanks to the fast development of new technologies and tools. Anyway, is this a positive or negative impact for companies? Digital innovation is so fast that it is very complex for companies to stay abreast of the times. For this reason, it would be incorrect to propose one technological system as the answer to all troubles, after a short period of time that technology might be considered obsolete. To better understand market dynamics, it is of paramount importance analysing the "enabling technologies" that are currently producing radical shifts in markets, business practice and society. On the other side, it is also important to distinguish three main concepts related to digital innovation: (i) **digitization**, which is about converting something non-digital into a digital representation or artifact; (ii) **digitalization**, which refers to enabling or improving processes by leveraging digital technologies and digitized data, so digitalization presumes digitization; (iii) **digital transformation**, which is actual business transformation enabled or forced by digitalization technologies (Gupta, 2020). The present study analyses part of the digital transformation process for the implementation of methods that involve the use of some of those "enabling technologies" currently in vogue in the AECO sector.

The other side of the coin is represented by attempts to deploy digital technologies that were not successful, resulting in many examples of implementation failures and cost overruns. Such failures tend to be analysed focusing on the technology introduced, rather than on the role played by cultural factors and by organizations' willingness to embrace new approaches and working practice, individual characteristics of team members, team sentiment and organizational governance, which result to be as essential to success as deploying the right IT (Mahroum, Ferchachi, & Gomes, 2018). For this reason, it is not only a question of choosing the right technologies, but also the way the implementation of such technologies is carried out establishes the real success of one choice over another, and therefore a great deal of effort must be put into the implementation process of innovative technologies from several aspects.

In the past, the need for innovation required the development of new methods, which in turn involved the invention of new tools. Nowadays, mainly around digital innovation, the opposite is often proved, because it happens more frequently that first there is the invention of new tools and later such tools are applied to new methods in several fields of application. Digital transformation describes the deep-seated changes in industrial and organizational activities, processes, and competencies required to seize the opportunities and respond to the challenges engendered by the new digital paradigm, including a vast array of enabling technologies, such as the Internet of Things, Additive Manufacturing, Big Data, Artificial Intelligence, Cloud Computing, Augmented and Virtual Reality, and Blockchain (Rindfleisch, O'Hern, & Sachdev, 2017). Therefore, the time needed to develop and launch innovative technologies is decreasing the lifecycle of items and services, because customers and users are always looking for flexibility and personalization of products (Li, 2018). Furthermore, digital innovation requires companies to cross fertilize their basic knowledge with technologies they are not familiar with in a very short time and to step out of their comfort zone, possibly eliminating previous practices (Saarikko, Westergren, & Blomquist, 2020).

Within this context, digital innovation is often referred to as a "black box", that can be compared to the mythological **Pandora's box** in the sense it includes heterogeneous factors that taking all together bring confusion and difficulty of application. Indeed, the metaphor of Pandora opening a box containing all the evils of human is particularly appropriate within this context, because "seeking to implement innovation leads to the emergence of unsuspected difficulties when the idea has arisen; innovation breaks the routines" (Laperche, 2018). Such "chaos" can be contrasted with strategic planning on how to approach new technologies, new processes and new professional skills. At this point it is necessary to introduce the concept of **digital consciousness**, which requires taking into account several factors such as social, technical, and organizational ones applying them in both strategy and practice (Saarikko, Westergren, & Blomquist, 2020), because **"Strategy, not technology, drives digital transformation"** (Kane, Palmer, Philips, Kiron, & Buckely, 2015). Such a consciousness is achievable thanks to an improvement of technologies together with an innovation management as discussed in the following paragraphs.

1.2 Enabling technologies and innovation management

The Business Dictionary defines an **enabling technology** as "an invention or innovative system that, alone or in combination with associated technologies, provides the means to drive radical change in the capabilities of a user or culture". The examples of such enabling technologies are uncountable throughout history, such as glasses and ceramics in ancient and prehistorical eras or the printing press in the classic era, which ushered in the period of modernity. However, the meaning has evolved over time; for instance, according to the European Commission definition, enabling technologies are "knowledge-intensive technologies associated with intensive R&D, rapid innovation cycles, significant investment costs and highly-qualified labour". For this reason, enabling technologies are of great relevance and capable of driving innovation in processes, producing radical shifts in markets, business practice and society. To define the context of the present research, it was considered fundamental to introduce the three enabling technologies that enabled the diffusion of collaboration design methods such as Building Information Modelling (BIM) and that play a role in the definition of Digital Twins: cloud-computing, IoT and Big Data.

The first technology enabling great improvements in society is **cloud-computing**, which is described as "the delivery of computing services – including servers, storage, databases, networking, software, analytics and intelligence – over the Internet" (Microsoft, 2021). The introduction of cloud computing gave more flexibility in the way firms and individuals used storage capacity, processing power and software applications, such as Google Drive or Gmail. This way companies were able to provide flexibility without the need to dedicate resources and additional investments to increase their computational power and storage capacity. Therefore, cloud-computing increased market concentration in ICT vendors, with a few but very large players leading the market. Such a trend represented a peculiar trait of the internet society, influencing also the AECO sector, which is "dominated" by big software houses producing tools for different purposes related to specific disciplines, such as Autodesk and Bentley.

The second enabling technology is the **Internet of Things** (IoT) described as "the concept of gathering information from physical objects using computer networks or accelerated wireless connections" (Dilberoglu, Gharehpapagh, Yaman, & Dolen, 2017). IoT allows objects to be seized and controlled remotely across an existing network infrastructure, creating more opportunities of a more direct integration between the physical world of objects and computer based. Within the AECO sector such infrastructure is extremely important because it represents the basis for specific analysis in several fields of application, such as Structural Health Monitoring (SHM). Indeed, monitoring existing infrastructures by equipping bridges and buildings with sensors represents the basis for real digital twins, allowing them to run more efficiently and to monitor their safety. Therefore, IoT enabled products to communicate with computers in a way that information is captured and directed where it can produce more economic value. IoT also allowed changes and innovation in business models in the way companies produce economic value for customers and make money. This trend raised new managerial challenges; IoT inside products often implies the increase of its mechanical complexity, whereas companies that were not specialized in information processes now have to become expert in data analysis and software to be competitive on the market. The same happened in the Construction Industry, where engineers and architects are currently required to have advanced ICT-related skills also, forcing companies to make large investments in training of their employees and hiring new dedicated professionals.

A world where objects producing big amount of data can be monitored and sensed remotely is a world made of **Big Data**. For this reason, Big Data is the third enabling technology taken into consideration for the development of the research framework for the present thesis. This enabling technology has provided new opportunities including: the chance to observe products in use, which in the AECO sector is translated in the possibility to monitor buildings and infrastructures for several purposes, from structural health up to energy performance; the use of machine learning (ML), which encompasses a series of algorithms developed between 70s and early 90s when their applications were limited by constraints in storing and processing data. ML was defined as the study of computer algorithms able to automatically detect patterns in data, and then use the uncovered patterns to predict future data; the whole system of data prevision improves automatically through experience (Mitchell, 1997) (Kodratoff, 1989). Thanks to the three enabling technologies above mentioned, ML was provided with more support; persistence, big data and a lot more computer power made it possible for deep learning to make big breakthroughs (Sejnowski, 2018). Such a connection shows there is an important complementarity among enabling technologies as often happened in the past also; the development of some has also enabled other technologies that were already present but poorly exploited to become established and increase their influence and use.

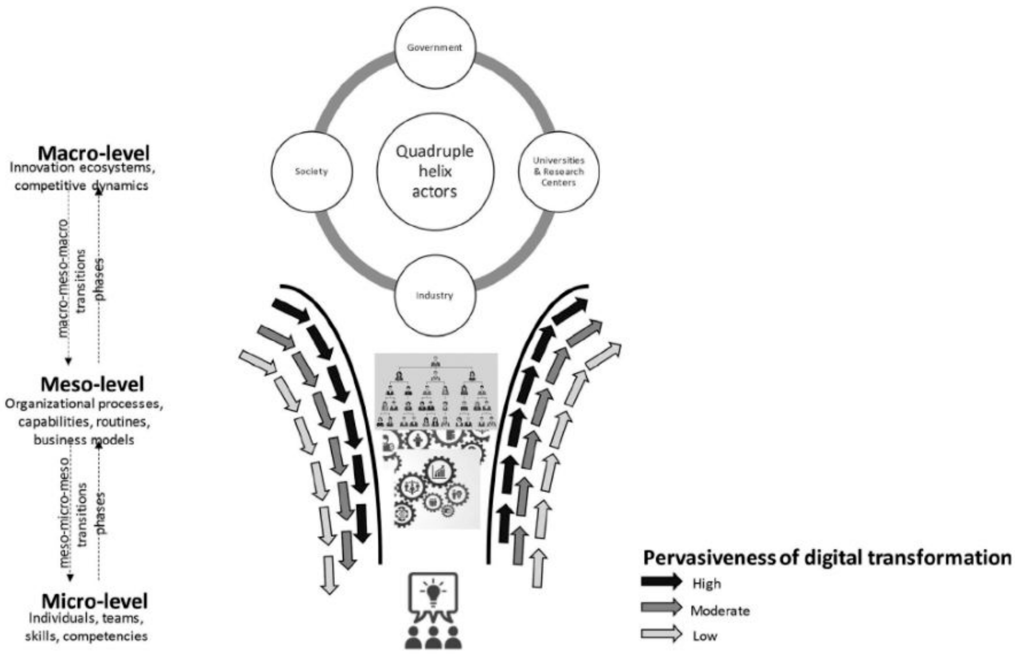


Fig. 2: Framing Digital Transformation and Innovation Management at Multiple Levels
Source: Appio, Frattini, Petruzzelli, & Neirotti (2021)

Enabling technologies play a leading role in digital innovation of course, but as Kane, Palmer, Philips, Kiron, & Buckely (2015) said the real driver of digital transformation is strategy, not technology. Indeed, even though technical limits have gradually been overcome, technology does not automatically bring added value unless companies carefully consider how to implement it within the existing processes to gain benefits. Within this context, any company "seeking to make hay of digital technology must be willing to adapt its strategies and capabilities to accommodate new ways of perceiving and creating value" (Saarikko, Westergren, & Blomquist, 2020). For this reason, new challenges have been faced by managers to remain competitive on the market because of digital innovation. Digitalization is regarded as an essential driver of innovation and for this reason has a great influence on **innovation management** (Niewohner, et al., 2019). However, finding the right strategy should not be taken for granted. Indeed, especially in the AECO sector, there is still a lack of frameworks able to guide companies towards the creation of value and competitive advantage by using digital technologies within their innovation activity, as well as practical solutions on how companies should use digital technologies to transform their work practices and management of knowledge resources. Appio, Frattini, Petruzzelli, & Neirotti (2021) proposed an approach to organize the fragmented debate on digital transformation and innovation management by identifying **three levels of analysis** (i.e., *macro*, *meso* and *micro*), as shown in Fig. 2. The ***macro-level*** refers to the ability of digital transformation to influence industries organization and companies interconnection, considering contextual conditions which are in turn related to social, economic, political environments; the ***meso-level*** focuses on the way companies structure their processes and capabilities to embrace digital transformation; finally, the ***micro-level*** refers to the changes in micro-foundations of companies, investigating the way digital transformation influences routines and work practices underlying innovation processes (Appio, Frattini, Petruzzelli, & Neirotti, 2021).

Within this context, the research carried out in this thesis focuses on the last two levels, analysing the **implementation approach of InfraBIM methodology** within companies. Such implementation involves a digital innovation in the way new processes, systems and tools had to be integrated into daily work procedures (*micro*-level) and also had an impact on the company organization (*meso-level*) through the necessity of rearranging the company organizational chart adding new professional figures, new roles and responsabilities.

1.3 New opportunities in the AECO sector

Even though innovation is a phenomenon affecting all sectors of society, the Construction industry is still lagging behind other fields, such as automotive or manufactoring industries. Such a gap influenced productivity also. The McKinsey Global Institute (MGI's) within the "*Reinventing construction: A route to higher productivity"* report, released in February 2017, highlighted the productivity problem of the AECO sector. Indeed, global labor-productivity growth in construction has averaged only 1% a year over the past two decades, against a growth of 2.8% in the world economy and 3.6% in manufacturing (McKinsey & Company, 2017). These results clearly prove that the **AECO sector is underperforming**, relying mainly on traditional methods for many projects rather then transform itself to boost productivity as other sectors have done. For example, the US Construction industry has witnessed a decline in labor productivity since 1968, as shown in Fig. 3, while Agriculture, Manufacturing achieved quantum leaps. For example, the compound annual growth rate between 1947 and 2010 has been 4.5% for Agriculture, thanks to the land assembly, automation and advanced bioengineering to increase yields and 3.5% for Manufacturing, thanks to new concepts of flow, modularization and automation to increase production (McKinsey & Company, 2017). The report also highlights the major reasons for such a poor performance, including stringent regulations and dependence on public-sector

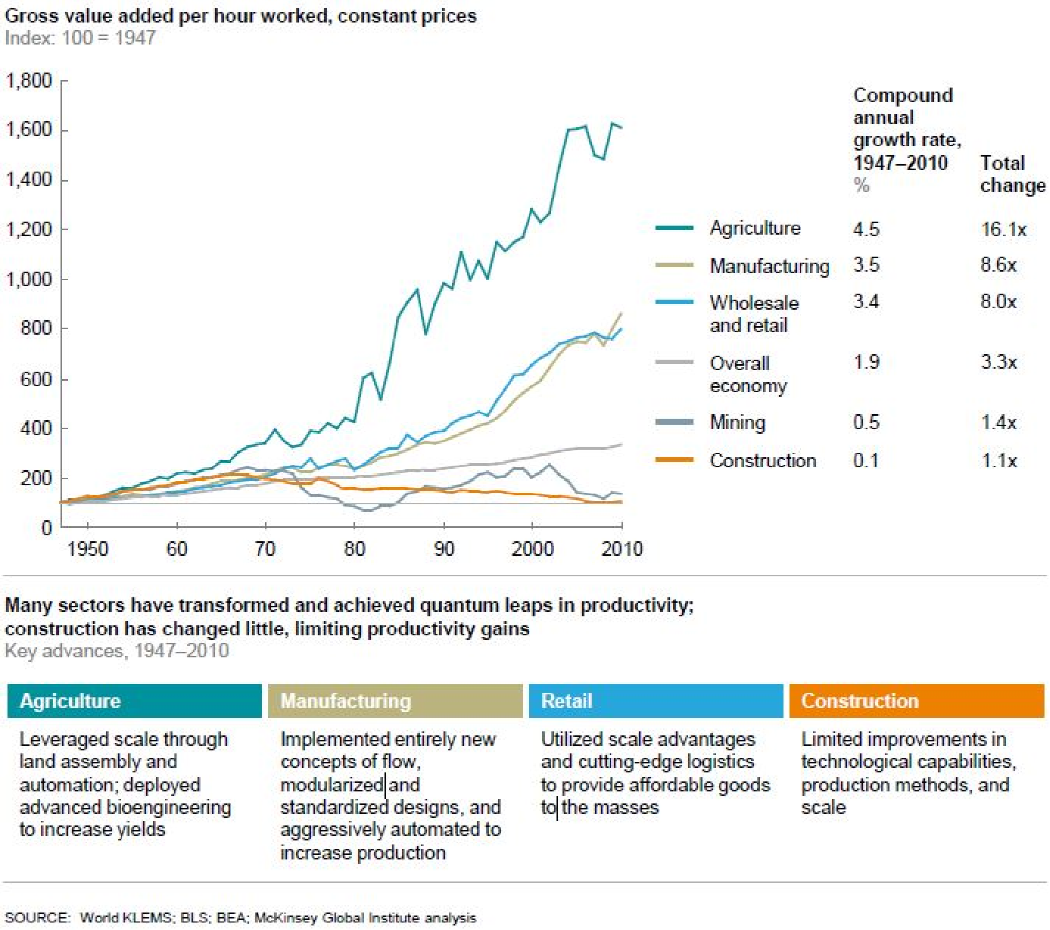


Fig. 3: Global labor-productivity growth in different sectors
Source: McKinsey & Company (2017)

demand, informality and high likelihood of corruption, fragmented nature of industry, inadequate design processes and underinvestment in skills development, R&D and innovation. Furthermore, the **AECO sector** results one of the **least digitized**. Indeed, The Digital Economy and Society Index (DESI) Report 2018 Integration of Digital Technology reported that in the construction sector **only 7.7%** (European Commission, 2018) of **enterprises** have a **high** or very high **Digital Intensity Index** (DII), which measures the use of different digital technologies at enterprise level (European Commission, 2020). Such negative trend cannot be constrasted only with digital innovation of course but the integration of concept such as Digital Twin and process optimization through the use of IoT, Big Data and other enabling technologies would certainly **boost new opportunities** for the AECO sector.

Digital Twin (DT) concept is assuming more importance and meanings over times. Amongst its definitions, a very interesting one is provided by Coupry et al. (2021): "A Digital Twin is a multi-scale representation of a whole consisting of a potential or existing system (physical product, user and activity) in the real environment, its virtual reflection in the digital space and the processes of

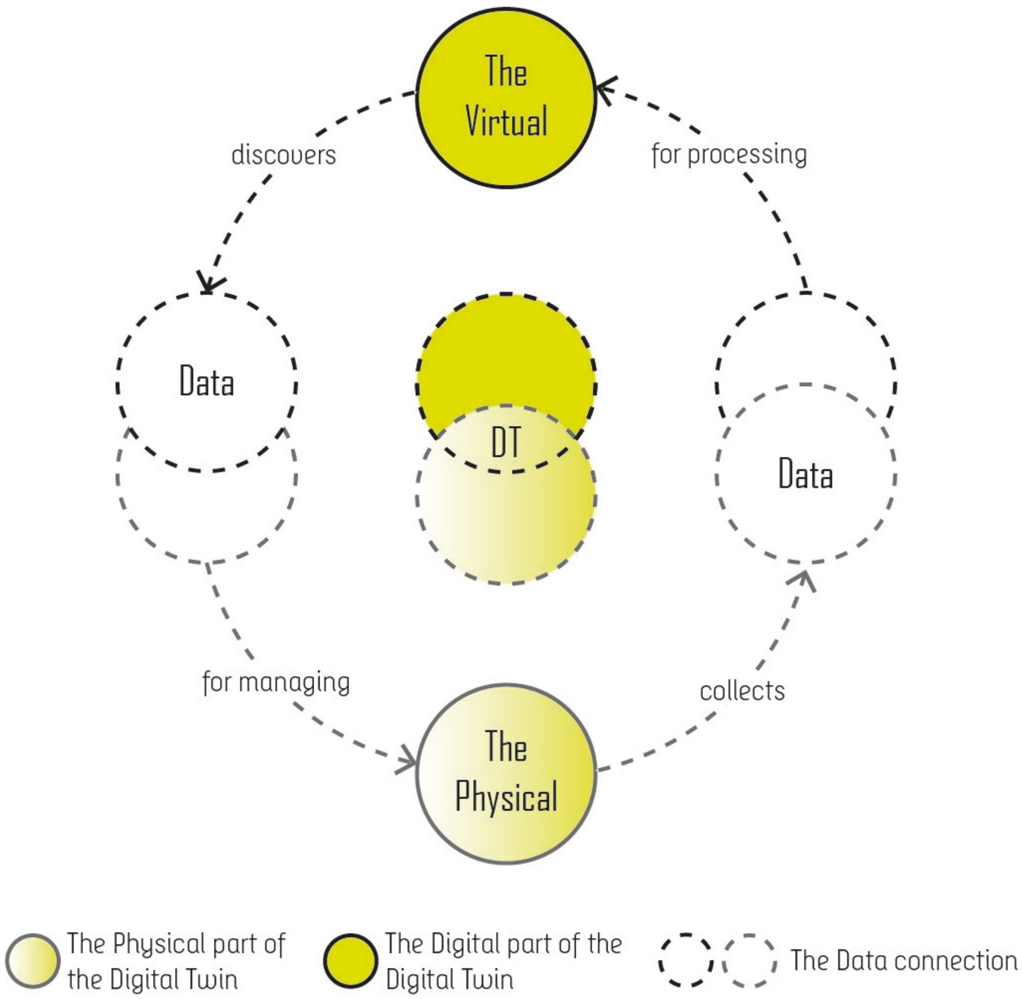


Fig. 4: The digital Twin Paradigm
Source: Adapted from Boje, Guerriero, Kubicki, & Rezgui (2020)

automated exchange of data and information in real-time and using simulation algorithms and historical data or collected from smart sensors to predict the system's future state or its response to a given situation. A Digital Twin may also include the Digital Twins of its subsystems" (Coupry, Noblecourt, Richard, Baudry, & Bigaud, 2021). This definition takes inspiration from different observations and declination of DT (Grieves & Vickers, 2017)(Kritzinger, Karner, Traar, Henjes, & Sihn, 2018) (Aheleroff, Xu, Zhong, & Lu, 2021) (Glaessgen & Stargel, 2012) and focuses on DTs using predictive algorithms to envision the evolution of a system or its response to a specific situation. Also Boje et al. (2020) reasoned on the composition of DT, introducing the DT paradigm which considers three main components interacting with each other (Fig. 4): (i) the **Physical components**; (ii) the **Virtual models**; (iii) the **Data** that connect them. Within this context "the connection loop between the "Virtual-Physical" duality of the system is provided by the "Data" in its various forms" (Boje, Guerriero, Kubicki, & Rezgui, 2020).

Within this context, data is the element connecting the two environments, from the one hand the "original" one and thus "The Physical", and on the other hand the "new" one, "The Digital". This vision totally reflects the current trend of trying to consider these two environments as pieces of a larger whole. A real connection between them enables the optimization of not only the design and the construction phases, but the asset and facility management also. Furthermore, the immediate and great availability of real-time information possible thanks to IoT technologies gives the chance to use such a data in order to **predict** and **anticipate** how "The Physical" will behave on the basis of simulations perfomed on "The Virtual". One is linked to the other and needs its counterpart to "survive". However, despite the potentialities of such integrated matching between physical and real, there are still some **open questions** on how to put it into practice, also because there is no agreement on how the different systems and technolgies (BIM, InfraBIM, GIS etc.) should interact with each other.

Furthermore, the increasing use of digital information models in the Construction industry allowed the integration of Computer Science, Machine Learning and Artificial Intelligence for various purposes. Certainly, these technologies dialogue better with a digital representation of the built heritage rather then the "physical" one and give the possibility to use data on buildings/cities/infrastructures contained in the models to develop simulations and prefigure scenarios and related consequences. Another example of innovation producing real benefits in the AECO sector is related to the production of **machine readable data-documents**, which bring automation from the design phase to the construction.

The other side of the coin of digital transformation is the necessity to take into account that automation put at risk the labor-market. Within this context, COVID-19 pandemic did not help at all; indeed the pandemic had a great impact on boosting productivity through automation, digitalization and reorganization of activities and operations, including a fast shift from office to at-home work, but some issues are still unsolved. Furthermore, this trend of growing productivity should spread from the large firms to those small and medium-size enterprises that have have been reluctant to increase their investments in automating or digitalizing processes and operations. Indeed, such a refusal increased even more the productivity gap between large companies and smaller competitors, "exacerbating the trend towards greater inequality in economic performance across firms and regions and more market concentration" (Tyson & Mischke, 2021). To conclude, technology alone will not solve poor productivity and decline of AECO sector, because fundamental culture change is needed alongside adequate systems and processes to embrace the new opportunities previously described. Furtermore, an important topic is linked to finding new opportunities to the labor force. The present thesis aims at analysing not only advancements and innovation brought by technologies and new design methods, but also the transformation of companies' organization and processes necessary to achieve higher digitalization, productivity and optimization of the overall industry.

Chapter 2

Research framework

2.1 Problem statement

As discussed in Chapter 1, enabling technologies have broadened up the prospects of digital innovation up to the extent that the **real advantage** and benefit is necessarily given from a **combination** of **methods** and **practices**. However, the present research focuses on the implementation of BIM methods and tools within companies working in the infrastructural domain. As an activity, **Building Information Modelling** is composed by the "set of processes applied to create, manage, derive and communicate information among stakeholders at various level, using models created by all participants to the building process, at different times and for different purposes, to ensure quality and efficiency throughout the entire building lifecycle" (Osello, 2012). Another fundamental concept that needs to be introduced is **interoperability**, as the "ability to exchange data between applications, which smooths workflows and sometimes facilitates their automation" (Eastman, Teicholz, Sacks, & Liston, 2011). In the last decades, the benefits of a BIM-oriented approach resulted attractive not only at building level, but as far as infrastructural projects are concerned too. On the other side, despite the benefits, **new issues** and **limits** have arisen by the application of **BIM** to the **civil environment**, mainly in terms of interoperability and scale. However, in the last decade a series of acronyms have been developed to define the application of BIM to the infrastructural sector. Three different possible definitions of Infrastructural BIM are the following.

"Horizontal BIM, Heavy BIM, VDC, Civil Information Modelling […] all of these phrases, and more, are being used in the construction industry to describe the way companies are deploying model-based technologies and processes to non-building projects" (McGrawHill, 2014).

"Civil information modelling (CIM) is a term commonly used in the AEC industry to refer to the application of BIM for civil infrastructure facilities" (Cheng, Lu, & Deng, 2016).

"**InfraBIM** is the acronym for Infra Built Environment Information Model, which includes the infrastructure information model and related structures and environment information" (buildingSMART Finland, 2014).

Within this thesis, when referring to the application of BIM methodology to the infrastructural domains the choice has fallen on the acronym InfraBIM. As it is possible to notice, all these definitions are quite recent in terms of time, which means that BIM application to the infrastructural domain is still under development and relatively limited due to a series of issues. Among the issues, the scale of reference when talking about network infrastructures is considerably spread horizontally, determining the necessity to extend models for hundred kilometres at least. This represents the first issue when trying to use a BIM authoring platform created mainly to model buildings. For this reason, even if some processes in using BIM tools and platforms have been confirmed after some experience in the application to buildings, such procedures have to be updated to design, build and manage infrastructures. Therefore, platforms, tools and the interoperability among such systems can change a lot when talking about InfraBIM.

Indeed, the transition of BIM methodology to the infrastructural domain has emphasized its prospects, **providing new challenges** and pushing the process beyond any previous limit. Within the Italian context, the process of BIM implementation started because of market demands; the process of adopting BIM does not have its origin in a benchmark case study project, but in the experience of each company, who implemented BIM processes to stay abreast of the times. The Italian guideline on this topic is the technical regulation UNI 11337/2017, while D.lgs. n.50/2016 and DM n.560/2017 and DM n.312/2021 are official regulations. While UNI 11337 discusses technical details, such as documents, concepts and definitions, and information process, the DM signed in December 2017 determines a **progressive duty** of **introducing BIM** as a procedure for construction processes. Such progressive duty and the whole decree have been reviewed recently with the publication of DM n.312/2021, whose aim was to give more details and also to take into account the difficulties caused by the pandemic. Furthermore, the document also refers to the technical specifications as required by the UE regulation n.1025/2012 following a specific order.

Currently, the BIM maturity level within the infrastructure field corresponds to an intermediate grade because interoperability is not yet error-free and not all data is exported when using standard file formats. On a United States perspective, the first "Business Value of BIM for Infrastructure SmartMarket Report" was published in 2012 (Dodge Data & Analytics, 2017); this survey highlighted that BIM adoption in the infrastructural sector was about 3 years behind that of buildings, only reaching a 50% adoption rate in 2013. After five years, an updated version of the report has been published. This time the study was focused entirely on transportation infrastructure, and it included European countries too (Dodge Data & Analytics, 2017). The most striking conclusions of the updated study refer to the quantity of BIM users at high level of implementation (on at least half of their projects), who grew from 20% in 2015 to 52% in 2017, and 61% envisage that they will be at that high level of implementation by 2019. As far as the "Sector" is concerned, a higher percentage of companies working on tunnels (86%) report using BIM than do those who are specialized in roads (76%), bridges (79%), or rail/mass transit (77%) (Dodge Data & Analytics, 2017). Another difference is linked to the size of the company; a lower percentage of small companies is reported using BIM than large companies, both for engineers and contractors. Furthermore, among the necessities of companies, not only the large ones but especially the SMEs, there is the identification of the most efficient workflows to develop specific **BIM uses**, where BIM use is defined as "a method of applying Building Information Modelling during a facility's lifecycle to achieve one or more specific objectives" (Kreider & Messner, 2013).

2.2 Aims and research questions

Against the background presented in Chapter 1 and based on the problem statement previously presented, the research activity had a **twofold objective**. On the one hand, the research analysed how to **renovate existing processes** and **workflows** towards the implementation of enabling technologies and, in particular, towards the introduction and use of InfraBIM methods and tools, working on standardization, collaboration and production processes at company level. This aim refers to the *meso-level* presented by Appio et al. (2021) to frame research activities on digital transformation. On the other hand, the research focused on defining an **assessment framework** to identify the **most efficient workflow** for several BIM uses. The assessment framework was built considering specific parameters useful for defining companies' priorities, working on daily procedures for the production of digital information models and related data and documents (*micro-level*).

The reasons for the development of the research topic are related to the lack of a standardized process able to prevent any kind of data loss in exchanging data within the BIM, and even more InfraBIM environment. For this reason, the present work is of interest to the scientific community in terms of deepening in details specific workflows to integrate several discipline purposes. Therefore, the core objectives of this research topic can be summarized as follows:

- Start and develop a **process of re-organizing** the actual structure of companies during the design phase in order to satisfy the needs of a highly competitive market;
- Analyse and develop processes necessary to a **InfraBIM-oriented procedure** and management of the entrusted works;
- Analyse the **possibilities of integration** among existing processes and those introduced because of InfraBIM implementation;
- **Develop standards**, documents and **guidelines** on the practical operations to follow when developing digital information models;
- **Test several workflows** to identify the best way to achieve the required results using specific pilot projects for the selected InfraBIM uses;

– **Benchmark** and **comparison** of selected workflows to define an assessment framework;

– **Dissemination** and **communication** of results to highlight the replicability of the methodology. This objective was achieved by developing a web-platform with a guided process including information on how to apply the implementation on a daily practice.

To sum up, the research aims at combining both knowledge on the specific field of infrastructures and tools-related skills, in order to define strategic planning at company level; however, communication with project coordinators and other professionals is essential because the implementation process needs to face and find **solutions to practical issues**.

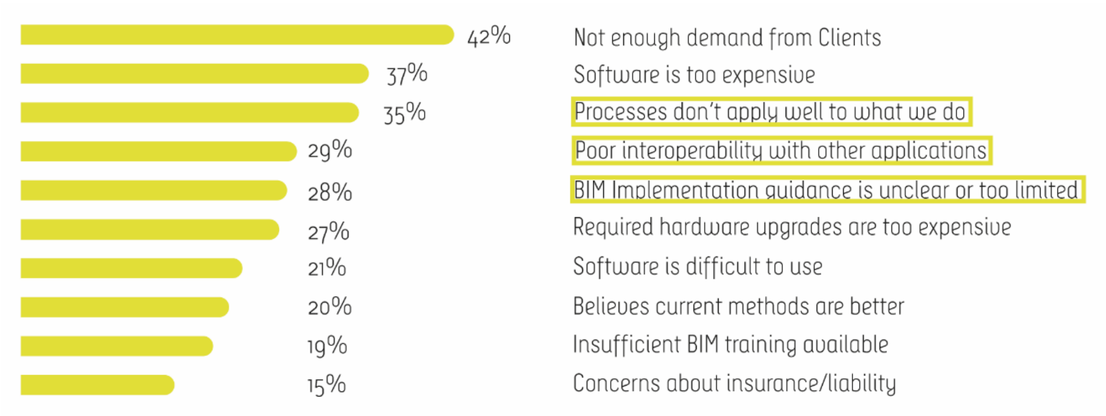


Fig. 5: Reasons why companies are not using BIM
Source: Adapted from Dodge Data & Analytics (2017)

The inspiration for specific research questions to answer came from the report "The Business Value of BIM for Infrastructure 2017" by Dodge Analytics which highlights ten main reasons why companies are not using BIM as shown in Fig. 5; the order is from the highest to the least important issue (Dodge Data & Analytics, 2017). By reasoning on these answers given from professionals, it is noticeable that the biggest issues in adopting BIM within infrastructure sector concern the **change** of **methods** and **tools** to be used. This also means that new processes must be implemented, and it is not clear how to proceed with such an implementation. Other big issues concern the cost of new software to be implemented and the poor interoperability with other applications. These results show to what extent the difficulties in approaching an unknown environment are relevant towards the decision of professionals of not using BIM. However, the trend requires a change, not only in terms of technologies to implement but also related to cultural factors and human capital. Within this context, the research focused on the three highlighted aspects in Fig. 5, which resulted critical from different points of view. For the motivations previously defined, this study aims at answering the three main research questions in Fig. 6. The **first** one refers to the third reason presented in Fig. 5 "processes do not apply well to what professionals are required to do". The meaning of this assumption is strictly linked not only to tools but to methods also. Indeed, the use of new tools such as BIM platforms and other software applications means that current processes have to change also because "traditional" workflows are no more effective and efficient. In this regard, the research focused on the different types of processes that the InfraBIM environment requires to implement, analysing them to understand how to proceed with their integration in the daily practice. The **second** research question is closely linked to the issue of interoperability, so the aim is to define specific InfraBIM uses and for each of them develop related workflows with different combinations of tools and methods. To conclude, the **third** research question is specifically related to analyse the efficiency of workflows, in order to study how to create a framework of assessment which is able to define the most efficient workflow on the basis of specific requirements.

The innovative contribution of the proposed research consists of the integration among standardization processes and benchmark of methods and tools; the aim is to highlight how important the analysis phase is in order to define the best approach. Also, trying to define a benchmark, the contribution is related to finding solutions to gaps in the interoperability process and ways to reduce or purge data losses in the exchange of information among professionals and software platforms. Furthermore, the research fully meets the latest National and International directives on digital innovation in the AECO sector, working on the implementation of BIM in the infrastructure sector, which is the most affected one when considering Italian legislation on public works such as Dlgs. 50/2016 and DM 560/2017 and 312/2021.

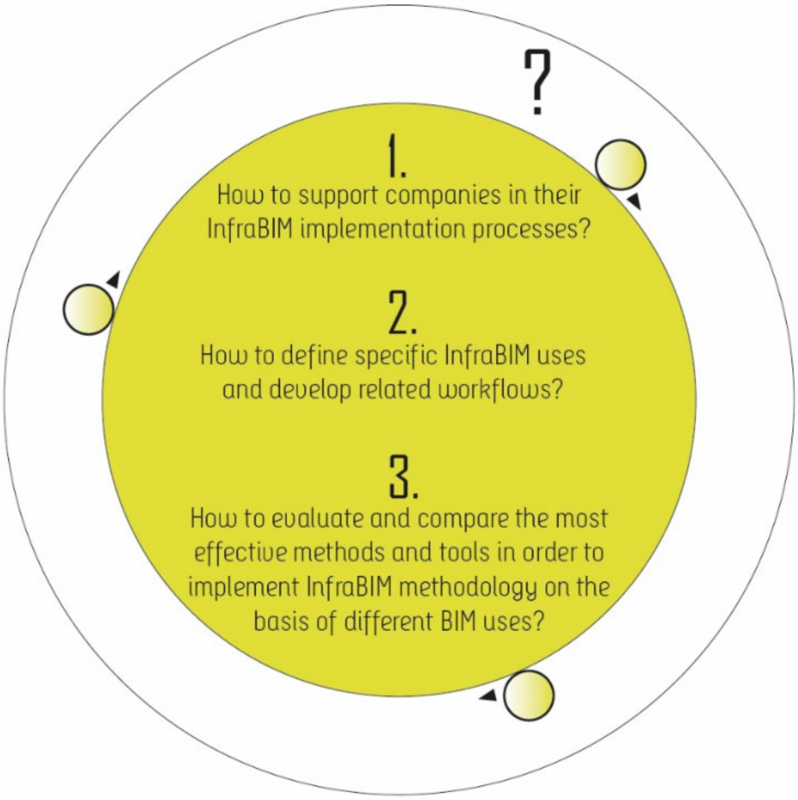


Fig. 6: Research questions

2.3 Methodological framework

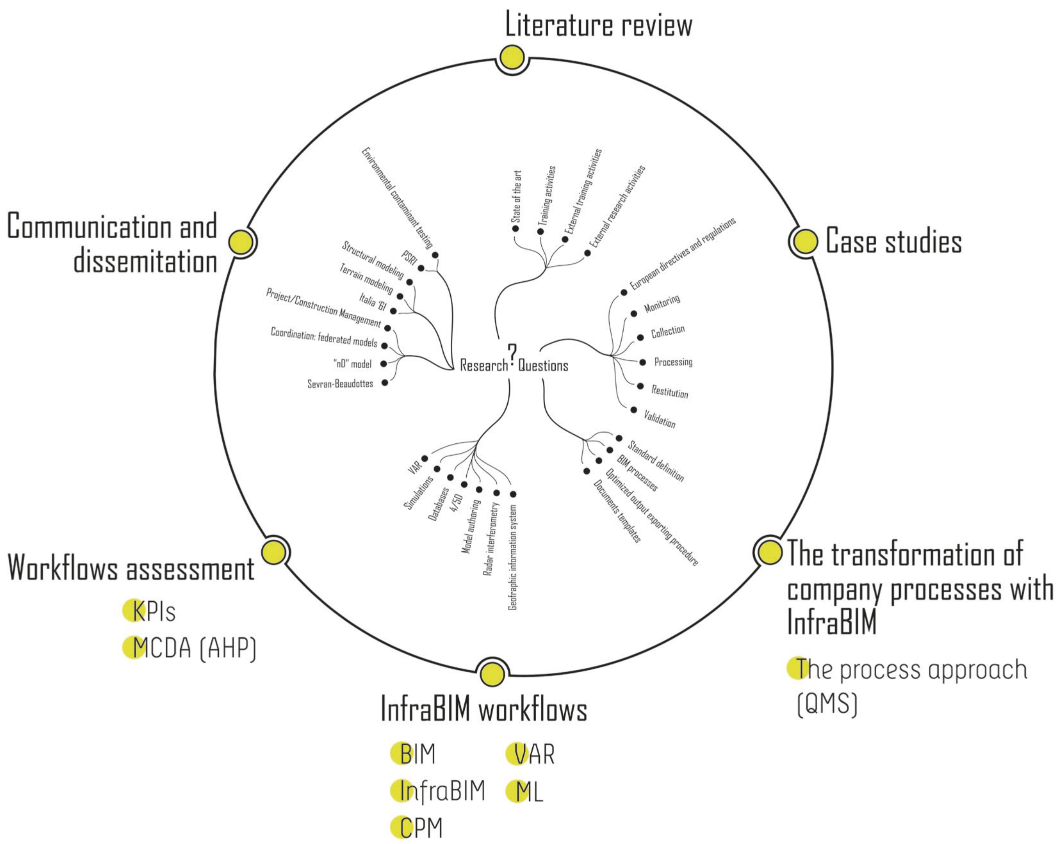


Fig. 7: Methodological framework

As discussed in the introduction, BIM and InfraBIM represent just a small part of the bigger picture of Digital Innovation in the AECO sector. This means that when facing digital innovation, the approach to follow must consider a "mix of methodologies". For this reason, this study **embraced** and **integrated different methods** depending on the specific section considered. The methodological approach has been organized under the following six main sections, as shown in Fig. 7:

- **Literature review** on several aspects related to the InfraBIM environment (Regulation and guidelines, Data standards, InfraBIM uses and tools etc.);
- Identification of **case studies**. The selection of case studies has a two-fold characterization, on one side the engineering firm Lombardi Ingegneria as example of company implementing BIM in the infrastructure sector and on the other side three main projects, useful to test and develop workflows including different tools and approaches towards specific objectives;
- **The transformation of company processes with InfraBIM.** This section includes the analysis and study on the transformation of process management when working in an InfraBIM-based environment, starting from the ISO 9000 series of standards on Quality Management System (QMS). Furthermore, the section includes a proposal for the implementation

of InfraBIM methods and tools: standardization, strategy documents, template and encoding rules, InfraBIM uses application, training etc.;

- Identification of **InfraBIM** uses and development of related **workflows**, performing interoperability tests through the application on the selected case studies. This section involved the use of several approaches and systems: BIM and InfraBIM methods, that differ among each other on several aspects as it is discussed in Chapter 3; Construction Project Management (CPM), whose concepts and tools were used mainly to develop the 4th and 5th dimensions (4/5D) of BIM; Virtual and Augmented Reality for the data visualization; Machine Learning for specific simulations and to assess different scenarios. Furthermore, the development of workflows required the use of an iterative process of data collection, data processing and data restitution, that also guided the phase of assessment;

- Development of an **assessment** framework for the **workflows** previously developed through one of the Multi-Criteria Decision Approach (MCDA): the Analytical Hierarchy Process (AHP), which requires specific parameters of evaluation and the collection of values for the Key Performance Indicators (KPIs) to be used for the assessment;

- **Communication** and **dissemination** of the results obtained within the research by developing a BIM decision support tool for companies approaching BIM implementation, including the results on the assessment of workflows;

2.4 Structure of the thesis

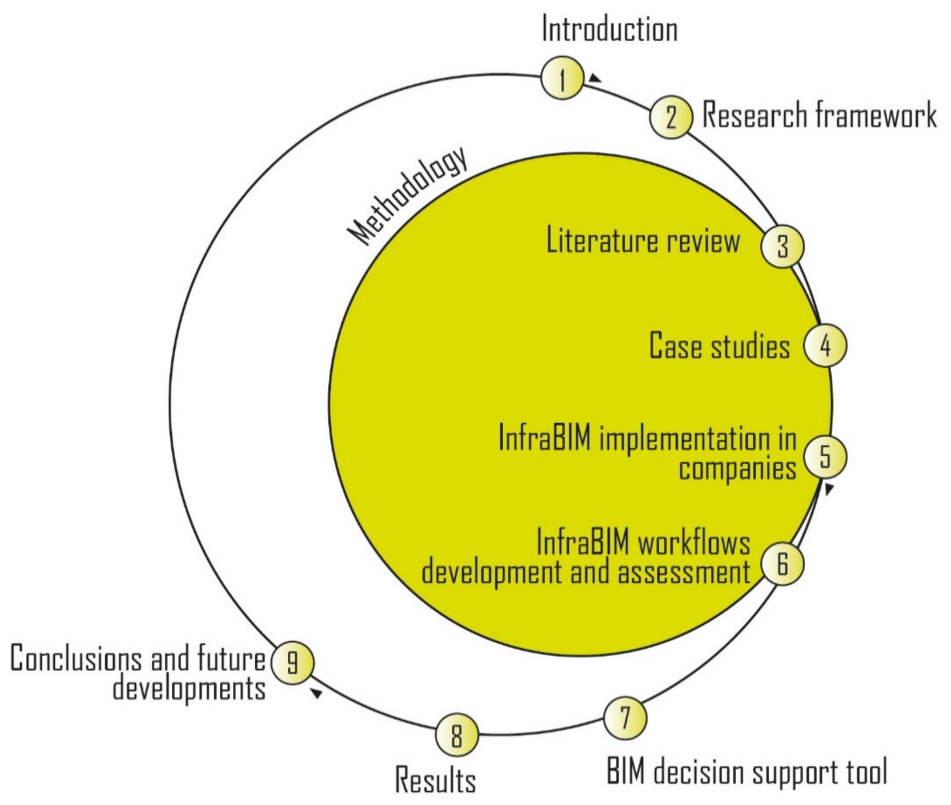


Fig. 8: Structure of the thesis

The structure of the thesis is presented in Fig. 8 and is designed to introduce the subject of InfraBIM implementation in a step-by-step manner, starting from the analysis and definition of processes through the application and optimisation of specific workflows.

Chapter 1 introduces the research context by presenting the concept of "Pandora's box" of digital innovation.

Chapter 2 fixes the problem statement, summarizes the main aims and research questions, and presents the methodological framework developed in the present study.

Chapter 3 presents the literature review of the topic of research, analysing some specific applications of BIM/InfraBIM processes.

Chapter 4 describes the case studies to which the methodology was applied.

Chapter 5 and **6** focuses on processes, standards and workflows for InfraBIM implementation.

Chapter 7 describes the BIM decision support tool for communication and dissemination purposes.

Chapter 8 and **9** summarizes the results obtained, current issues and further possible developments.

Chapter 3

Literature review

What if we could design, build, maintain with a strategy? A real collaboration requires agreement on methods, processes, tools from all the actors involved.

Building Information Modelling methodology has been characterized by a fast evolution of its concepts and procedures over the last thirty years, also thanks to the requirement of the market. Implementing and evolving from Computer-Aided Design CAD 3D systems, in the 1980s the introduction of object-based parametric modelling started significant innovations in the design workflow: "A parametric object consists of a series of geometric definitions and their associated data and rules" (Osello, 2012).

One of the milestones for the BIM methodology is the *BIM Handbook* (Eastman, Teicholz, Sacks, & Liston, 2008) recognized worldwide as one of the most influential manuals on BIM. This publication is almost 12 years old, but it still represents an extensive guide on what this methodology is about, including tools and methods, domains, field of applications and various possible links with other disciplines. The second edition was published in 2011 (Eastman, Teicholz, Sacks, & Liston, 2011); both editions include a first chapter on the introduction of the topic and a second chapter on BIM tools and parametric modelling, where the first differences are visible, showing the evolution of BIM concepts and theories.

While in the first edition the evolution of the methodology is referred to "History of Building Modelling Technology", in the second edition the same sub-chapter is entitled "The Evolution to Object-Based Parametric Modelling", shifting from general technological system to a very precise definition of how modelling has to be in order to be considered within the BIM workflow. The second edition presents a very structured definition of what in the first edition is called "BIM Model Generating Systems", distinguishing among BIM Environments, Platforms and Tools. This difference is paramount in understanding the several fields of application within the BIM methodology and highlights the great complexity behind it. Once the difference among those terms is clear, no one could say BIM is just software. BIM tools can be defined as applications developing a specific task, which produces a specific outcome. BIM platforms are applications that generates data for multiple uses. Finally, BIM environment is defined as the data management of information deriving from several data sources, integrating tools and platforms within an organization (Eastman, Teicholz, Sacks, & Liston, 2011). To summarize, the environment represents the *deus ex machina* setting the rules and taking decisions on how to integrate and platforms and tools. Furthermore, these three concepts are grouped under the umbrella of BIM implementation process, which includes procedures, workflows, data repositories that collaborate in defining the BIM environment. We could define all these as BIM "boundary conditions" that contribute to developing the BIM implementation process.

Another fundamental concept highlighted in both editions is represented by **interoperability**, which links all the components previously defined and describes how a system perform data exchange with another system. This concept can be associated also to the collaboration among different actors involved in the process, not only to software interaction. For this reason, standards in model interoperability have been developed to facilitate data exchange between two distinct domains (Sanguinetti, et al., 2012).

Within the BIM handbook the difference in the definition of interoperability is highlighted by the fact that, in the second version the use of building model repositories for data exchange is further developed than in the first edition, where the focus is mainly on file exchange. Building model repositories are defined as "database system whose schema is based on a published object-based format" (Eastman, Teicholz, Sacks, & Liston, 2008). In the second edition, the section related to building model repositories is further developed, highlighting the evolution from file-based exchange to building model repositories, slightly changing the definition of BIM repositories as "server or database system that brings together and facilitates management and coordination of all project-related data" (Eastman, Teicholz, Sacks, & Liston, 2011).

It is essential to underline the twist within the exchange process is something "evolutionary", as stated by Eastman, because it no longer involves the management of files, but **managing** of **information objects**. It must be said that this change just started to take place, which means that still the greatest part of data exchange within the AECO sector is performed by using file-based exchanges. Anyway, the market is moving fast towards web-based management systems, which represents the perfect approach within a collaboration environment. The concept has evolved during time: the focus has moved from files to data. The concept is that in future data is going to be visualized through different platforms and tools for a specific purpose without using file format exchange; each actor of the process will retrieve and visualize data as needed, without necessity of files. This approach is reflected in the development of **Common Data Environment** (CDE) which are defined as "agreed source of information for any given project or asset, for collecting, managing and disseminating each information container through a managed process" in the ISO 19650-1:2018. The term "file" is changed into "**information container**", which corresponds to a "named persistent set of information retrievable from within a file, system or application storage hierarchy" (ISO 19650-1:2018).

The third edition of BIM handbook shows how BIM concepts and processes have evolved over time; the difference between BIM platforms and tools remains, but it is introduced the term “BIM processes”, which better underlines the great complexity of relations and procedures involved within the application of BIM methodology. Furthermore, it is introduced a new chapter in which BIM is considered as a Lifecycle Platform; indeed “many people refer to BIM as project lifecycle management (PLM) or building lifecycle management (BLM), stressing the importance of BIM as a platform for the creation and management of information about buildings throughout their design, construction and serviceable life. In the chapter related to collaboration and interoperability, two paragraphs are added. The first one, “Semi-Automated Approaches”, explains to the chance to use automated interfacing technologies in order to add newly required information to BIM models in order to reuse it for a different purpose to which it was created. The second paragraph added is entitled “Semantic Approaches” and introduce the topic of apply artificial intelligence techniques to BIM models to interpret what is included in those models in much the way a human expert might and to write the implicit information into the model explicitly (Sacks, Eastman, Lee, & Teicholz, 2018).

Another paramount concept is related to the development of modelling activity, which involves a different level of geometrical and alphanumeric information for each object within the model. **LOD** is a concept used in a slightly different way depending on the guidelines produced by different countries, but in general the aim is to facilitate the management of information within BIM models, by establishing a progressive reliability of objects within BIM models over time and consequently over design phases. The concept adopted by the American Institute of Architects (AIA) in 2008 is LOD defined as “Level of Development”, which is the combination of LOD in terms of element geometry and LOI in terms of attribute information. The AIA defined five levels of development (LOD100-LOD500) within the E202^{TM}-2008. Building Information Modelling Protocol Exhibit. In the UK, the definition is slightly different; in the PAS 1192-2 indeed (19650-2:2018, 2018) (PAS 1192-2:2013, 2013) (PAS 1192-3:2014, 2014) (PAS 1192-5:2015, 2015) (PAS 1192:2007 + A2:2016, 2016), LOD is intended as “Level of Definition”, which is made of geometrical attributes measured with LOD as “Level of Detail” and alphanumeric attributes measures with LOI as “Level of Information”. At this stage, LOD values are referred to models and not objects within the model, reflecting the Royal Institute of British Architects (RIBA) stages and namely: Brief, Concept, Developed, Production, Installation, As constructed and In use. The use of numbers to define LOD on objects is then introduced by BIM toolkit. For the first time in UK, BIM toolkit talks about LOD for objects and introduces five levels of detail and six levels of information. With the introduction of ISO 19650-1-2:2018 LOD is no longer used as term to define the level of definition/development of objects within the model; the new term is “**Level of Information Need**”, which is defined as a “framework defining the extent and granularity of information” (ISO 19650-1:2018, 2018) (ISO 19650-2:2018, 2018).

In this case, it is not given a specific range of metrics to follow, but it is required to describe the metrics chosen among all the existing ones within the documents mandatory to be submitted for the appointment. In general, the new approach, based on the lessons learnt from previous experience in appointments requiring the highest Level of Development/Definition without specific purpose, is to avoid irrelevant information, in order to guarantee an appropriate determination of quality, quantity and granularity of information.

3.1 Regulations and guidelines

International guidelines on the adoption of BIM methodology have been developed worldwide both at public level, produced by Government strategic departments, and at private level, for instance the proprietary guidelines of several Organizations worldwide. Within this context it is of paramount importance to highlight the three-level structure of voluntary technical standards.

ISO is the International Organization for Standardization. ISO regulations are usually giving a horizon, to be applicable worldwide, then each country can decide whether apply those standards at national level or not. **CEN** is the European Committee for Standardization. These standards serve to standardize technical regulation throughout Europe, so it is not permitted for standards to exist at national level that are not in harmony with their content. The application of EN regulations is mandatory for CEN countries. **UNI** is the acronym of "Ente Nazionale Italiano di Unificazione", which is a private association that develops and publishes technical standards for all industrial, commercial and service sectors. It represents Italy at the European (CEN) and worldwide (ISO) standards organizations. It characterizes all Italian national standards and, if it is the only acronym preceding the number of the standard, it means that it was drawn up by the UNI Commissions, or by the Federated Bodies. Within this context, there are several standards related to Information management using BIM, the most important that are going to briefly presented are: ISO 19650, ISO 16739, UNI 11337, UNI EN 17412.

ISO 19650 represents the most recent reference standard to which all other European and National directives are going to be based on. For this reason, within the next few years all national voluntary regulations are probably going to be reviewed on the basis of concepts included within ISO 19650. What is important is the fact that the regulation is entitled "Information management using building information modelling", moving the focus from the IT sector, to which are related the greatest part of ISO that can be seen as digital environment applied to AEC industry, towards a world of management. This standard, compared to previous ones, lacks specifications on some aspects, such as the organization of the Common Data Environment (CDE), in order to leave freedom of interpretation to national training providers. Among the definitions, ISO 19650 introduced new terms such as Appointing and Appointed Party: the former identifies the receiver of information, the latter refers to the supplier of information. As previously enounced ISO 19650 also introduced the concepts of "Level of Information Need". Another difference compared with the past is the meaning of the acronym EIR which changes into "Exchange Information Requirement" instead of "Employer's Information Requirements". ISO 19650 was implemented also at CEN and UNI level, resulting in the UNI EN ISO 19650.

ISO 16739 is referred to the openBIM process and is dedicated to the presentation of the Industry Foundation Classes (IFC) considered the open international standard for BIM data that are exchanged and shared among software applications used by the various participants in the construction or facility management industry sector. This release, and upcoming releases, extend the scope to include data definitions for infrastructure assets over their life cycle as well.

UNI 11337 represents the reference standard in the Italian regulatory framework within the "Digital management of information processes of the construction sector". It consists of several sections, some of them still must be published. Fig. 9 shows the state of approval of each section as reported from Prof. Pavan within a presentation entitled "BIM Standards at UNI EN ISO level" at the InfraBIManager Master at Polytechnic of Turin (Pavan, 2021).

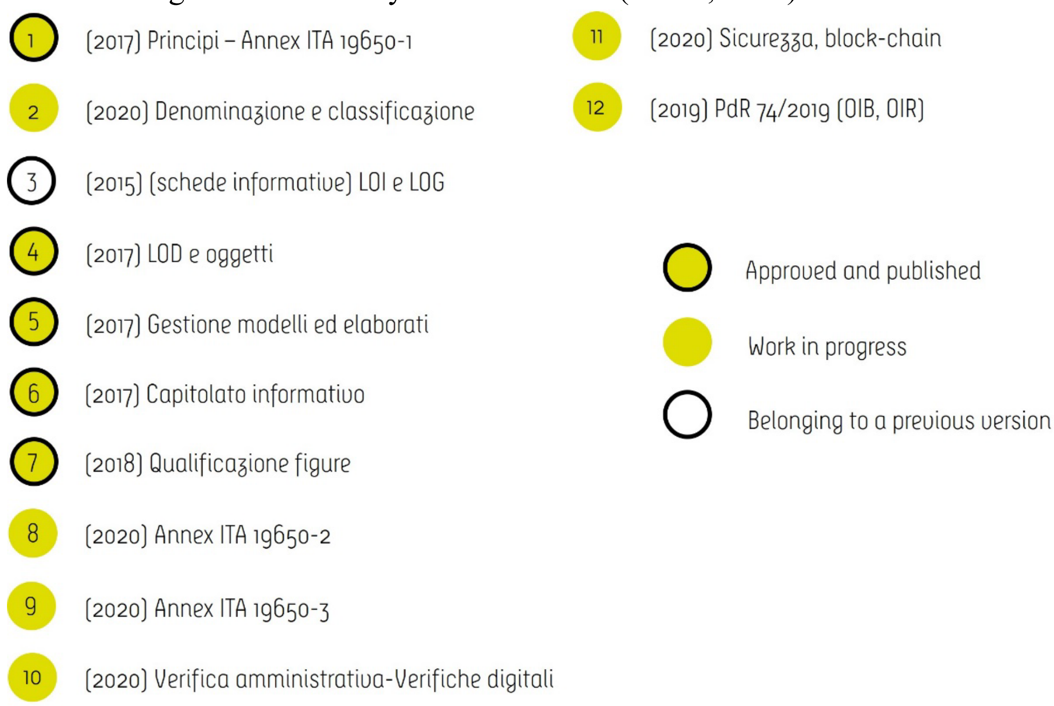


Fig. 9: Sections of UNI 11337
Source: Adapted from Pavan, (2021)

Each section is specifically directed to one particular aspect of information processes: Section 1 is focused on principles developed through the standards; Section 2 includes definitions and classifications; Section 3 includes information sheets distinguishing between Level of Information (LOI) and Level of Geometry (LOG); Section 4 is dedicated to Level of Developments (LOD) reporting several examples for different object categories and giving a scale of reference from LOD A (symbolic object) to LOD G (updated object); Section 5 focuses on informative flows in the digital processes, defining roles, rules and workflows necessary to produce, manage and exchange information and its connection and interaction within construction digitalized processes; Sections 6 gives a template for the EIR, in the Italian context called *Capitolato Informativo* (CI), suggesting how to organize the document and which sections must be included; Section 7 identifies the specific tasks and activities of BIM professional figures (CDE manager, BIM manager etc.) and also skills and competences required for each role; Section 8-12 are still under development.

UNI EN 17412 focuses on the definition of "Level of Information Need", which is defined as a "framework defining the extent and granularity of information". The core reason of introducing this concept is to prevent delivery of too much information. Indeed, the level of information need should be determined by the minimum amount of information needed to answer each relevant requirement, including information required by other appointed parties, and no more; anything else is considered waste.

The majority of these standards introduces information on how to organize a Common Data Environment (CDE). Indeed, section 12 of ISO 19650:1 is dedicated to the principles guiding the information management using CDE, defining its main characteristics such as the states in which information containers should be organized, the metadata to be included etc. Furthermore, it is introduced the concept of distributing the CDE workflow across different computer systems or technology platforms, especially for large or complex assets or projects, or widely dispersed teams. This concept is paramount mainly in the relationship between the appointing and the appointed parties, whose CDEs could differ to better define the property of information. Within this context, exchange workflows between the CDEs and coordination levels must be agreed since the beginning and monitored along the whole process, to avoid any kind of issues. The CDE in the Italian regulation is called *Ambiente di Condivisione Dati* (ACDat) and it is described as: "An environment for an organized collection and sharing of data related to digital models and output for a single work or a single complex of works" (UNI, 2017). The UNI 11337 distinguishes the ACDat from the *Ambiente di Condivisione Documenti* (ACDoc) or data room, which is defined as "a physical environment for an organized collection and sharing of copies of models and copies and original output on non-digital media for a single work or a single complex of works" (UNI, 2017). For example, the ACDoc contains original papers of previous documentation or any copies of outputs and information model extracts on non-digital media. The ACDoc represents a specific characteristic of Italian approach because it does not exist in international standards. Furthermore UNI 11337-5 deepens the requirements of CDE; furthermore, it is said that "the CDE should rather be in the employer's (Appointing party) hands, who should manage it directly or delegate the management to a specially appointed external party" (UNI, 2017).

On the other hand, In Italy regulations are represented by codes; this means that technical standards become mandatory only when they are cited within a code or a law. In 2013 UK Government Strategy introduced the use of BIM as mandatory for all projects by 2025; in 2014 the European Community with the Directive

2104/24/UE introduced the opportunity of using BIM as optional. After this Directive, all European Countries had to apply this regulation within their own codes. For this reason, in Italy D.Lgs. 50/2016 (D.Lgs. 50/2016) implies the use of BIM methods and tools, which are then made compulsory by D.M. 560/2017 (D.M. 560/2017). Within the D.Lgs. 50/2016 it is stated that for public works contracts and design contests, Member States may require the use of "specific electronic tools", such as of building information electronic modelling tools or similar. What is said within D.Lgs. 50/2016 is then make it compulsory within the D.M. 560/2017, in which the introduction of specific electronic tools is compulsory by 2019 for works of over 100 ML € and by 2025 will be mandatory for all public works under 1 ML €. Recently, the D.M. 312/2021 (D.M. 312/2021) introduced some amendments and additions to the D.M. 560/2017. The major differences can be summarized as follows:

- Art. 2 - (Definitions): it includes clarifications on the term "information model", as it is intended within the ISO 19650; furthermore, it is better defined the difference between the *Offerta di Gestione Informativa* (oGI) and the *Piano di Gestione Informativa* (pGI), which represents the documents that the appointed party has to submit before and after the contract award;

- Art. 3 - (Preliminary obligations of contracting authorities): it better clarifies the meaning of *atto organizzativo* (organizational act), stating that it has to explicit the monitoring process and management of each procedural phase, the identity of data managers and the property of data itself, the ways of managing conflicts;

- Art. 4 - (Interoperability): it replaces the term model with information model, distinguishing between single and aggregate. Within this context, a single model is defined as "a virtualization of a work or its elements according to a discipline or specific use for the model, it could also be defined disciplinary or mono-disciplinary model" (UNI, 2017). On the other hand, aggregate model means "a virtualization of a work or its elements according to the aggregation (stable or temporary) of several single models, as a tool for coordinating several models. An aggregate model can be either a set of several coordinated single models or several single models that are merged into a single model; it could also be defined federated or multidisciplinary model" (UNI, 2017);

- Art. 6 – (Time for the mandatory introduction of electronic modelling methods and tools for construction and infrastructures): it changes the time and the object of the mandatory use of "specific electronic tools" for public works. For instance, ordinary, or extraordinary, maintenance is not affected by the mandatory use of electronic modelling tools and methods and the date to apply those for works with a contract value of EUR 15 million or more is postponed to the 1st of January 2022, instead of 2021. Furthermore, the compulsory use of methods and information tools is limited only above the EUR 1 million threshold, and not for smaller project.

- Art.7 (Exchange Information Requirements and technical specifications): reference is made to European (UNI EN/UNI EN ISO), international (UNI ISO/UNI EN ISO) and national technical standards (UNI) for the first time in the codes. Indeed, this reference is not present either in the D.Lgs. or in the D.M. 560/2017, so it is introduced in D.M. 312/2021 for the first time. Furthermore, the Art. 7bis is added, and it is included a list of possible rewarding criteria, such as the integration of project management aspects with information modelling management and the use of innovative augmented reality tools.

Amongst all, Italy is the first countries in making the compulsoriness so strict because it applies to all public works, while, for example, in UK the mandatory use of BIM is related only to infrastructures of the Government.

In parallel with regulations, private companies but also other organizations, defined guidelines with "instructions" to follow in developing and implementing BIM/InfraBIM methodology and modelling. The greatest part of those guidelines satisfy the requirements within the ISO/TS 12911:2012, which in relation to the exchange of information can be summarized in: delivery agreement, contents definition, validation, use rights, responsibilities, traceability, compliance and potential implications in the case of non-compliance (Di Giuda, Maltese, Cecconi, & Villa, 2017). The AEC (UK) BIM Protocol for Autodesk Revit, AEC UK Committee, for instance, is a guideline produced to standardize the modelling and management phase within an organization, with details on file naming and practical examples in the use of a specific software. In this case, the AEC UK Committee states that the supplement is intended to support all BIM work undertaken using Autodesk Revit across a practice or on a specific project (AEC UK Committee, 2016). Another worldwide key reference in the drafting of guidelines is represented by the Singapore BIM Guide v.2, which aims to outline the various possible deliverables, processes and professionals involved when Building Information Modelling is being used in a construction project; furthermore, it clarifies the roles and responsibilities of project members when using BIM in a construction project. The roles and responsibilities are then captured in BIM Execution Plan, to be agreed between the Employer and project members (Singapore BIM Guide - Version 2.0, Building and Construction, 2013). It is immediately evident how two guidelines, both related to the implementation of BIM methodology, present different focuses and details; on one side the first is strictly focused on the use of a specific model authoring platforms, while in the second case the focus is on BIM deliverables and procedures. For this reason, it is paramount to understand the goal and use of a guideline in order to obtain the best results on the basis of the pre-defined requirements. The process explained within guidelines must be put into practice in order to verify and validate the efficiency of the standardization documents. For this reason, applications of methods and tools are fundamental within the interoperability testing process in a multidisciplinary environment. For instance, the increasing integration between BIM and scheduling process (4D) highlights opportunities for using these capabilities in new digital management systems replete with role reorganization, new practices and workflows (Jupp, 2017). The organization, within this context, has to structure the whole implementation process, by creating its own documents to define the strategy towards the implementation process of such methodology, transferring traditional customized processes into innovative ones based on BIM environment, platforms and tools.

3.2 Data standards and integration

As previously anticipated, interoperability is one of the key concepts when dealing with BIM/InfraBIM methodology. In the BIM Handbook interoperability is defined as the "ability to transfer data between applications, enabling to standardize workflows and sometimes facilitate their automation" (Eastman, Teicholz, Sacks, & Liston, 2011). This exchange of data between applications is inevitably reflected in the relationship between the different actors in the process, which in turn must be able to prepare templates and standardize the data necessary to ensure the exchange of information. This allows for full cooperation and integration between different skills. The workflow is organized according to an exchange structure based on specific standards, which are currently under development, especially if considering the InfraBIM environment (Fonsati, 2019). A format represents a standard encoding mode for archiving information (Shala & Shala, 2016); file formats can be public, open, as the specifications have been published, or owners for specific links between BIM-oriented tools (Osello, 2012). Some formats are used exclusively for the exchange of information; in this case the format is called interchange format. Interoperability between the different software platforms is therefore guaranteed through the use of exchange, defined on the basis of computer languages, which map the information specifications they contain so that they can be shared with other platforms.

If interoperability initially relied on formats of exchange limited to the export/import of geometry, now the target is to implement an openBIM workflow (buildingSMART, 2021), a collaborative design based on the use of standards and non-proprietary formats. The interoperability process allows users to select the data necessary for the development of specific disciplinary investigations, determining their extraction from the database as needed. The most common exchange is the one generated in integration between BIM platforms and BIM tools. During the export phase, within the BIM platform the model is "translated" into the open format language, which means that proprietary features are mapped into open categories of objects. This operation is not yet free of errors, mainly because of inexperience or disregard of certain aspects. A major level of difficulty in exchanging data takes place in the interaction platform-platform. This difficulty is due to the different structure of the rules on which the different platforms are set;

therefore, during the exchange the features of the starting platform should be translated in the features of the target platform (Fonsati, 2019). Undoubtedly, each format guarantees a different degree of accuracy in the transfer of the given, as certain formats are better suited to transfer a certain type of information than others. Therefore, the import/export procedure inevitably leads to a percentage of data loss; according to the interchange format used the loss may be more or less important and can be alphanumeric, geometric or both (Fonsati, 2019). Within this context, the following paragraphs present some of the most common built environment standards the aim to understand main commonalities and differences among them.

The **Industry Foundation Classes (IFC)** is a data scheme that is mainly used to exchange complex building and infrastructure data in the AECO industry. This standard was developed by the current buildingSMART International (bSI), formerly the International Alliance for Interoperability (IAI), with the aim of producing and publishing a neutral product data model for the construction industry. Among bSI standards it possible to cite the following: i) IFC (ISO 16739), the basic operating system that transfers data and information; ii) International Framework for Dictionaries (IFD) (ISO 12006-3), which includes the buildingSMART Data Dictionary (bSDD), the standard that collects terminology, vocabulary and object attributes; iii) the Information Delivery Manual (IDM) (ISO 29481-1; ISO 29481-2), which defines process flows; iv) the Model View Definition (MVD), which translates into computer language the processes defined in the IDM into technical specifications and requirements; v) the BIM Collaboration Format (BCF), which supports a complete management of the content control and verification cycle; vi) the Information Delivery Specification (IDS), which is a machine readable document that defines how objects, classifications, properties, etc. need to be delivered and exchanged, on the basis of the Exchange Information Requirements (EIR) given from the Appointing party (buildingSMART, 2021). The effort of buildingSMART within the infrastructure domain has been confirmed with the establishment of several IFC projects specifically directed to deep some

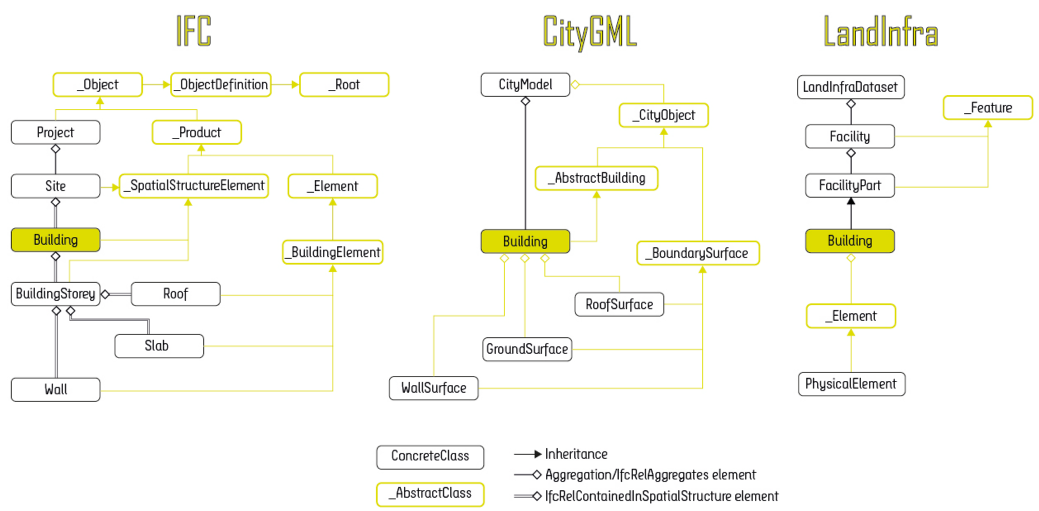


Fig. 10: The concept of a building is represented by all three standards: the UML diagrams show possible representation of a very simple building
Source: Adapted from Gilbert et al. (2020)

infrastructure disciplines. These research groups are called “buildingSMART rooms” and are focused on extending the IFC data model to allow “a precise description of the semantics and geometries of the different elements that make up tunnels, being, geotechnical subsoil conditions and treatments, civil engineering components, and functional systems that equip them” (bSI, 2020). For this reason, rooms such as IFC-Bridge, IFC-Rail, IFC-Tunnel etc. are currently working on the extension and development of new versions of IFC for the infrastructural domain.

The **Geographic Markup Language (GML)** was developed by Open Geospatial Consortium (OGC) as the XML grammar to express geographical features and includes several application schemas (OGC, 2021), such as: (i) **CityGML**, open data model, and XML-based format developed for the storage and exchange of virtual 3D city models; (ii) GeoSciML (OGC, 2021) and GroundWaterML2 respectively oriented towards geology and hydrogeology. GeoSciML describes a logical model and GML/XML encoding rules for the exchange of geological map data, geological time scales, boreholes, and metadata for laboratory analyses. On the other hand, GroundWaterML2 introduces extra concepts such as hydrogeologic unit, fluid body, discharge, and recharge. Another format developed by OGC is the **LandInfra/InfraGML**, which emphasizes land use, topographic modelling, and infrastructures parts such as roads and rainwater management works (OGC, 2021). In particular, LandInfra could act as a “connecting bridge” for BIM-GIS integration for several reasons, but still the following issues have to be solved: (i) LandInfra is much closer to 3D GIS than BIM; (ii) the data model of LandInfra cannot be extended or modified; (iii) the current lack of software packages to read/write, edit, or manipulate LandInfra makes it rather difficult to convince practitioners to convert their datasets to it, which makes extensive testing and validation difficult (Kumar, Labetski, Ohori, Ledoux, & Stoter, 2019).

The integration among some of the previously presented standards, and mainly IFC, CityGML and LandInfra, was studied by the Integrated Digital Built Environment group (IDBE), which is a research group founded by bSI and OGC, that on March 2020 published the document "Built environment data standards and their integration: an analysis of IFC, CityGML and LandInfra" (Gilbert, et al., 2020). They analysed the main commonalities and differences, for instance all the standards share the concept of a building and Fig. 10 shows how objects classes of each standard can be used to represent a building instance. Furthermore, the authors proposed three main integration paradigms: (i) schema mapping, which is a process that enables an object in one schema to be converted to its equivalent (or nearest) in another, constituting a complete read-rewrite process; (ii) federation, which is an alternative paradigm in which a software environment can simultaneously interpret instances from multiple schemas and offer functionality that operates across; this is particularly relevant given the general trend away from static file-based representation and towards web services that are connected to various static and dynamic data sources; (iii) link referencing, which represents a third paradigm that achieves integration through embedding links (such as Uniform Resource Identifiers - URIs) in the primary, working model to components from instances of secondary schemas (Gilbert, et al., 2020). They also consider a combination of paradigms to make the approaches effective; such a combination could differ on the basis of the specific application domain and use cases. However, in all these approaches, the starting point should certainly be the harmonization of terminology and semantics shared by the different actors involved in the lifecycle of buildings, cities and infrastructures. At the same time, the abstraction of existing standards is "neither feasible nor desirable given the value of the rich modelling present in each standard" (Gilbert, et al., 2020) because it is paramount that each standard preserves its own specificity to preserve efficient information exchange in their own disciplinary area. Within this context, an increasingly important role is assigned to the CDE, which acts as the manager of collaborative practices. Current available commercial solutions for CDEs allow the input of data from heterogeneous sources, and also the visualization of models in several formats. This trend is going to be deeper developed until the moment in which the CDE will result in a real "hub" for information. There will be no more barriers for the information exchange, guaranteeing a transparent and well-defined information flow, in which everyone will share his work effectively with other professionals. The CDE could be seen as a tool to get professionals, standards, data and languages "talk" and "agree" with each other.

3.3 BIM maturity assessment

Together with regulations and standards for the adoption of BIM processes, methods of evaluating BIM maturity have been developed also. Indeed, the adoption of BIM methodology represents a process of gradual growth, as it requires to reach a level of collaboration that must be established as the working method is understood; it is impossible to think that a complete level of maturity of BIM can be reached without training and preparation. Several research activities have been focused on this topic, defining different kind of metrics useful in the assessment of different "dimensions".

One of such assessments in terms of BIM maturity gave birth to the definition of specific "Levels", depending on the sharing system set up in the company and based on its effectiveness and efficiency also in the relationship with the other actors in the building process:

- "Level 0" or "standardized CAD": it represents the first level of adoption, still considerably linked to the use of CAD systems without the chance to collaborate with other users, but organized under standardized systems;
- "Level 1" or "lonely BIM": this level involves a structured project-related data management, linking information to the model that is shared among all the professionals within a company. At this stage, there is still no

collaboration among professionals in the supply chain, but just internally in companies;

- "Level 2" or "collaborative BIM": it refers to a high collaboration level, in which all professionals are involved in the process of sharing data since the first design phases. The data exchange is performed using open standards, such as IFC or Cobie, in order to coordinate them using a collaboration platform, useful to identify clashes and inconsistencies;

- "Level 3" or "iBIM": at this level data is shared among all professionals involved within the process through a Common Data Environment (CDE), who can receive real-time updates on the project. However, issues related to worksharing emerge at this stage; full cooperation is not without problems of intellectual property, responsibility and regulation of access, modification and saving of the model. For this reason, specific contracts are needed to protect everyone involved in the partnership. Therefore, multiparty agreements, risk-benefit sharing and specific assurances are key issues to consider when adopting iBIM (Barnes & Davies, 2014).

In general, this kind of performance evaluation is used to assess countries' BIM level of adoption, because it refers to the application of BIM methods and tools at generic level in the AECO sector of specific countries.

Another standard in terms of BIM performance assessment is given by Succar, who purposefully developed a set of metrics to measure BIM performance (Succar, Sher, & Williams, 2012). These include:

- **BIM capability stages:** BIM capability is defined by Succar as "the basic ability to perform a task or deliver a BIM service/product", so BIM stages represent the minimum BIM requirements that teams and organizations have to achieve within the BIM implementation process. Three stages are identified as following: object-based modelling, model-based collaboration and network-based integration;

- **BIM maturity levels:** Succar fosters that "the term BIM maturity denotes the extent of BIM capability in performing a task or delivering a BIM service/product". He identifies the following five levels: (i) initial/ad hoc, (ii) defined, (iii) managed, (iv) integrated and (v) optimized.

- **BIM competency sets:** Succar defines competency sets as abilities suitable for implementing or assessing BIM capability and/or maturity. He identifies three main sets of abilities: (i) technology, which includes *software*, *hardware* and *data/networks*; (ii) process, which includes *resources*, *activities/workflows*, *products/services*, and *leadership/management*; (iii) policy, which includes *benchmarks/controls, contracts/agreements* and *guidance/supervision*.

- **Organizational Scales:** in order to allow BIM performance assessment related to the diversity of markets, discipline and company size, an organizational scale has been developed within the research of Succar.

- **Granularity Levels:** in order to increase flexibility of BIM maturity assessment, Succar developed a four levels granularity filter. The progression from lower to higher levels implies and increase in: (i) assessment breadth; (ii) scoring detail; (iii) formality; (iv) assessor specialization.

These five metrics, as components that complement each other, provide a range of opportunities to measure BIM performance in different businesses, enabling highly targeted yet flexible performance analyses to be conducted.

3.4 InfraBIM uses and tools

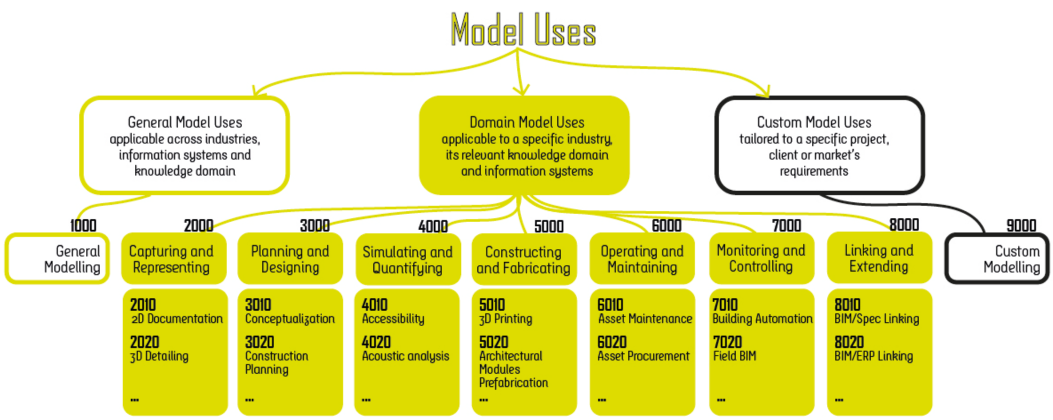


Fig. 11: Model Uses
Source: Adapted from Succar et al. (2016)

The term BIM or Model Use appears frequently in the literature review, assuming different nuances in terms of meaning. For instance, the BIM Dictionary defines Model Uses as "intended or expected project deliverables from generating, collaborating-on and linking models to external databases" (BIMe Initiative, 2020). On the other hand, BIM uses taxonomy is defined from Kreider & Messner (2013) as a "method of applying Building Information Modelling during a facility's lifecycle to achieve one or more specific objectives" (Kreider & Messner, 2013). Another definition of Model Uses is given by Succar et al. (2016) who specify that in their vision "Model Uses are a major reinvestigation and a practical expansion of the 'BIM Uses' taxonomy, and of 'BIM outcomes'. . . . Model Uses represent a *conceptual departure* from BIM Uses and an *umbrella term* covering multiple industries and their varied model-based use cases". This taxonomy is very detailed because Model Uses are divided into three main categories each of them includes single or multiple series of more specific Model Uses, as shown in Fig. 11. For instance, under the "Planning and Designing" Domain Model Uses can be listed the following "sub-uses": Accessibility Analysis, Acoustic Analysis, Augmented Reality Simulation, Clash Detection etc. This structure is very detailed, while for the aims of the present

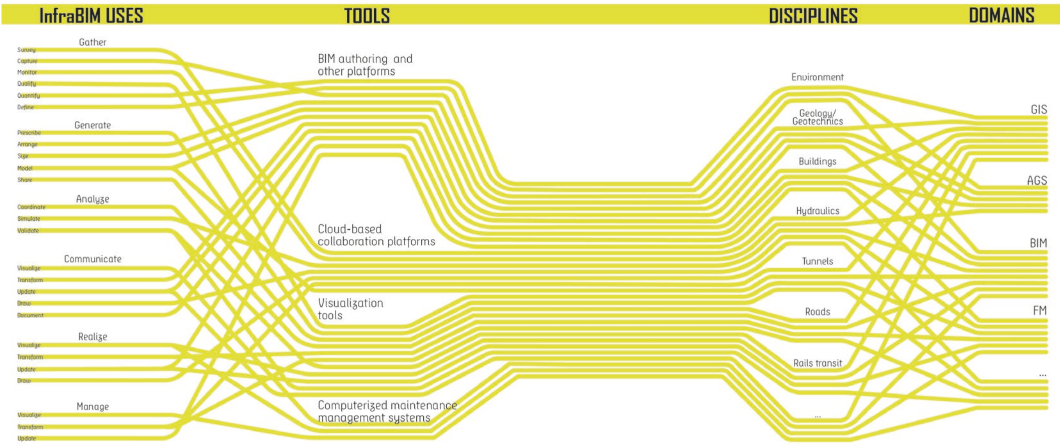


Fig. 12: InfraBIM sankey diagram
Source: Adapted from Osello et al. (2019)

study a wider and less specific taxonomy was required. Fig. 12 shows the InfraBIM sankey diagram as presented by Osello et al. (2019) which reflects the approach followed within this study. Compared to BIM, InfraBIM environment is characterized by a **much higher complexity**, because of the number of domains and disciplines involved. However, BIM uses as intended by Kreider & Messner (2013) are applicable within the InfraBIM context; for this reason the term InfraBIM uses is applied in this study to refer to the different purposes to achieve. The diagram can be read both from right to left and vice versa. The identified domains such as Geographic Information System (GIS), Geotechnical and Geoenvironmental System (AGS), BIM and Facility Management (FM) are intersecting the different disciplines involved within infrastructural projects. This great amount of data once collected is then processed using several different tools in order to obtain specific outcomes that are useful to achieve the different InfraBIM Uses. The integration challenges are many, as introduced within the Data Standards and Integration section, because each discipline involved owns its taxonomy, standards and approaches.

Another classification within the BIM environment is related to its "dimensions", which are defined as simulations of the work (building, infrastructure etc.) or its elements on the basis of a specific aspect (UNI, 2017). The description of dimensions as listed below considers as reference the UNI 11337:1/2017 "Building and civil engineering works - Digital management of the informative processess - Part 1: Models, documents and informative objects for products and processes" (2017). The second (2D) and third (3D) dimensions refers to the graphical representation of the BIM model; in the first case it is function of surface (bidimensional), while in the second case it is function of space, because the height is the dimension that creates the three-dimensional environment. The fourth dimension (4D) defines a model already developed in previous dimensions (2/3D) with the addition of time variable; each element is assigned an identification code for the construction/installation in order to obtain a simulation of construction/installation times. This dimension brought new opportunities in within information modelling, such as the visualization of the project in several phases, the simulation of time schedule, an accurate planning of products and materials delivery times. The fifth dimension

(5D) involves a further development by including the variable cost; this way model quantities are directly retrieved from the model performing a Quantity Take Off (QTO), to produce cost estimation-related documents. The sixth dimension (6D) is the simulation of the work or its elements based on use, management, maintenance and possible decommissioning, in addition to space. For example, to develop such a dimension the database associated to the model could contain information relevant for the asset/facility management, such as the space management or maintenance plans. The seventh dimension (7D) is a simulation of the work based on sustainability (economic, environmental, energy, etc.), using for instance energy-related data. Considering a wider context, this dimension could investigate methods and tools linked to topics close to the design of spaces and systems; for instance, BIM models can be used in Fire Safety Engineering (FSE) simulations to analyse the spread of fires scenarios or to verify escape routes and way-finding systems (Fonsati, 2019).

In terms of literature review, each InfraBIM use or more generally each area of application of InfraBIM is characterized by different levels of implementation. For instance, if the interaction of InfraBIM processes with CPM, which means considering the 4th and 5th dimensions, appears to be consolidated, the integration among InfraBIM processes and geotechnical and geological disciplines requires further analysis and work. The following paragraphs will address these topics by way of example but not of limitation, presenting some examples of research carried out to study the integration of InfraBIM and the following main areas: Construction Project Management, Geotechnical and Geological data management, Virtual and Augmented Reality (VAR), Facility Management, Machine Learning.

InfraBIM and Construction Project Management

The integration between BIM processes and Construction Project Management (CPM) lays its foundation in the association of BIM model objects to planning schedules, which in turn resulted in the necessity of classification and codification of BIM objects in order to have a unique identifier associated both in the information model and in the schedule of activities. For this reason, Work Breakdown Structure (WBS) has been extensively applied within the BIM environment. The PMBOOK defines the WBS as a "a hierarchical decomposition of the total scope of work to be carried out by the project team to accomplish the project objectives and create the required deliverables" (Project Management Institute, 2013). The decomposition follows specific techniques that are used to divide the project scope and deliverables into more manageable parts called "work packages". The work package represents "the work defined at the lowest level of the WBS for which cost and duration can be estimated and managed" (Project Management Institute, 2013). On the basis of the complexity of the project, the level of detail for work packages can vary also in relation to the degree of control needed to effectively manage the project. When approaching planning and scheduling phases of Project Management, the WBS must be detailed to the point that a single one final unit will be identifiable and controllable, and that small unit of work could be managed easily by a human resource that will be assigned to that unit. The three main types of WBS are the following: (i) **Project WBS**, which is an operational tool generally elaborated by contractors as tool to monitor the work development; (ii) **Standard WBS**, which is represents a past project WBS that can be used as a template for new ones; (iii) **Contract WBS**, which is the WBS agreed between owner and contractor (De Marco, 2011). Furthermore, the project is decomposed according to the structure itself of the product that will be developed. For this reason, various decomposition approaches are available: the functional approach, which is based on the following decomposition levels of the project: main functions of the product, items, units, work packages and tasks the defined functions of the product itself; the process approach, based on the phases of the process that will be carried out to develop the project itself; the physical approach, which is mainly used in the construction industry and could be based on the following decomposition levels: 0. Project; 1. Main building, 1.1 First floor, 1.1.1 Structures, 1.1.2 Plumbing, 1.1.3 HVAC etc. 1.2 Second floor etc. 2. Service buildings, 2.1 Structures etc (De Marco, 2011).

Within this context, the WBS specifies "What" is going to be done in a specific project. The other tools part of the planning process that are then used for the next phase of scheduling are: Organizational Breakdown Structure (OBS), which defines "Who" will be doing activities and Cost Breakdown Structure (CBS), which defines "How much" activities will cost. All these structures are useful with the integration with BIM/InfraBIM processes. Indeed, the WBS decomposition is

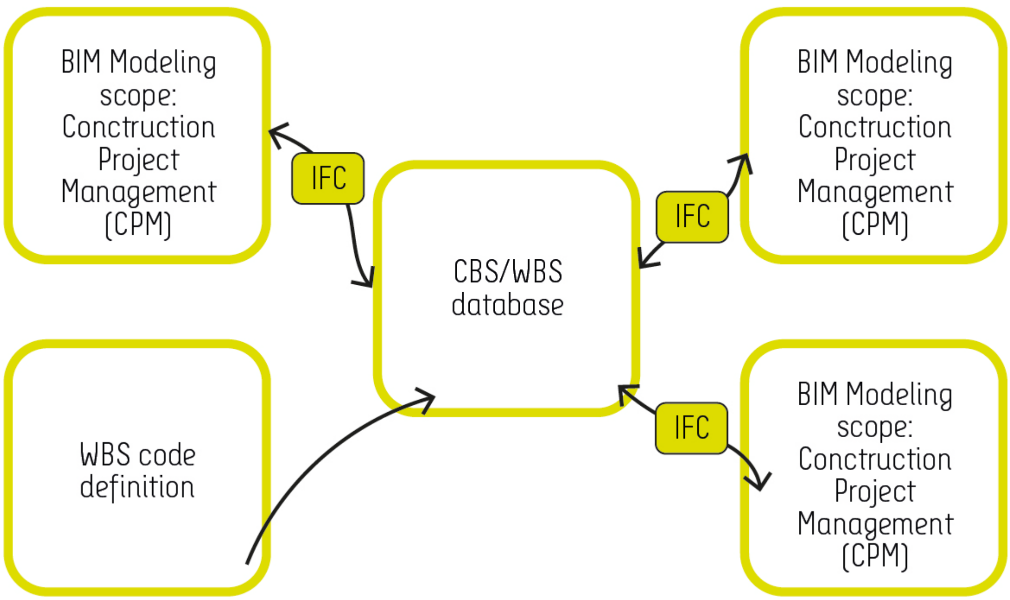


Fig. 13: openBIM methodology framework for CPM
Source: Fonsati, Osello, & De Marco (2021)

of paramount importance when working within the InfraBIM domain, because of the subdivision in several facilities, categories, disciplines etc. An example of decomposition for infrastructures can be found in the Anas price list (Anas, 2021), where components are classified using the following hierarchical structure: *Opera d'arte* (Facility), *Parte d'opera* (Facility part), *Sub-Categoria* (Sub-Category) and

Disciplina (Discipline). This subdivision does not include a high level of detail in terms of decomposition, but it represents a starting point useful for all infrastructural projects. Over the years, several research activities focused on the definition of a proper methodology able to keep the association between BIM model objects and WBS/CBS updated with the progress of the project. Within this context, several different approaches have been implemented, testing the possible outcomes that each approach could produce (Hardin, 2009) (Song, Yang, & Kim, 2012) (Hartmann, van Meerveld, Vossebeld, & Adiaanse, 2012) (Puri & Turkan, 2020). Some research activities also investigated the use of **openBIM procedures**, bringing successful outcomes in the integration of the IFC standard with the CBS/WBS database, resulting in a "structured organization of linking project cost and schedule elements to digital objects of physical components" (Fonsati, Osello, & De Marco, 2021). Such a methodology is shown in Fig. 13. Furthermore, the possibilities given by the integration among BIM platforms and 4D-simulation tools consolidated the concept of modelling temporary elements necessary to the construction such as caseworks, scaffolds and props (Ciribini, Mastrolembo Ventura, & Paneroni, 2016). Such an approach resulted very useful in studying the construction layout, where dynamic clash detection is fundamental to understand any possible interferences caused by temporary elements or construction site vehicles (Kumar & Cheng, 2015) (Ji & Leite, 2018) (Zhou, Ding, & Chen, 2013) (Kim, Anderson, Lee, & Hildreth, 2013) (Moon, Dawood, & Kang, 2014) (Yang, Park, Vela, & Golparvar-Fard, 2015). Therefore, 4D simulations also generate animations showing the construction process and pointing out information such as day, time and percentage of work completion; this is mainly useful in complex projects where the laying procedures must be clear in order to simplify workers' activities and to prevent possible difficulties or unexpected events. The animations also give the chance to have a preview of the construction phases and enable the comparison among different construction scenarios. Within this context the use of systems such as Virtual and Augmented Reality (VAR) is greatly impactful, mainly when clients do not have an AECO background.

InfraBIM and Geotechnical and Geological data management

The use of InfraBIM for the purpose of managing geotechnical and geological information has already been tested, but there still a lot of limitations in terms of both standards and data exchange among software applications. Within this context, the concept "**GeoBIM**" means Geo Building Information Model and it is defined as a straightforward extension of the BIM/InfraBIM concept enabling the modelling and management of subsoil along with all geo-related (subsurface) data, such as geological, hydrogeological and geotechnical objects and properties (Zobl & Marschallinger, 2008) (Noardo, et al., 2019) (Whang, Qu, Wu, & Wang, 2018). Within the present study, GeoBIM concept is related to the environment in which a **digital information model containing data related to subsoil layers** retrieved from environmental and geotechnical surveys interact within BIM/InfraBIM processes (Fonsati, Cosentini, Tundo, & Osello, 20201). When dealing with geotechnical data management traditional procedures follow specific operation steps. After having conducted site investigations, data collected is interpretated and archived following specific classification standards, such as the Unified Soil Classification System (D2487 ASTM, 2018) adopted by the Italian Geotechnical Association (AGI). This process is often repeated different times; the

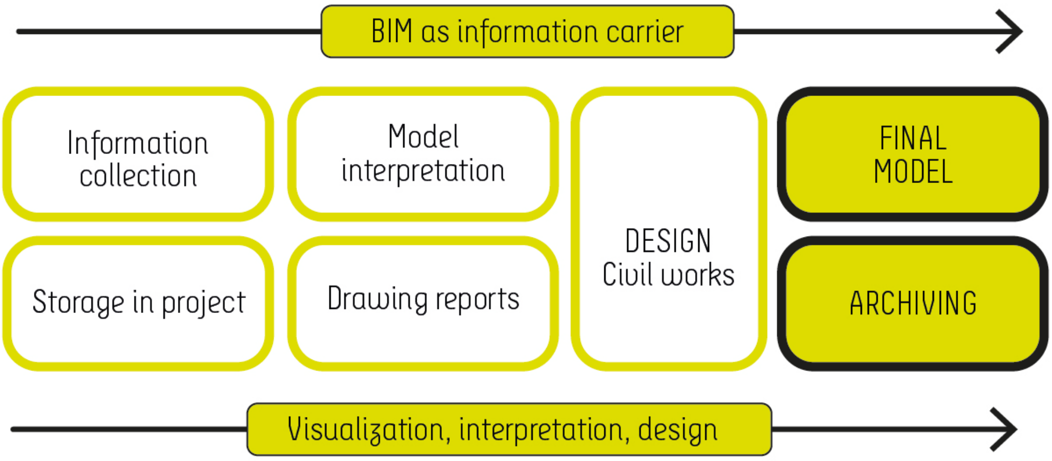


Fig. 14: Data management approach: "rise and fall" of geotechnical data
Source: Adapted from Svensson & Friberg (2017)

result is a very confused collection of data difficult to manage for further developments.

Within this context, InfraBIM processes would help in the storage and management of data; by integrating geotechnical models with InfraBIM since the beginning of design phases is there is the potential to create sub-soil information models that evolve with the project. For instance, the proposal for data management given by Svensson & Friberg (2017) refers to a "rise and fall" of geotechnical data during a project; all the phases have in common BIM as **"information carrier"**, as shown in Fig. 14. Therefore, further information coming from new investigations or other analyses can then be added when the project moves to desk study to phases of ground investigation and interpretation. For this reason, the InfraBIM environment could represent the context of creation of a database where data coming from heterogeneous sources and disciplines could be stored, used and updated during the whole lifecycle of buildings, infrastructures or other kind of assets. Starting from these considerations, several different methods have been developed through the past years, and software houses also implemented tools able to meet the needs of professionals (Hamdi, et al., 2018) (Høyer, et al., 2019) (Jin, et al., 2020) (Molezzi, Hein, & Manzi, 2019) (Fosu, Suprabhas, Rathore, & Cory, 2015) (Liu, et al., 2017) (Song, et al., 2017) (Ohori, et al., 2017). More specifically, most studies addressed the use of borehole and cross-section data to develop 3D subsurface geological modelling. However, the majority of current BIM/InfraBIM models still omit details on the subsoil for several reasons such as lack of significant data, interoperability limitations, coordination issues among different disciplines and actors involved in the process etc. The spread of knowledge on such integration is carried out at international level thanks to the effort of associations such bSI that are studying the implementation of geology and geotechnics modelling requirements (bSI, 2020). Despite the effort of researchers and association, several aspects of the integration for the purpose of GeoBIM development remain unsolved. For this reason, future research should focus on the definition of standards and the implementation of strategies that could improve interoperability not only between systems but also professionals involved in the process.

InfraBIM and Facility Management

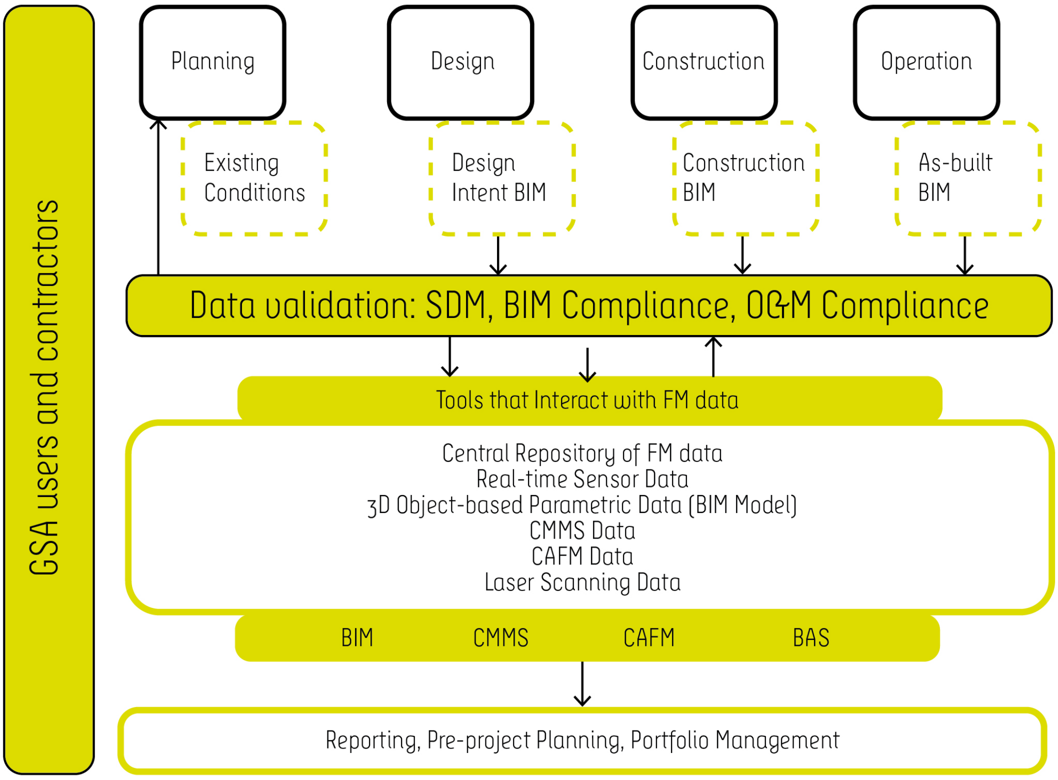


Fig. 15: GSA's vision for BIM and FM integration to manage facility lifecycle data
Source: Adapted from Teicholz, 2013

The management of infrastructures along their life cycle is one of the most-talked topics nowadays. For this reason, it is important to introduce the discipline of Facility Management, which is defined by the International Facility Management Association (IFMA) as "a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology" (IFMA, 2021). Another definition given by UNI EN 15221-1/2007 says that FM is the "integration of processes within an organisation to maintain and develop the agreed services which support and improve the effectiveness of its primary activities". These definitions present communalities with BIM/InfraBIM processes, such as multi-disciplinarity, integration of technologies, competences, and procedures towards an optimization of the overall process. For this reason, the integration between BIM and FM has been greatly analysed and developed both in research and in practice at building level (Teicholz, 2013) (Osello & Ugliotti, 2017), but the application of InfraBIM with the aim of FM at infrastructure level is still an almost unexplored path in terms both of processes and tools. Since infrastructure projects are characterized by a great complexity it is important to get on the right track since the very first phases, so "the key is a process that involves FM from the beginning, ensuring the availability of the right data/information" (Ugliotti, 2017). Fig. 15 illustrates the vision of General Services Administration (GSA), the U.S. Government agency responsible for office space, goods and services to other federal agencies, of integrating BIM with FM systems to support the life-cycle data needs of a building.

Within FM domain, specific systems have been developed to manage the physical asset under several aspects. Some examples are the following:

- Computer Aided Facility Management (CAFM) includes the creation and utilization of information Technology (IT)-based systems in the built environment (Watson & Watson, 2016). CAFM were the first platforms that started to combine CAD or images with alphanumeric information for FM purpose, and have always been used to manage space and capital assets mainly;

- Computerized Maintenance Management System (CMMS) refers to applications specifically used to schedule and record operation and preventive/planned maintenance activities associated with facility equipment (Sapp, 2016). Such database, that mainly manages Mechanical, Electrical and Plumbing (MEP) assets, are not necessarily related to spaces. These systems enable the operational management of the asset and when merged with CAFM, so by adding the relation to spaces, become Integrated Work Order Management Systems (IWOMS).

- **Integrated Workplace Management System** (IWMS) currently represents the most comprehensive systems that integrate data, technologies etc. IWMS are more advanced than CAFM in terms of integration with modelling technologies such as GIS and BIM systems and it is also typically connected to various other IT solutions, like Building Management Systems (BMS), Enterprise Resource Planning (ERP), Human Resources (HR) or Smart Meters (Planon, 2021).

The application of such systems at infrastructural domain is still limited, apart from specific projects in which hardware and software applications have been developed *ad hoc* for the remote control of components, for instance in railways systems.

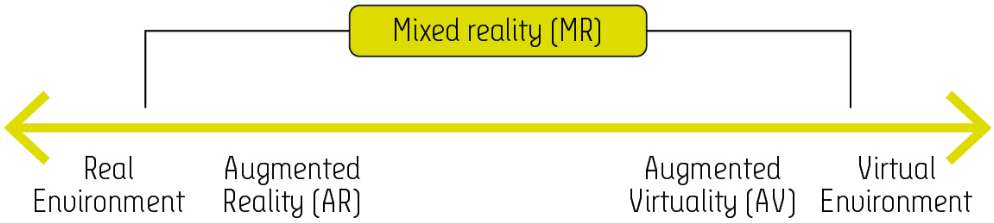


Fig. 16: Reality-virtuality continuum
Source: Adapted from Milgram et. al (1994)

Among the possible uses of an InfraBIM models, its visualization through technologies such as Virtual or Augmented Reality is one of the most impactful. As far as definitions are concerned, amongst the most interesting ones there is the concept of **Reality-Virtuality (RV) Continuum** developed by Milgram et al. (1994) where AR and VR are considered as lying at opposite ends of a *continuum* as shown in Fig. 16. The RV Continuum goes from the Real Environment to the Virtual Environment; in between these two there is Mixed Reality (MR) that comprehends Augmented Reality, which means adding VR elements being in the Real Environment, and Augmented Virtuality, when moving from the Virtual towards the Real Environment (Milgram, Takemura, Utsumi, & Kishino, 1994). Both VR and AR have been extensively applied with several purposes, such as education and training in several fields (Ugliotti, De Luca, Fonsati, Del Giudice, & Osello, 2021), manufacturing (De Luca & Osello, 2021), medicine (Iacono, et al., 2021), museums and cultural heritage (Verhulst, Woods, Whittaker, Bennet, & Dalton, 2021) (Banfi & Bolognesi, 2021) etc. For example, VR training is used to teach technicians to perform specific operations, for instance maintenance activities, without being physically on site. This procedure is useful because technicians, for instance, will know exactly how to perform repair procedures on machines when breakdown occurs. However, the feasibility in applying such technologies in everyday practice depends on several factors, but it is often underestimated. For instance in the AECO sector VR is mainly used for visualization reasons, to communicate with the client whose background is probably not technical. This application is a bit limited because it could be used also as a **powerful tool** of **verification** for design purpose, for intance, checking interferences or that rules on dimension of spaces are respected etc. This is mainly related to the fact that VR is still considered just as a tool for gaming rather than a real opportunity also in the construction industry. Furthermore, VAR could be useful combined with **different kind of simulations**, such as the FSE ones, supporting for instance fire brigade in the exploration of buildings before entering or training people on how to behave in emergency situations (Rahouti, Lovreglio, Datoussaid, & Descamps, 2021). Within this context, the chance to create virtual environments and situations that reflect real ones could be useful in order to make users aware of what could happen during an emergency and drive them towards the best reactions and operations (De Luca, Fonsati, & Osello, 2019). Indeed, such virtual simulations offer the possibility to analyze people's reactions and behaviors in a safe, "not real", environment. To conclude, VAR enables users to interact, manipulate and monitor information in a very easy and fast way, indissolubly connecting the Physical and the Digital among each other.

InfraBIM and Machine Learning (ML)

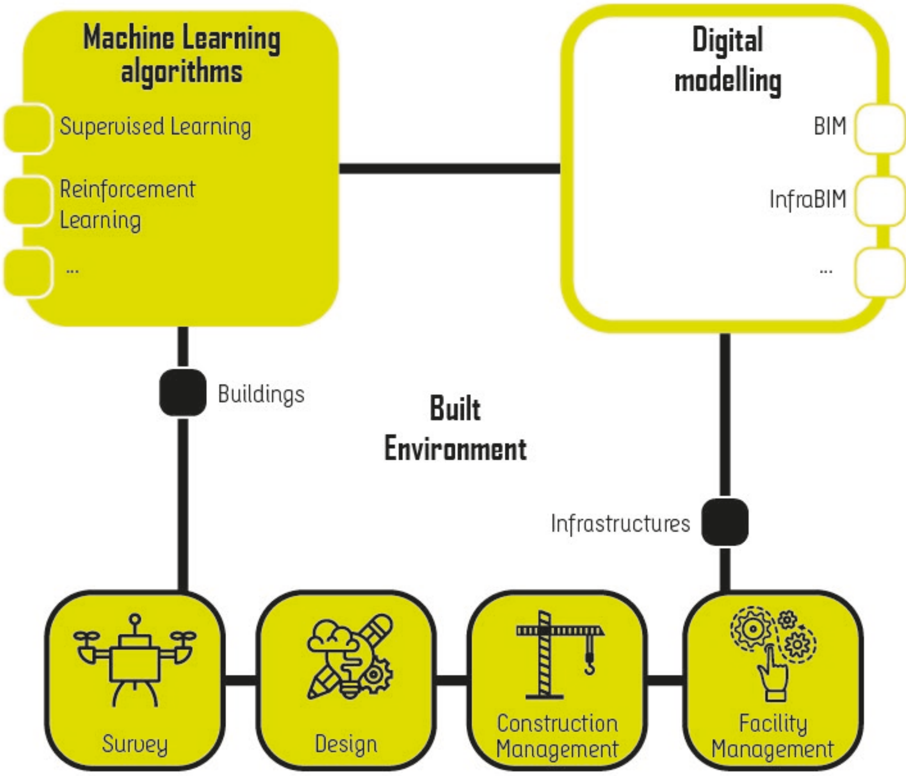


Fig. 17: ML integration with digital modelling for several uses in the built environment

The infrastructural domain, characterized by the integration of several different disciplines and heterogenous data-sources, represents a challenging field of application for ML techniques integrated with digital information models produced InfraBIM processes (Fig. 17). However, few attempts have been done towards the application of disciplines such as **Artificial Intelligence** (AI) and **ML** to the AECO sector, where the potentialities of such methods result still unexplored. Machine learning is defined as the study of computer algorithms able to automatically detect patterns in data, and then use the uncovered patterns to predict future data; the whole system of data prevision improves automatically through experience (Mitchell, 1997) (Kodratoff, 1989). Indeed, learning algorithms for layered neural network models are inspired by the way that neurons communicate with one another and are modified by experience (Sejnowski, 2018). In terms of categories, machine learning is usually divided into the following types (Murphy, 2012): (i) Predictive or Supervised learning approach, in which the goal is to learn a mapping from inputs x to outputs y, given a labeled set of input-output pairs; (ii) Descriptive or Unsupervised learning approach, in which only inputs are provided to the machine whose goal is to find "interesting patterns" in the data in order to extract structures that link them; (iii) Reinforcement learning (RL), which is useful for learning how to act or behave when given occasional reward or punishment signals, according to the solution the algorithm proposes. As far as the building and infrastructure fields are concerned, the application of machine learning algorithms is still quite recent. Some attempts towards the integration of ML algorithms have been developed within the context of several BIM processes, starting from the "**Scan to BIM**" sector, through **classification** and **sustainability**, in terms of energy resources, fields up to application within the infrastructural domain. Firstly, machine learning techniques found wide application within the survey context, in which the increasingly advance tools developed over the last years implied the necessity to deal with a great amount of data, for instance concerning point clouds. Within this context, specific studies aimed to: (i) develop semiautomatic approaches exploiting machine learning to pass from semantic point cloud to Heritage-Building Information Modelling (H-BIM) (Croce, et al., 2021); (ii) develop new terrestrial laser scanning (TLS)-based methods using machine learning to automatically classify rebar diameters and accurately estimate rebar spacing to safeguard the structural integrity of structures (Kim, Thedja, Chi, & Lee, 2021); (iii) develop Random Forest machine learning approach to improve the classification accuracy and efficiency of terrestrial LiDAR monitoring of complex natural slopes, in which the algorithm classifies points as vegetation talus, snow and bedrock using multi-scale neighbourhood geometry, slope, change, and intensity features; (iv) propose LiDAR point classification methodology to create 3D city models with building footprint using a machine learning approach (Park & Guldmann, 2019). These are just a few but representative examples of the research directions within this field. Moreover, ML has been implemented in the energy reduction and efficiency sector too, with several in-depth studies related to the development of deep learning algorithms to optimize energy efficiency and daily operations in building energy and storage systems (Narciso & Martins, 2020) (Ikeda & Nagai, 2021) (Gao & Lu, 2021), define energy consumption prediction models (Shapi, Ramli, & Awalin, 2021) (He, et al., 2020) (García-Martín, Rodrigues, Graham, & Grahn, 2019) in urban context (Fathi, Srinivasan, Fenner, & Fathi, 2020) both for residential buildings (Naji, Al Tarhuni, Choi, Alshatshati, & Ajena, 2021) and non-domestic ones (Seyedzadeh, Pour Rahimian, Oliver, Rodriguez, & Glesk, 2020) (Amasyali & El-Gohary, 2021). Furthermore, some practical issues related to the implementation of machine learning models for building energy efficiency have already been published, analysing how to move beyond such obstacles (Wang, et al., 2021). Applications of machine learning algorithms become even more interesting when implemented within Building Information Models (BIM). Such integration heralds numerous and sundry benefits for several BIM uses, which means "the method of applying Building Information Modelling during a facility's lifecycle to achieve one or more specific objectives" (Kreider & Messner, 2013). Indeed, methods integrating ML and BIM are used not only to read and manage data from BIM models, but also for parameter classification, database settings and further elaborations. Several studies have shown how their application gives **excellent results** to fulfil aspects such as classification of BIM elements, code compliance checking (Zhang & El-Gohary, 2019), lighting simulations (Troncoso-

Pastoriza, Eguía-Oller, Díaz-Redondo, & Granada-Álvarez, 2018), construction site monitoring (Braun & Borrmann, 2019), risk assessment and management (Lin, Shen, Zhou, & Xu, 2021) and visualization through Virtual Reality (VR) (Pour Rahimian, Seyedzadeh, Oliver, Rodriguez, & Dawood, 2020). For instance, Zhang & El-Gohary 2019 implemented a methology for code-checking that associates the IFC parameters of a BIM model and building codes by using a supervised learning-based method. Within this context also Facility Management (FM) could take advantage of code management, from the point of view of McArthur et al. (McArthur, et al., 2018) machine learning could help to improve the management of Work orders (WO) and promote an efficient communication with the facility team. By processing datal directly inked to the model it is possible to create summ dashboards related to the status of the WO in the case study analyzed. In general, the application of machine learning methods in the construction sector, and in particular in the integration with BIM methodology, is useful when dealing with Big Data, because algorithms need to get knowledge from data itself. For this reason, ML results of paramount importance in dealing with the great amount of data generated and processed within this context. Indeed, Marcher, Erharter and Winkler (Marcher, Erhater, & Winkler, 2020) carried out some analyses of possible applications of ML in the tunnelling field, such as: (i) autonomous support installation, (ii) automatic rock (mass) classification, (iii) geological prognosis updating ahead of the tunnel face, (iv) overcoming of limitations in the definition of constitutive behavior of soil and rock, (v) exploration of the applicability of reinforcement learning to fully automate different construction processes (self-driving TBMs) (Rimella, 2020). They also described how the world of construction and tunnelling will be affected in the future. From their point of view, the great potential lies in unsupervised Machine Learning approaches, where the system of ML learns by the use of data, without superimposing the final classification upon it. Finally, the authors give practical advices for the application: (i) using ML to optimize the whole process of realizing and maintaining tunnel projects; (ii) enhance the data collection performed during excavation, preserving all relevant information such as scanning and photos from the tunnel face and all monitoring data; (iii) combining ML and BIM; (iv) defining a standardisation for data input selection and data partitioning methods; (iv) defining a standardization of ANN (Artificial Neural Network) model architectures and performance measures of ANNs for tunnel engineering (Rimella, 2020).

InfraBIM tools

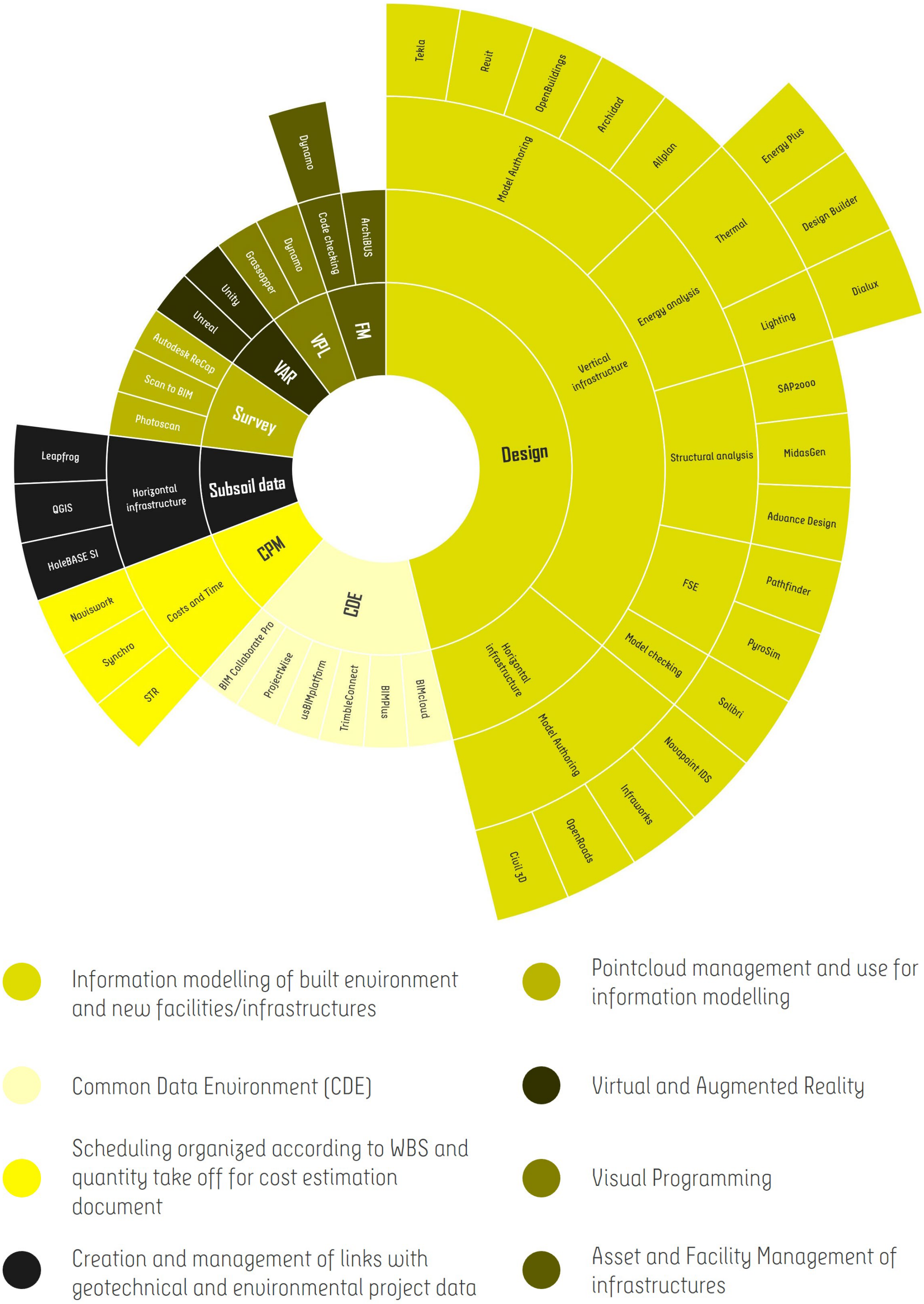


Fig. 18: InfraBIM tools: examples

Nowadays, platforms and tools for InfraBIM are developing fast thanks to the push given by national regulations and international standards towards the use of digital information models for big assets, which are mainly infrastructures. At the beginning of Chapter 3 the main differences between BIM platforms and tools have been highlighted. These differences are maintained also when talking about InfraBIM, even if in addition to traditional BIM authoring platforms, there are also other platforms that enable the design and therefore the modelling of specific infrastructure facilities. Starting from the very first digital parametric software ARCHICAD, a considerable number of new BIM authoring platforms have been implemented. However, BIM authoring platforms with a good performance in terms of modelling and interoperability when applied to buildings are not always efficient when applied to infrastructures too, mainly because of their predominantly horizontal development. Fig. 18 shows some of the most popular and used platforms and tools. In this case the focus is on the InfraBIM sector, therefore platforms and tools only developing the architecture discipline were not included. Interoperability is a core element because the exchange of information is necessary and it is paramount to clearly understand which kind of data is retrievable from one tool or another, in order to properly assign information to the correct domain.

table G.8 Example LOD for road layouts

LOD A	LOD B	LOD C	LOD D	LOD E	LOD F	LOD G
Geometry Base planimetric layout (2D).	**Geometry** Planimetric layout including transition bends. Altimetric layout including vertical connections.	**Geometry** Complete planimetric and altimetric layout.	**Geometry** Road and surface model constructed on 3D axes.	**Geometry** Complete road and surface model constructed on 3D axes.	**Geometry** As in LOD E (as-built survey).	**Geometry** New works: As in LOD F (with updates) Maintenance and management on existent layouts: As in LOD C or D (starting from).
Object 2D Axis	**Object** 2D Axis on the horizontal plane 2D axis on the vertical plane	**Object** 3D Axis	**Object** 3D Axes 3D Surfaces	**Object** 3D Axes 3D Surfaces	**Object** 3D Axes 3D Surfaces	**Object** 3D Axes 3D Surfaces
Characteristics - Straight-line length - Circular bend radius	**Characteristics** - Clothoid parameters - Steady gradients - Vertical connections - Road category	**Characteristics**	**Characteristics** - Cross-section according to the road category - Roadside rotation - Widening on bends	**Characteristics** - Section types - Slope gradients - Surface water drainage - Material volumes (earth moving, paving, etc.)	**Characteristics** - Product certification - Approval certificates - Information about earth and rock excavation - On-site test results - Laboratory test results	**Characteristics** - Last maintenance date - Maintenance party - Type of work - Survey results

Fig. 19: Example LOD for road layouts
Source: UNI 11337-4:2017

Within this context, it is impossible to think that when dealing InfraBIM only one platform could be used. For instance, Fig. 19 shows the LOD example for road layouts presented in the UNI 11337-4:2017. In this case the road component is developed starting from its planimetric alignment, the altimetry profile and the construction of the 3D components on the basis of typological cross-sections, up to the development of "corridor", which represents the 3D solid extruded on the basis of sections. Such a process involves several different tools, starting from specific software dealing with civil works until platforms for objects-oriented modelling, where details on components are added. Further detailed on the workflows and tools used for the case studies development are included in Chapter 6.

Chapter 4

Case studies

The development of case studies for the research topic has a twofold meaning. From one side, the aim is to **analyze** the required **processes** for **InfraBIM implementation** within an Italian engineering company with the aim to integrate them with traditional ones. On the other side the research topic has been developed through **application case studies** useful to **deepen specific infraBIM uses**. These case studies have been selected because they represent perfect pilots to create best practices applicable in further projects. Such experiences enabled the development of the methodology presented in Chapter 5 and 6 and supported its application in practice.

4.1 The reality of an Italian engineering firm

As discussed in Chapter 1, the AECO sector is still far behind other fields in terms of digital innovation. However, examples of excellence show that this change of course is possible, also in the Italian context where firms have reasons to hope, especially in a revival of their domestic market, despite the consequences of covid-19 pandemic (Norsa, 2020). The 2020 edition of the Report on the Italian Construction, Architecture and Engineering Industry provides all available data and insights on the top offer from the entrepreneurs shaping the built environment. The report also comments the rankings on the top contractors, architecture and engineering firms in Italy, which is a useful tool also to understand the approach of companies towards innovation. As far as the professional service industry is concerned the distinction between architecture and engineering firms is mainly due to their business structure, which is bigger and powerful in engineering firms for at least two reasons: (i) they work for all the spectrum of construction; (ii) they are diversified in many other fields: industry as a whole (plants and facilities) but also other businesses such as agriculture, energy, environment, information, telecommunications, etc.

Within this context, **Lombardi Ingegneria** represents the engineering firm who financed the PhD scholarship; the company is placed 59th in the 2019 Guamari ranking, improving by four positions compared to 2018. The following paragraph will briefly present the company, its main services, organization and projects to understand the context in which the research activity has been developed. The Lombardi Group, which was founded in 1955 by Dr Giovanni Lombardi who organized a consulting company for engineering services (Lombardi SA, 2021).

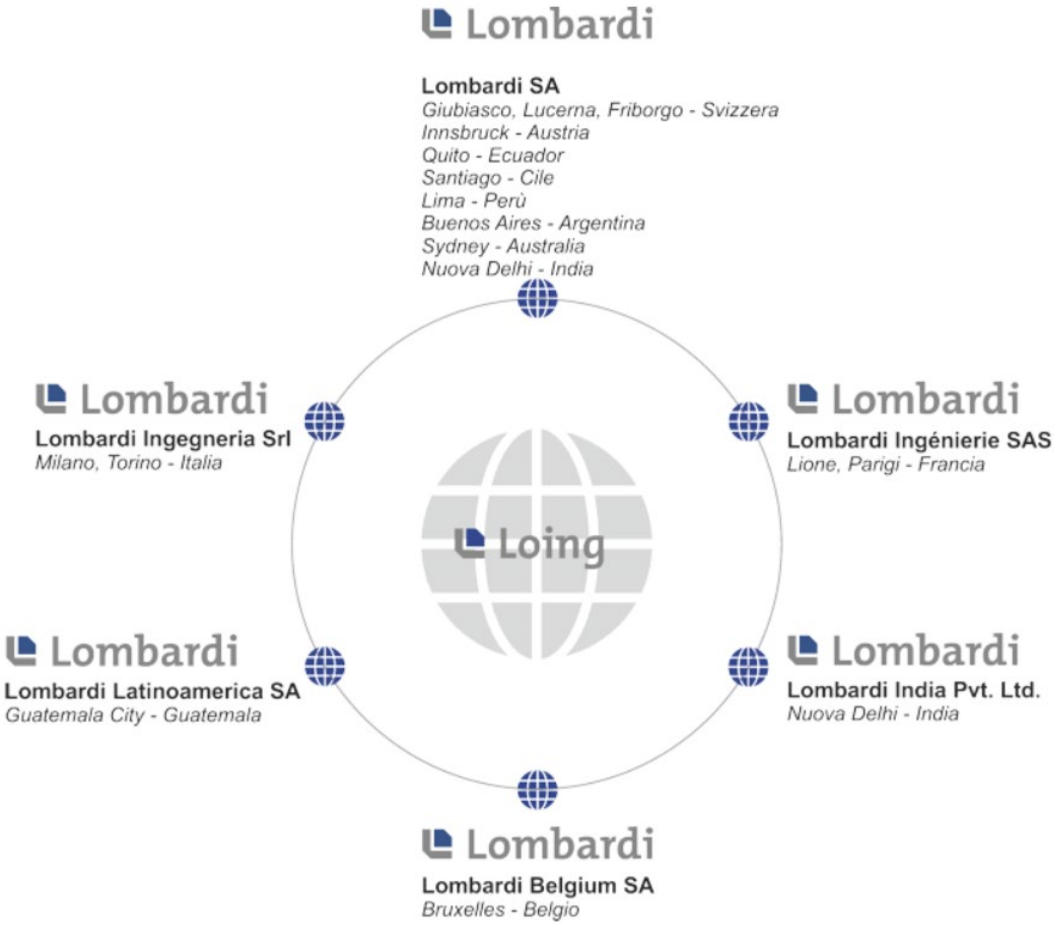


Fig. 20: Lombardi Group companies
Source: Lombardi SA website (2021)

Currently, the Lombardi Group consists of six companies and various branches, as shown in Fig. 20. Among these firms, Lombardi Ingegneria founded in 1997 as the Italian firm of the Lombardi group based in Giubiasco (TI) Switzerland. The company's main office is in Milan, since 2015 it has a branch office in Turin, and from 2022 it will also have a branch office in Rome. The company has a staff of over 100 highly specialised engineers and technicians, developing projects for a wide variety of civil works (roads, railways, bridges, highways tunnels, railways tunnels, underground railways, hydraulic works, civil and industrial buildings, underground structures, consolidation, etc.). The structure is organised according to ten operational Sections: Structures, Infrastructures, Underground Works, Tunnels, Geotechnics, Environment, Safety - Plants, Works Management, Life Cycle of Structures and Monitoring, CAD/BIM. The most important experiences carried out in BIM were the design of a new underground railway station in Turin (Fermata Grosseto) with the relative external arrangement (market area, largo Grosseto), the Bicocca station and the major works of the project to double the Bicocca-Catenanuova railway line and the stations of lot 16 line 2 of the Grand Paris Express and many other projects. Snowy Hydro 2.0 (Australia's largest hydroelectric project) and the Tremezzina diversion project, on Lake Como, are being designed in BIM. The company operates under a quality system as it is certified ISO 9001:2015, ISO 14001:2015 and ISO 45001:2018 for the following fields of application: design, works management, consultancy, appraisals, project-management, for civil engineering, electromechanical and similar works. The growth of activities during the last decades has been achieved by consolidating Lombardi's presence in their traditional markets and by a continuous search for innovative solutions, resulting in effective and efficient projects, characterized by optimized project costs and uncompromised quality. Lombardi's concept is towards the provision of made-to-measure and complete services, combining technological innovation with proven engineering practice in the best possible way.

Within the **transformation of work fostered by digital innovation**, it is undeniable that new roles and workflows had to be introduced by the company, to update business processes to the **new set of required competences** and professional figures. Towards this direction, in 2018 Lombardi Ingegneria started a process of implementation and analysis of best practices in the BIM environment adopting an integrated and mixed approach. On the one side financing the research project object of the present PhD thesis and on the other side by introducing new professional figures having the skills required for the use of InfraBIM methods and tools. Chapter 5 will analyse in more detail the path taken with the company during the years of research.

4.2 Application case studies

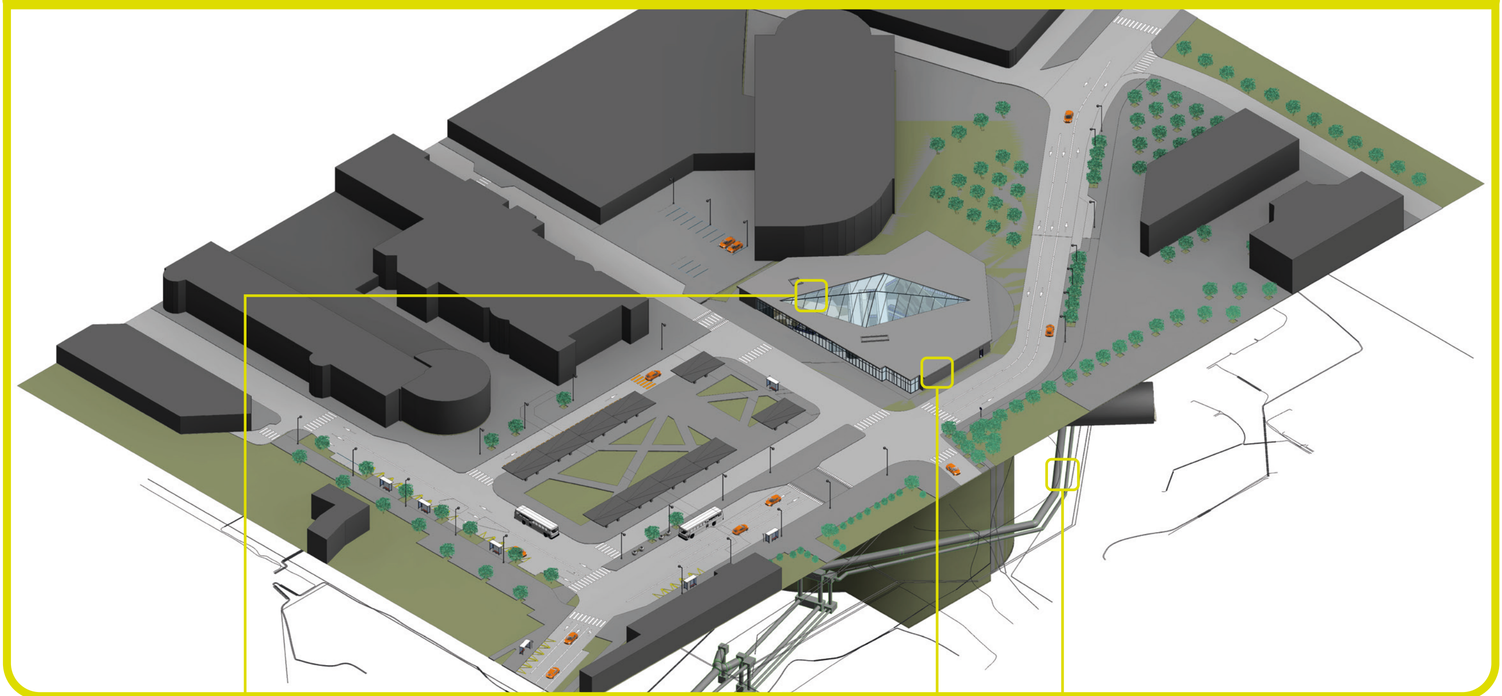
As previously enounced, three main application case studies have been developed for several InfraBIM uses, to test the interoperability among platforms and tools and to verify the efficiency of specific approaches and practices. The following paragraphs present the case studies developed during the research and their main scope.

Sevran Beaudottes underground station in Paris

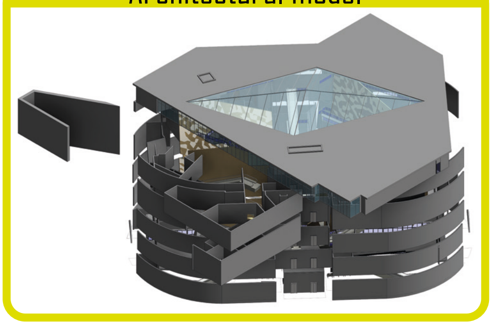
The first case study presented is the "Sevran Beaudottes" underground station in Paris, belonging to line 16 of the "Gran Paris Express" project. The Grand Paris includes the construction of four new rapid transport lines in the French region of Île de France, whose opening is planned in several steps from 2023. The station will be connected to the existing "Sevran Beaudottes" railway station of the RER B line, an important hub in the French transport network that connects the city with the area around Sevran. The construction method chosen is the "cut and cover", a system in which phases of excavation and construction go hand-in-hand. In the case in question, after having consolidated the soil through solid injections, the diaphragms walls are installed before the excavation starts (Fonsati & Osello, 2018). Then, the first excavation is carried out, up to a level just below what will be the intrados of the structural floor. After that, struts are placed to support the diaphragm walls, which in turn support the ground at the sides of the structure. The next phase involves the casting of the slabs of the ground floor and the first basement floor. The process continues in this way until the base slab is complete.

Sevran Beaudottes underground station in Paris

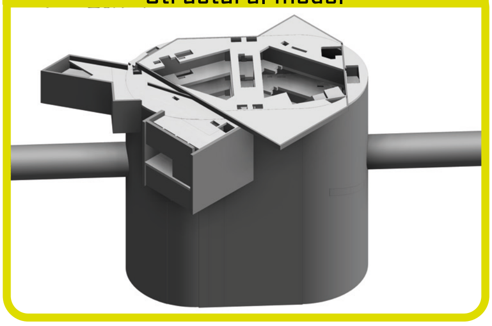
Federated model



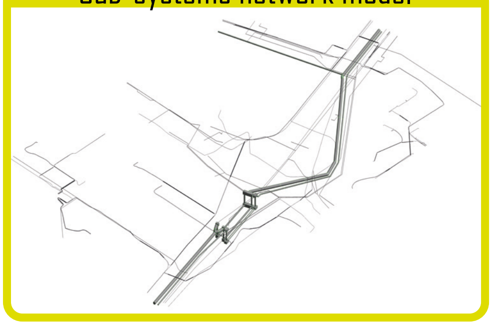
Architectural model

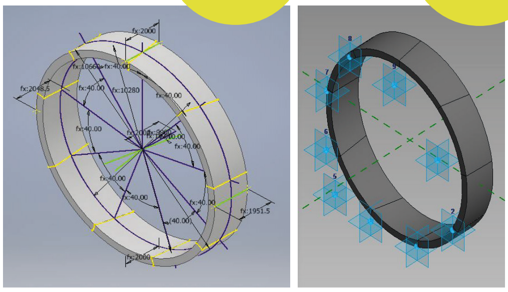


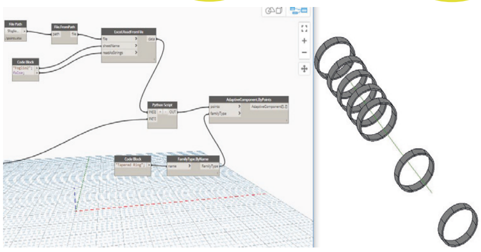
Structural model

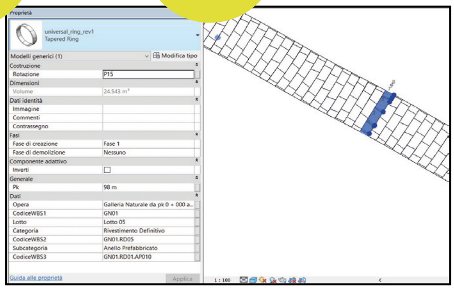


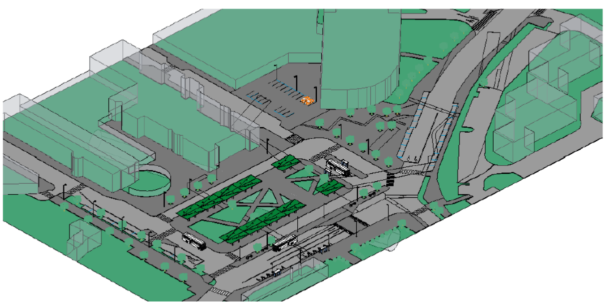
Sub-systems network model



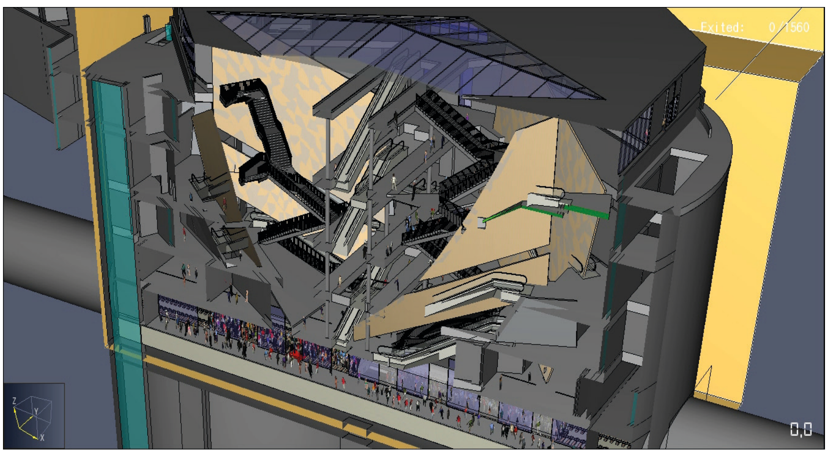








Abaco strade/marciapiedi_Demolizioni								
fase	codice elemento	Descrizione	Area [m²]	Volume [m³]	V. sciolto [m³]	Peso [t]	Fase di creazione	Fase di demolizione
Fase 1								
1.1	SEB_STS_I_1.1	Marciapiede	96	23.91	28.69	50.21	Esistente	Fase 1
1.2	SEB_STS_M_1.3	Marciapiede	225	56.3	67.56	118.23	Esistente	Fase 1
1.3	SEB_ZS_MST_1.3	Marciapiede	85	21.32	25.58	44.77	Esistente	Fase 1
			406.00	101.53	121.84	213.21		



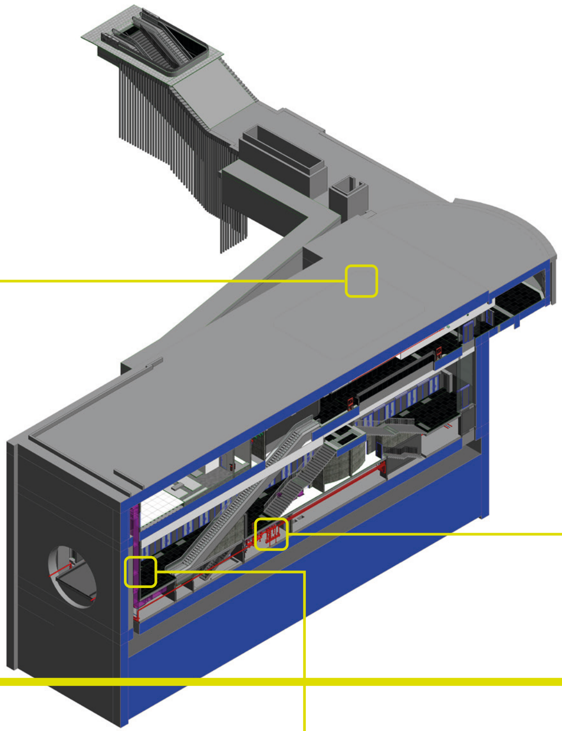
As far as the information modelling is concerned, the federated BIM model was organized under five main single models:

- **Preparatory works model**, which comprehended the different phases of preparation for the excavation site, such as changes in traffic flows, reconstruction of some sections of the urban pavement;
- **Sub-systems network model**, such as the drainage network;
- **Excavation phases model**, to estimate excavated quantities;
- **Structural model**, containing diaphragm walls, slabs and other components, including temporary elements such as struts;
- **Architectural model**, including finishes and other architectural components.

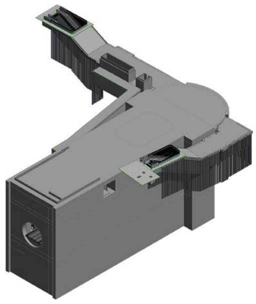
Therefore, the federated BIM model of the case study was useful to develop workflows for several scopes and mainly: 4/5 simulations (Bosio, 2018); analysis on scenarios for preparatory works before construction (Miletto, 2018); FSE simulations (Bosio, 2018); clash detection and code checking (Oskay, 2019); models coordination (Miletto, 2018) (Bosio, 2018); visualization using VR (De Luca, Fonsati, & Osello, 2019). Specific workflows are explained and discussed in Chapter 6.

Italia 61 underground station in Turin

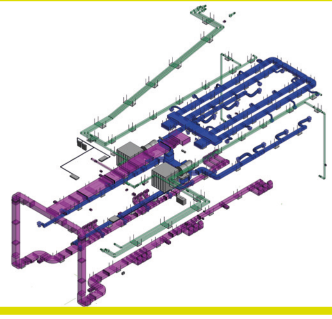
Federated model



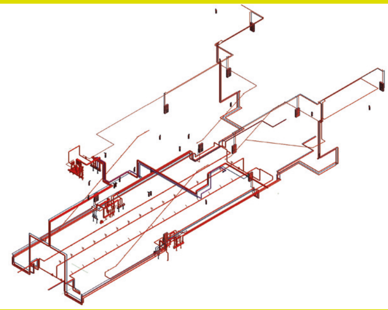
Architectural/Structural model

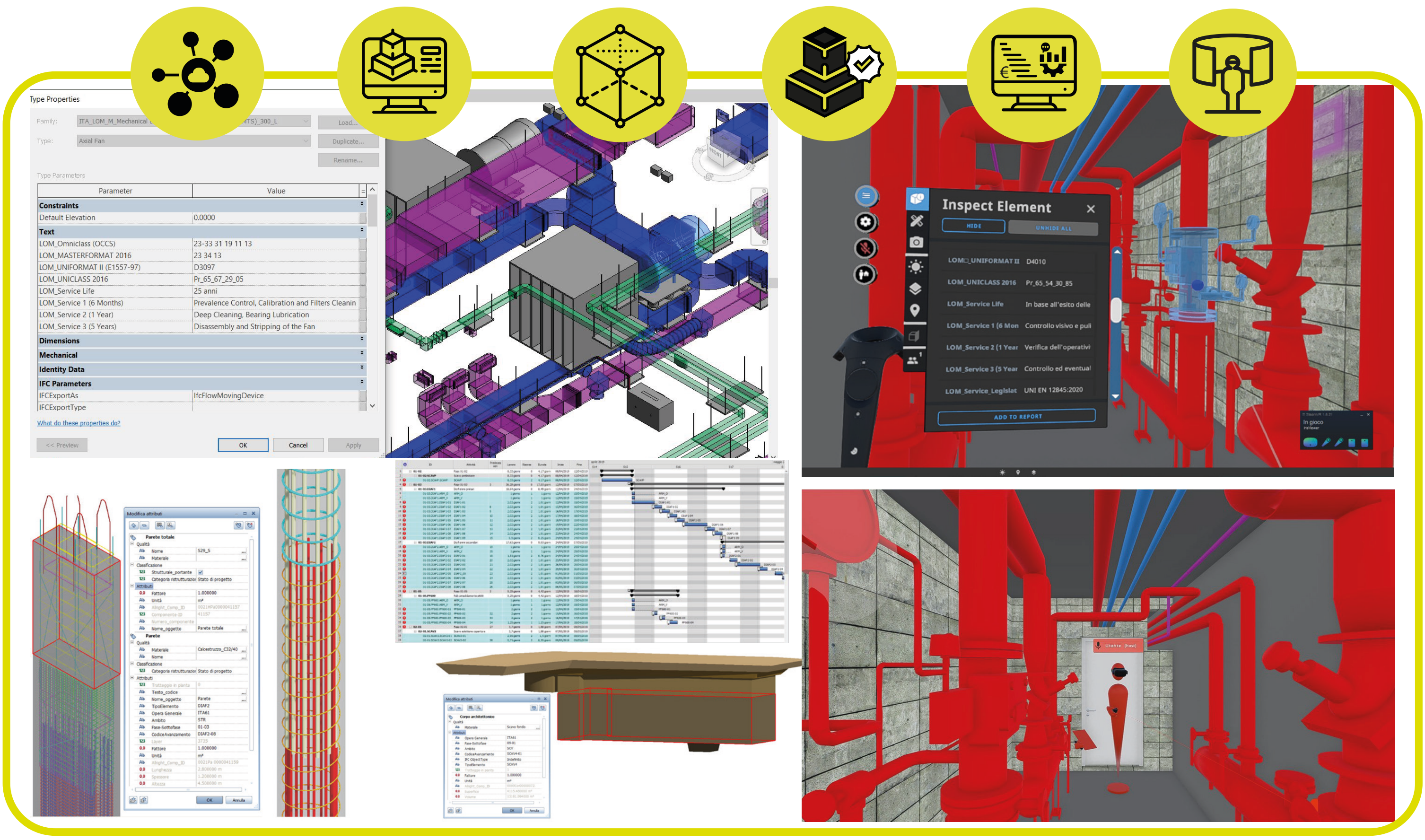


HVAC model



Fire Protection model





Underground station Italia '61, Turin

Italia '61 is a new station of the M1 line of the Turin underground. It is located in the widening between *Via Valenza* and *Via Caramagna*. It is an entirely underground structure, with the atrium facing north and two entrances. Its opening to the public is currently scheduled for April 2021. Italia '61 can be traced back to the typological station defined as "superficial"; this typology refers to an underground structure characterized by lateral quays and a minimum of two accesses to the ground surface. The plan of the typical station is characterized by a rectangular shape whose dimensions are about 68.50 m in longitudinal development (including the hemicycle of the atrium floor) while transversally 19.80 m south side and 26.40 north side towards the Lingotto. The construction method characterizing the station is represented by the top-down technique, since a rather prolonged construction site in Via Nizza was planned. Within such a construction methos, once the service networks have been moved, the work area is delimited and the vehicular traffic is diverted, diaphragm walls are created along the perimeter of the station, which constitutes the external walls of a large reinforced concrete box, containing the ground surrounding the excavation and preventing subsidence. The trenches for the concrete casting that constitutes the diaphragm walls are dug by means of hydro-milling and bentonite mud casting, which support the ground while waiting for the reinforcement cage to be lowered and for the concrete casting to be carried out. The diaphragm walls reach a depth of about 31 m and in correspondence with the area of passage of the TBM have a double reinforcement: steel for the sections not affected by the passage, and fiberglass for the sections concerned, this because fiberglass is a more fragile material and therefore easier to demolish during the excavation of the tunnel.

Also in this case, the BIM model was organized as a federated model, divided into four single models:

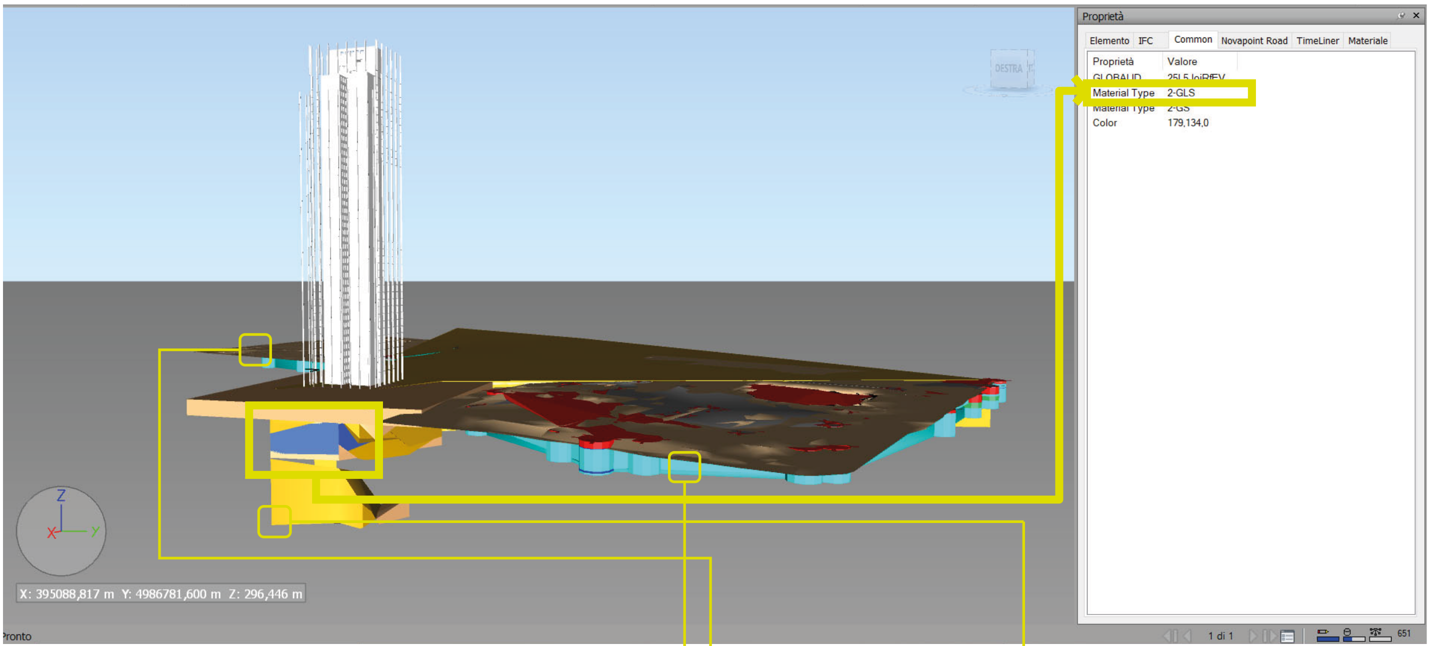
- **Subsoil model**, which served as a database containing information related to the characteristics of the subsoil and the quantification and management of extracted materials, useful for determining the appropriate choices of site related to parameters such as "Designated Authority", "Type of material", "CSC", "Site of intermediate storage", "Site of destination and Reuse";
- **Structural model**, characterized by elements that participate in the definition of the analytical model and that can be used for a structural analysis of the work. The digital information model is managed through its subdivision into phases, organized on the basis of the construction phases,
- **HVAC model**, characterized by high LOD and information parameters useful for FM purpose and maintenance on system components;

- **Fire-protection model**, characterized by high LOD and information parameters useful for FM purpose and maintenance on system components;

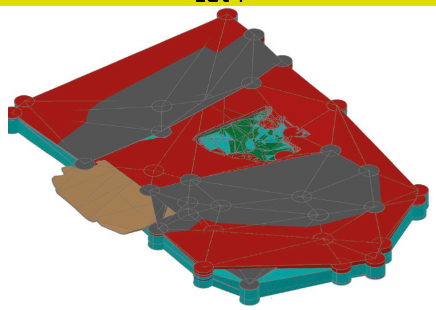
Therefore, the federated BIM model of the case study was useful to develop workflows for several scopes and mainly: Construction Project Management (Giovine, 2019); digital repository of information related to the characteristics of the subsoil and the quantification and management of extracted materials (De Conciliis, 2018); interoperability with Finite Element Method (FEM) tools (Ruano Bravo, 2021); FM purposes (Passeretti, 2020); clash detection and model validation using VR (Passeretti, 2020) (Lovisolo, 2020). Specific workflows are explained and discussed in Chapter 6.

GeoBIM of the “Parco della Salute”, Turin

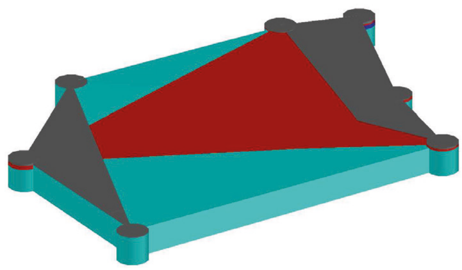
Federated model



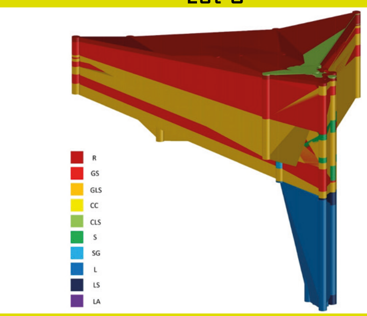
Lot 1

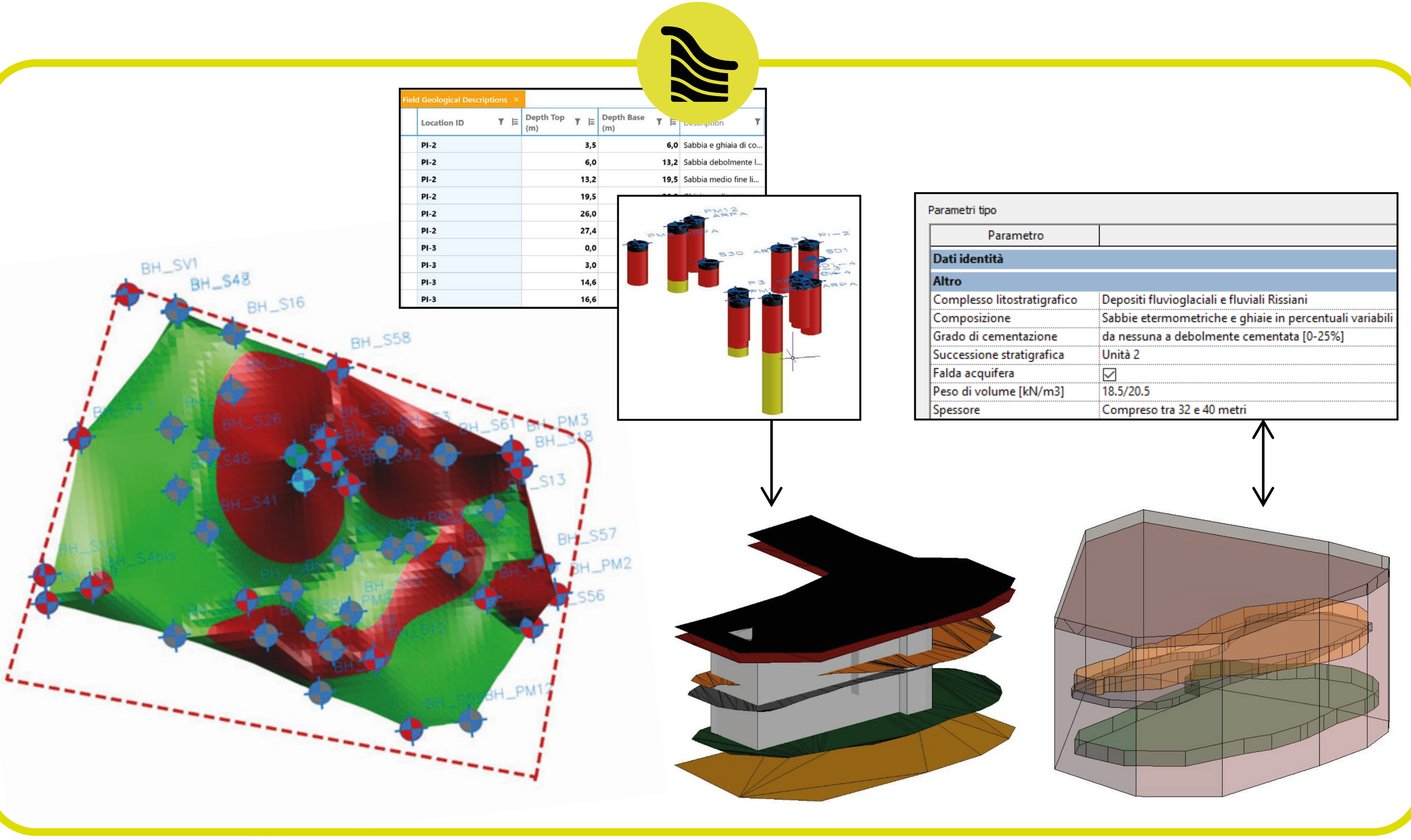


Lot 2



Lot 3





Parametri tipo

Parametro	
Dati identità	
Altro	
Complesso litostratigrafico	Depositi fluvioglaciali e fluviali Rissiani
Composizione	Sabbie etermometriche e ghiaie in percentuali variabili
Grado di cementazione	da nessuna a debolmente cementata [0-25%]
Successione stratigrafica	Unità 2
Falda acquifera	☑
Peso di volume [kN/m3]	18.5/20.5
Spessore	Compreso tra 32 e 40 metri

"Parco della Salute", Turin

The new "Parco della Salute, della Ricerca e dell'Innovazione" in Turin is included in the requalification plan of the ex-industrial site "Nizza Millefonti", located in the south-east of Turin. The whole area is 313.725 m^2 wide and it is divided in four districts. The first one is going to be converted into a medical centre, including hospital, research departments and universities. This district is composed of two lots (1 and 2), located at the side of a third lot that corresponds to the second district of the site. Information related to the stratigraphy of the area and its hydro-mechanical properties were retrieved from many investigation campaigns, performed over several years. Different types of investigations were performed to individuate eventual polluting chemical components such as electromagnetic investigations, georadar reliefs, electrical tomographies, piezometric surveys, water, and soil analysis. The maximum depth of boreholes was limited to 15-17 m, because of the reason of investigations. Instead, the investigation campaign performed in 2007-2008 on the lot 3 had the scope to define the geotechnical model for the design of the tower "Torre della Regione Piemonte". For this reason, several geotechnical tests were executed, both *in situ* (SPT: standard penetrometer tests, PMT: Pressiometer tests, Lafranc permeability tests etc.) and laboratory ones (Grain size distribution tests, Atterberg limits etc.). Two main different depths characterized boreholes performed in this area: until 80 m, in the zone where the skyscraper was built, and until 40 m in the area nearby (Fonsati, Cosentini, Tundo, & Osello, 20201)

In this case, the organization of the federated model was based on the different lots of the area. For this reason, the coordination model included three single models: lot 1, lot 2 and lot 3. The present case study was chosen to develop workflows aiming at creating an integration among InfraBIM processes and a digital repository for geotechnical and geological information related to sub-soil (Fonsati, Cosentini, Tundo, & Osello, 20201). Specific workflows are explained and discussed in Chapter 6.

Chapter 5

InfraBIM implementation in companies

5.1 The transformation of work and processes

As discussed in Chapter 1, Digital innovation is fostered by technologies but also innovation management; within this context **peopl**e have a **leading role** because they also have to introduce **cultural shifts** and transformation to working procedures to succeed. Indeed, successful business processes towards IT integration are characterized by several aspects: (i) the capacity to cover a wide span of services, because new ways of working can be applied to several areas of a company; (ii) the process changes enabled by new company systems produce results very quickly; (iii) such defined processes are extremely precise; (iv) consistency is a big advantage, because processes are executed the same way everywhere, every time; (v) monitoring is easier, because activities can be tracked and watched in real time, giving also the chance to test and give feedbacks more than ever; (vi) enforceability of such procedures is ensured (McAfee & Brynjolfsson, 2008).

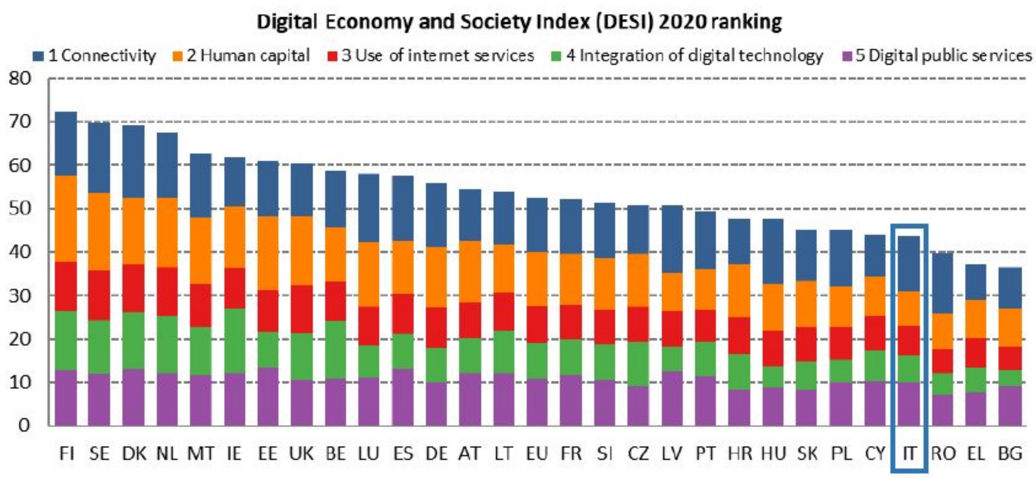


Fig. 21: DESI 2020 ranking – Italy ranks 25th out of the twenty-eight EU countries
Source: DESI 2020 report, (European Commission, 2020)

Furthermore, the importance of digital assets and the way connectivity, data, AI etc. as well as basic and advanced digital skills sustain our economies and societies have been highlighted during COVID-19 pandemic. Digital systems allowed work to continue, tracking the spread of the virus etc. and will also "play a key role in the economic recovery as the European Council and the Commission have undertaken to frame the support to the recovery along the twin transition to a climate neutral and resilient digital transformation" (European Commission, 2020). In this framework, **monitoring** such a **performance in digital innovation** is of paramount importance. Indeed, the European Commission uses the Digital Economy and Society Index (**DESI**) to monitor Europe's **overall digital performance** and track the progress of EU countries in their digital competitiveness (European Commission, 2020). The index is evaluated through indicators across five main dimensions: (i) Connectivity; (ii) Human capital; (iii) Use of internet services; (iv) Integration of digital technology; (v) Digital public services. In the 2020 edition of DESI rankings (Fig. 21), **Italy is 25th out of the twenty-eight EU countries**, showing significant gaps in terms of Human capital, recording very low levels of basic and advanced digital skills, which in turn are reflected in the low use of Internet services (European Commission, 2020). Furthermore, results in terms of Integration of digital technologies are very low also, proving that Italian enterprises still lag behind in the use of technologies such as cloud-computing, big data, etc. Also, the Italian "Piano Nazionale di Ripresa e Resilienza" (PNRR), prepared to access to the economic resources from the NextGenerationEU after COVID-19 pandemic, embraces digitalization and innovation among its missions. Indeed, digitalization represents a **transversal necessity**, as it concerns a continuous technological update of the production processes. It must involve infrastructures as a whole, from energy and transport infrastructures, where monitoring systems with sensors and data platforms represent an innovative archetype of quality and safety management of the assets (Governo Italiano, 2021). Among the consequences of digital transformation there is the **transformation of work**. Indeed, as IT systems facilitate the implementation and monitoring of processes, they also foster the capacity to optimize and invent better methods, so knowledge workers can prove their real added value because of the "return on talent" trend.

In this framework, the traditional approach to **process management** is expressed in the ISO 9000 series of standards, which define the fundamentals and requirements for the implementation of Quality Management Systems (QMS). A "process" is defined as "a set of interrelated and interacting activities that use inputs to deliver an intended result" (UNI EN ISO 9000, 2015). The International Standard promotes the adoption of the "process approach" when developing, implementing and improving the effectiveness of a QMS. Such an approach involves the **systematic definition**, **management**, **measurement** and **improvement** of **processes**, and the interactions among them, in order to achieve the intended results in accordance with the quality policy and strategic direction of the organization (UNI EN ISO 9001, 2015). Their effectiveness represents the ability to achieve the desired result, while the efficiency of the process represents the relationship between results achieved and resources used.

Although the types of process vary according to the needs of the company to meet specific business objectives, it is possible to identify some typical areas to address, as the ISO 9004:2018 specifies:

- Meeting the **needs** and **expectations** of interested parties, which necessarily implies strategic planning and the definition of company policies and objectives;
- The provision of **resources**, including those processes necessary to provide the resources needed to achieve the company's quality objectives and desired results;
- Operations related to **products** and **services**, including all those processes that achieve the desired results of the company;
- **Managerial** activities, including monitoring, measuring, analysis, review, improvement, learning and innovation (UNI EN ISO 9004, 2018).

One of the greatest benefits of this approach is the management and control of these processes and the interface between different functional hierarchies of the company, as the "**horizontal management**" is introduced to break down the barriers between the different functional units, unifying the focus towards the main objectives of the company itself. In the sequence of a process, it often happens that the outputs of one process are the inputs of others; this leads to an interconnection between processes in the overall management system. The introduction of digitalization in the construction sector requires a paradigm shift from the traditional process management approach; this innovation must involve every single actor in the construction process, clients, designers, enterprises, manufacturers, managers, etc., and affect every stage of the planning up to the operation. Therefore, this innovation inevitably involves the introduction of **new professional figures**, **new procedures**, new rules, **new workflows**, so as to determine a revision of the current processes.

5.2 InfraBIM processes

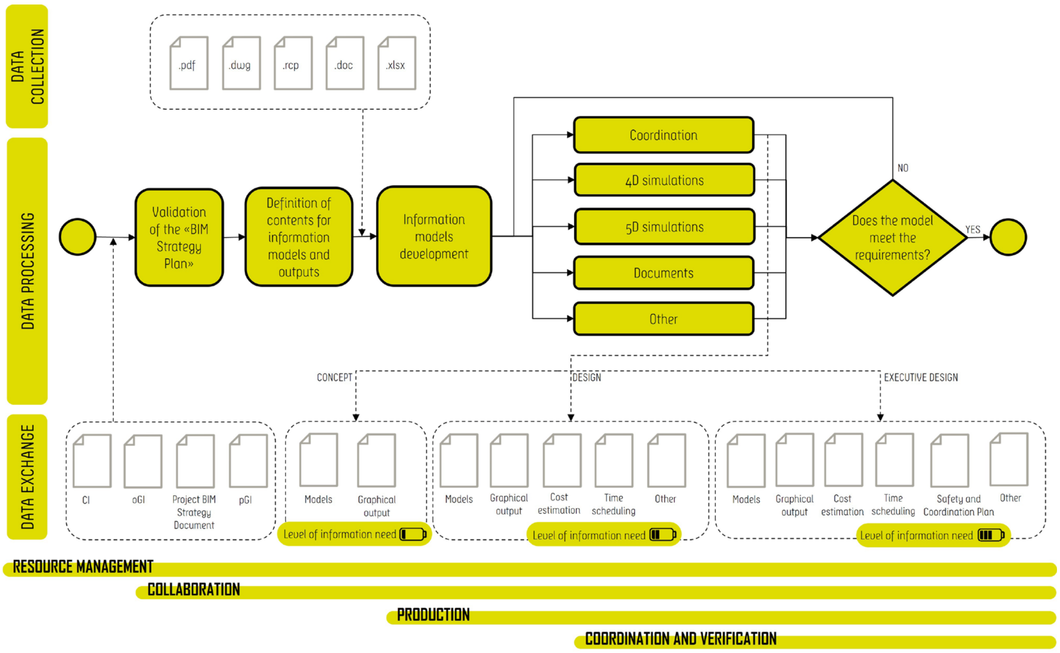


Fig. 22: InfraBIM strategy procedure and related processes

The process approach, as highlighted by ISO 9000 series, represents the starting point for the adoption of a new methodology and/or technology that would drastically change not only the "production", in the context of engineering firms the design and all the other services offered, but the whole organizational procedures and the structure itself of the company. For this reason, this approach is applicable in the digital innovation of AECO companies for the implementation of new methods and tools, such as InfraBIM. The aim of the research is to create an **implementation framework replicable** in different contexts to several companies, that could be applied not only for InfraBIM but also for all other future technologies and methods to implement. As previously enounced, during the research the developed methodology was applied to the company identified as case study, the Lombardi Ingegneria engineering firm, producing specific results, as reported in section 5.1. In this study, by analysing the company's needs and expectations the methodology was developed considering four main kinds of processes for implementation (Fig. 22):

- **Resource management:** it defines the process of managing new resources in terms of professionals with specific competences and skills, that have to be integrated within the organizational structure of the company;
- **Collaboration**: it defines the information sharing system to ensure that data ownership and management is correctly assigned;
- **Production:** it defines the process to produce information models and its related documentation;

- **Coordination and verification:** it defines the monitoring and validation of models, for their coordination according to the InfraBIM uses and purposes.

All these processes are closely linked to each other, which means that the inefficiency of one process would lead to the inefficiency of the other processes too. For instance, if the data sharing system is not working properly (collaboration) also the production of information models and its validation meet several critical issues, causing confusion in the development of the project tasks (resource management). These processes are described in a "strategy" document containing the company's policies and objectives, specifically developed within this research activity. The ISO 19650 defines such a document the Organizational Information Requirements (OIR), which "explains the information needed to answer or inform high-level strategic objectives within the appointing party" (ISO 19650-1:2018). The following sections aim at presenting each type of process more in detail, by giving the point of view of the author at the end of the research activity and by presenting some examples of how such processes have been developed.

5.2.1 Resource management

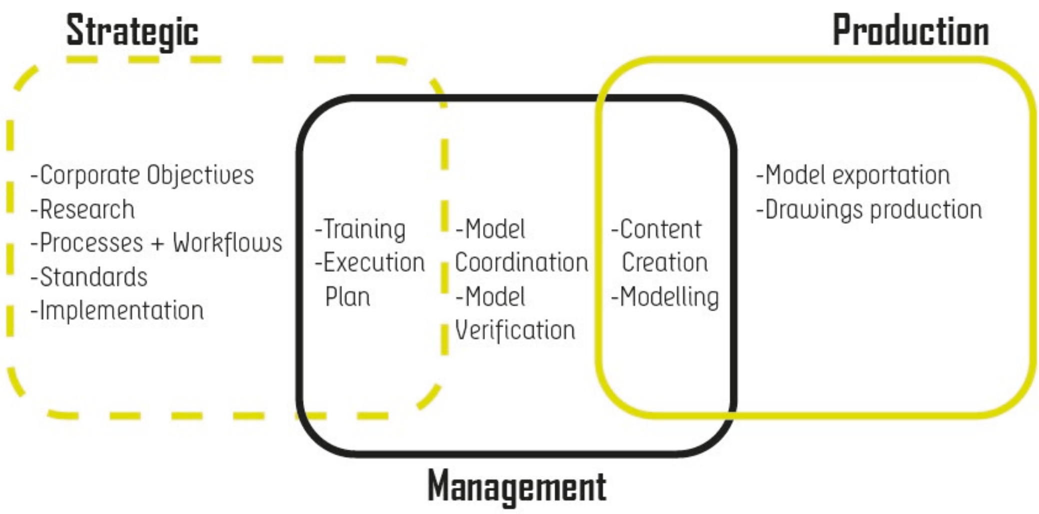


Fig. 23: Resource management skills matrix
Source: Adapted from AEC UK (2015)

The DESI 2020 report showed how much the human capital and its low digital skills is influencing the overall score of Italy and also the other domains of the index. In this framework, the AECO sector has been characterized by the increasing requirement of professionals with advanced digital skills in recent times, also because of the spreading of BIM and the production of information models that requires the use of digital parametric modelling and Visual Programming Language (VPL), which is defined as "object-oriented logical programming language, which uses algorithms by manipulating codes graphically rather than textually" (Rapetti, 2019). For this reason, the management of resources must be planned and analyzed to fulfill such a request, introducing new professional figures with specific competences and skills, and defining their roles and responsibilities. This section introduces the main resources in terms of roles required in the InfraBIM environment and provides examples on how these resources are hierarchically organized. First, it is necessary to identify the areas of influence of the different figures involved in the implementation process. The AEC (UK) BIM Technology Protocol define these areas in relation to three primary functions: strategy, management and production (AEC UK, 2015). Therefore, each role is entrusted with a series of activities grouped according to its primary function (Fig. 21).

Strategic

In terms of strategic management, a figure is needed to be the spokesperson for a process of change and impact at "cultural" level. This role mainly acts at company level and has a **managerial** and **strategic purpose** substantially. It defines responsibilities in the implementation of InfraBIM processes and strategy, the drafting of technical and operational documentation, resource management and guidance in the development of standards. In general, it operates on two main levels: **information management** and **coordination**. Its core functions are the following:

- Defining and updating corporate objectives in the BIM area;
- Creating a "best practice" as a background for future projects and develop research in specific areas in relation to the needs of the company;
- Defining and supervising the implementation, production, collaboration, verification and validation processes and workflows to ensure the best performance and optimization of resources;
- Supervising the preparation of business tools and infrastructure such as templates, standards, object libraries;
- Following the management of contracts, processing the required documents, including the oGI and the pGI;
- Coordinating the information and aggregation of information content by identifying any interferences or inconsistencies and proposing solutions to the managers of the disciplines concerned. Within this context, information content means "information set organized according to a specific scope for a systematic communication of a range of knowledge within a process" (UNI 11337-1:2017);
- Defining the structure of the information content that the model must have according to the design phase (level of information need, workflows and graphics);
- Participating in the definition of the ACDat and its management rules;

– Defining a strategic training for project leaders and project managers on the one hand and lead the technical selection to interviews for new resources on the other.

Management

This role operates mainly at **project level** and it is closely linked to the strategic one for the definition of project standards, applying and adapting them according to the characteristics of the specific project. In particular, this role deals with the following activities:

– Setting the structure of the models at the beginning of the work and follow them throughout the project, organizing them in more efficient structures at each phase change;

– Implementing the documents related to the project with the management department;

– Working closely with the project management department to ensure that the modelling and compilation of information is aligned with the material in the phase deliveries;

– Managing models and related data sets on a daily basis;

– Establishing protocols and procedures for sharing and collaborating with external working groups;

– Providing technical support and tutoring to the project team to complete deliveries.

Production

This role is closely dedicated to the production of the information. It requires both **technical skills** in **modelling** and **design competences**, so that the two phases go hand in hand; only this correspondence can ensure the full adoption of the methodology within the company policy. In particular, its functions include:

– Implementing object libraries;

– Defining the Level of information need for the objects according to their use and discipline;

– Producing the models for validation through the subsequent control and verification procedures;

– Producing the contractually agreed open format models and related drawings and documentation.

From these primary functions it is possible to identify specific professional figures; the UNI 11337:7/2017 provides indicative job titles linked to specific

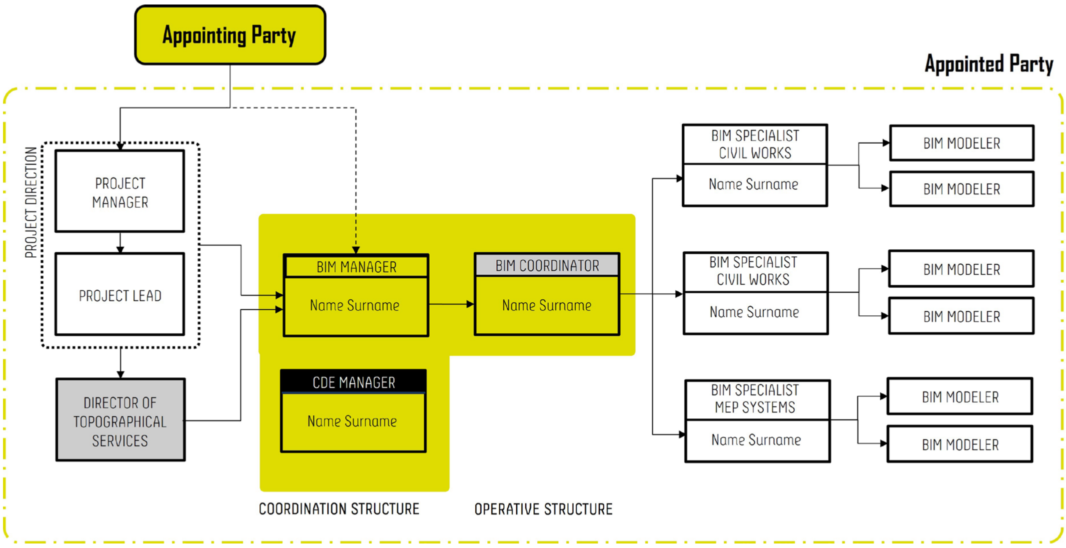


Fig. 24: Resource management between Appointing and Appointed party. The integration between Project direction (traditional figures) and Coordination and Operative structures (BIM professionals)

competences, skills, abilities etc. The UNI identifies four main types of professionals, two strictly related to the strategic primary function (CDE Manager and BIM Manager), one for the management (BIM Coordinator) and one for the production (BIM Specialist). Such figures result of paramount importance within this transition phase of shifting from CAD-based processes to InfraBIM-oriented ones. Fig. 24 shows possible interactions among the appointing and the appointed parties in terms of BIM professionals. Certainly, during the transition phase towards the adoption of InfraBIM methods and tools is characterized by having a dual professional for each primary function, at least. This means that professionals with specific BIM-related skills that probably have less experience in dealing with complex projects need to be supported by professionals with more experience at

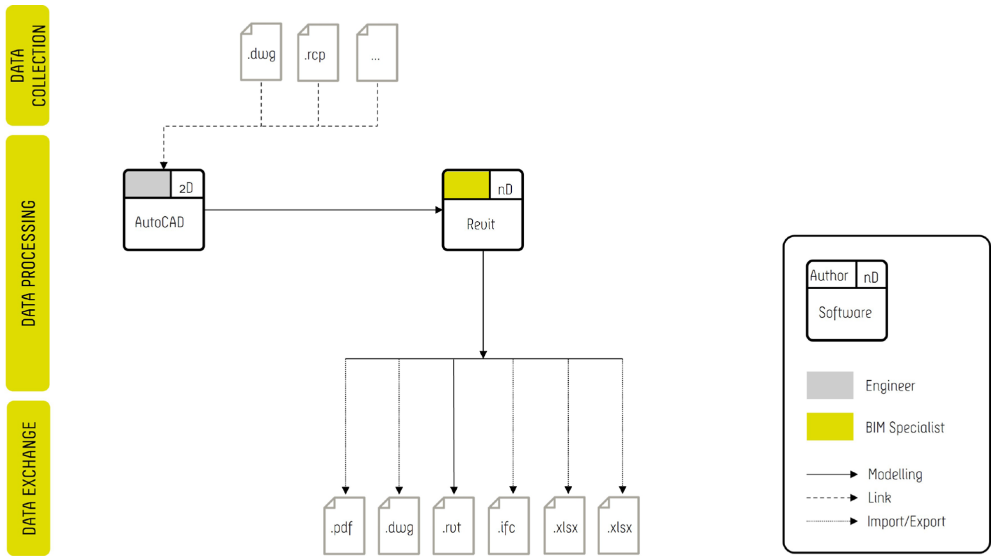


Fig. 25: Resource management in the transition phase

process level and less capacity in terms of technology and tools (Fig. 25). However, for the process to be truly efficient in long term, it is necessary that all designers gradually acquire a fair level of autonomy with the methods and tools and at the same time gain experiences in managing projects. At the same time, the number of professionals, of course, must be defined according to the size of the company, depending on possibilities in terms of economic and other resources.

5.2.2 Collaboration

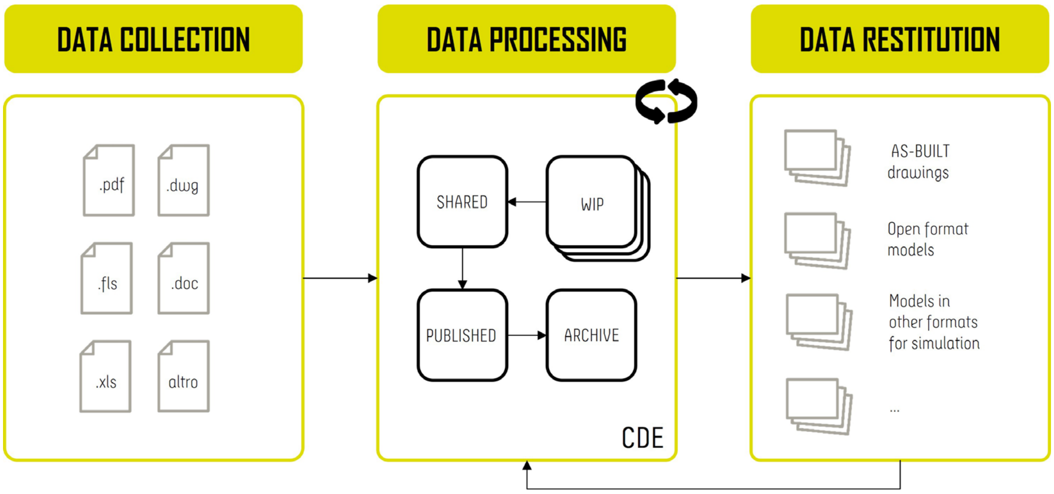


Fig. 26: Data management approach

Collaboration is one of the fundamental concepts to consider for an efficient implementation of the InfraBIM method. For this reason, it is necessary to define a sharing system that allows communication among all the actors and ensures the proper functioning of the collaboration processes. As previously described, such a system is defined CDE in the InfraBIM environment. The ISO 19650 introduced the possibility to "distribute" information between, for instance, the appointing party's CDE and the appointed party's one, instead of having a unique environment. Within this section the organization of the CDE is going to be deeply analyzed and some examples of how to share information between appointing and appointed parties' CDEs are presented. In general, the whole process involves a **data management approach** (Fig. 26) that is carried out through an iterative methodology; data is collected, stored to be "processed" and returned in different ways. These steps are repeated to ensure the data continuity and update, which means that there is always an **asset** (in terms of surveys, models from previous phases etc.) to be collected and to start from. In this framework, the CDE establishes the procedures for the iterative development of the project documentation, pursuing the objective of integrating and coordinating data coming from the different actors involved in the process and heterogeneous sources. To ensure a collaborative approach, the fundamental requirement is to **have confidence** in the **information** being shared. For this reason, specific project standards are set to ensure the transfer and release of information in a monitored way. This way, all stakeholders can access an environment where they can retrieve consistent and up to date

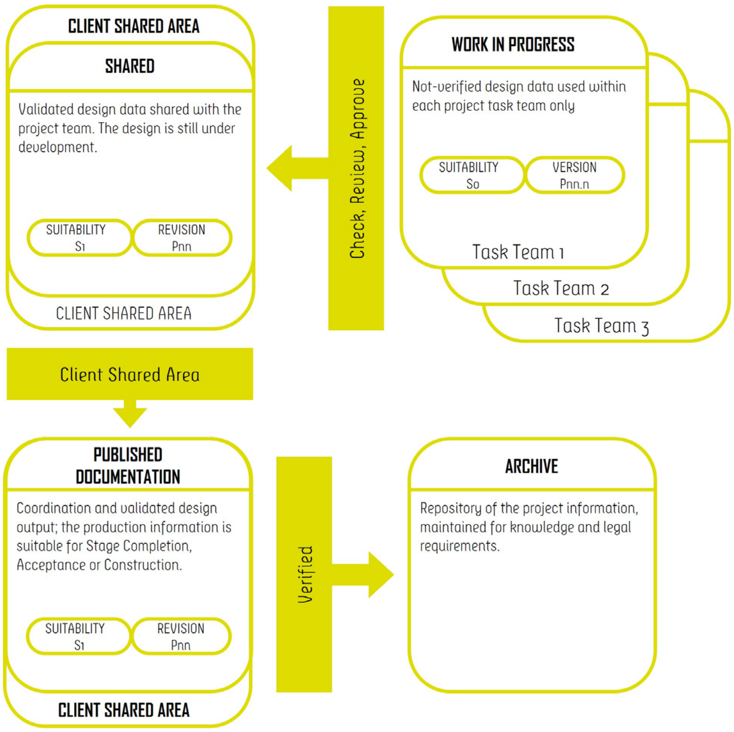


Fig. 27: Common Data Environment (CDE) sections
Source: ISO 19650-1:2018

information, which is the result of a precise activity and is defined by a process that is properly regulated, transparent and verifiable. Both in the ISO 19650 and UNI 11337, and all previous standards, the CDE is organized in four main sections as shown Fig. 27: (i) work in progress (WIP); (ii) shared; (iii) published; (iv) archive. These sections conceptually represent the information flow during asset management and project delivery. This conceptualization does not provide the real complexity of CDE workflows that must be thought on the basis of the specific

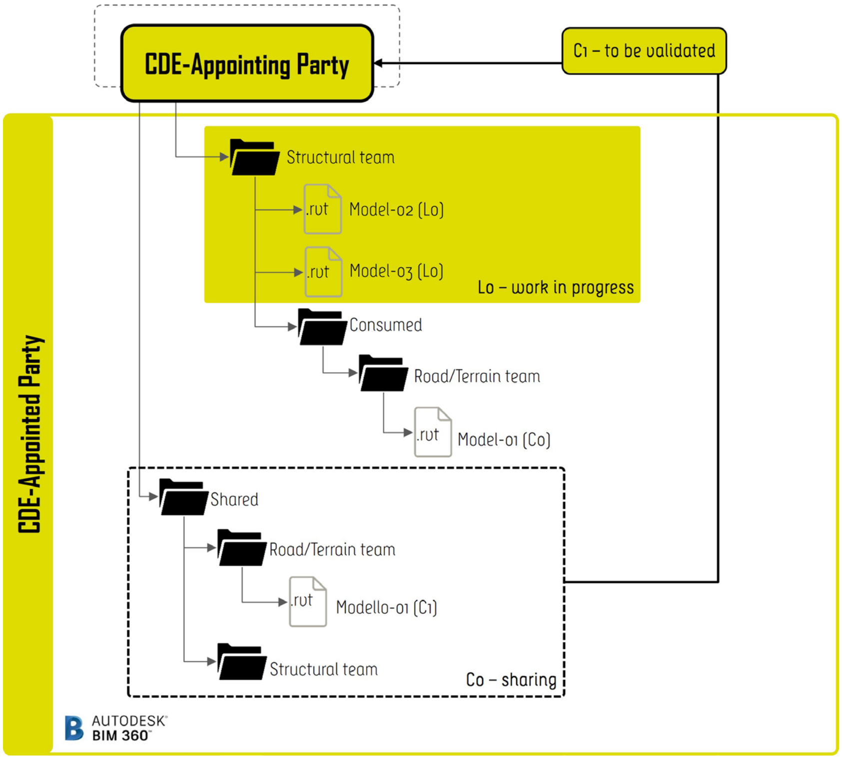


Fig. 28: Appointing/Appointed Parties CDEs

requirements and needs of the project. WIP state is used for information while it is under development by its task team (ISO 19650-1:2018); after this state the task team should face the check/review/approve transition, by checking if the produced information is compliant with the agreed standards, methods and procedures. The shared state represents the place where information is consulted by all appropriate appointed parties for the purpose of coordination with their own information. The information in the shared state is visible but not editable; if editing is required the information should be returned to the WIP state, where it is modified and resubmitted by its author. This state is also used for information approved for sharing among the appointing parties and are ready for authorization from the appointing party. After the shared state the review/authorize transition represents the moment in which the appointing party distinguishes between the information that can be relied on for the next stage of project delivery (i.e. more detailed design or construction) or for asset management and so moved to the published state and the information that cannot still be subject of change. This transition often reflects the information exchange between the appointing/appointed parties CDEs. Fig. 28 shows an example of such a transition, defining the *L0-work in progress* level and two levels of the shared state: the first one, *C0-sharing*, indicates the condivision of information among appointed parties within the same CDE; the second one, *C1-to be validated*, refers to the transition from the Appointed party's CDE to the Appointing party's CDE; therefore the information is submitted in order to obtain the approval for the next stage of the process. The collaboration process also requires that professionals are given a precise set of tasks to complete, in relation to the primary function of their role as discussed in section 5.2.

5.2.3 Production

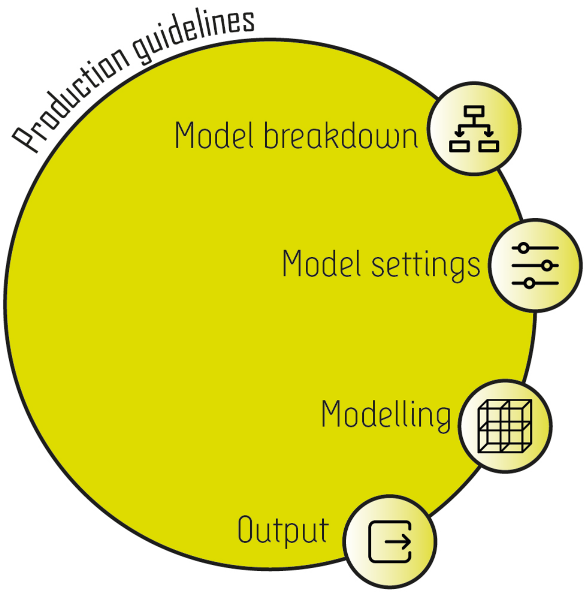


Fig. 29: How to approach the definition of guidelines for production

The production of information involves several different processes when working in an InfraBIM environment. Indeed, InfraBIM requires the use of several approaches to modelling, which means that compared to the CAD systems, more tools and workflows are used with several different purposes, as shown in section 3.4. For instance, when designing the horizontal alignment of an infrastructure, the information is probably produced in a tool such as Autodesk Civil 3D or Bentley OpenRoads, while for the modelling of facilities like bridges or railway stations Autodesk Revit or Bentley OpenBridge is probably used. For this reason, it is of paramount importance to define not only the preferred tools to use but also the interoperability workflows among these systems. Therefore, specific documents must be drawn up and organized in a way that professionals are guided towards the production of information. This section gives some input on how to organize the modelling phase in a way that could be applied to several contexts; further details on workflows and tools to produce information models are reported in section 6.4. The initial procedure starts with the validation of the project documentation as well as the strategy related to the InfraBIM process. Then, it is necessary to establish the contents of the models based on their BIM uses: coordination and interference checks; project time simulation; project cost estimation; energy performance analysis; maintenance management etc. Once having defined the scope of the production process the further step concerns the setting of rules for the modelling phase. Rules change on the basis of the scope of modelling and the tools, but some common aspects to consider when writing guidelines are reported in Fig. 29.

Model breakdown

FUNCTIONAL BLOCK TYPE	FACILITY	DISCIPLINE	FACILITY CODE	WBS	Discipline	INFORMATION CONTAINER TYPE	Rev	MODELS
MAJOR FACILITY (BRIDGE)	BRIDGE XXX (L16.5m)	ROADS	P01	PS-01	TRA	MI-01	A	P01-PS-01-TRA-MI-01_A
		STRUCTURES	P01	VI-01	STR	MI-01	A	P01-VI-01-STR-MI-01_A
		HYDRAULICS	P01	OI-01	IDR	MI-01	A	P01-OI-01-IDR-MI-01_A
		MEP SYSTEMS	P01	IM-01	IMP	MI-01	A	P01-IM-01-IMP-MI-01_A
		CONSTRUCTION SITE	P01	CA-01	CAN	MI-01	A	P01-CA-01-CAN-MI-01_A
		EXISTING FACILITIES/SOIL	P01	GE-01	GET	MI-01	A	P01-GE-01-GET-MI-01_A
	BRIDGE YYY (L25m)	ROADS	P02	PS-01	TRA	MI-01	A	P02-PS-01-TRA-MI-01_A
		STRUCTURES	P02	VI-01	STR	MI-01	A	P02-VI-01-STR-MI-01_A
		HYDRAULICS	P02	OI-01	IDR	MI-01	A	P02-OI-01-IDR-MI-01_A
		MEP SYSTEMS	P02	IM-01	IMP	MI-01	A	P02-IM-01-IMP-MI-01_A
		CONSTRUCTION SITE	P02	CA-01	CAN	MI-01	A	P02-CA-01-CAN-MI-01_A
		EXISTING FACILITIES/SOIL	P02	GE-01	GET	MI-01	A	P02-GE-01-GET-MI-01_A

Table 1: Example of a model breakdown

The model breakdown refers to the organization of the single models based on the project breakdown; in this framework the WBS is fundamental for the subdivision into single models. Table 1 shows an example of a model breakdown on the basis of "functional block type", "facility" and "discipline". In this case, the extracted part of the table shows two facilities both belonging to the same functional block type "Major Facility: Bridge". For each facility six main disciplines are defined: Roads, Structures, Hydraulics, MEP Systems, Construction site, Existing facilities/Soil. Each discipline is assigned a facility and a WBS code. The information container type is always the same because they are all information models. The last column shows the six single models in which the major facility is divided, providing the code for the file naming.

Model settings

The model setting phase includes the definition of a set of rules on modelling standards. Some examples of aspects to be regulated are reported below:

- Organization of the user interface for an efficient hierarchy of object visualization;
- Shared coordinates, which are essential for coordination with models from other disciplines;
- Nomenclature of objects, views etc.;
- Visualization rules, using filters to show information as efficiently as possible;
- Data sharing through the use of the CDE;
- Creation of object libraries according to the needs of the specific discipline, customizing objects according to the level of information need;
- Shared parameters to add specific information to components;
- Systems for object classification;
- Graphic standards of the outputs;
- Exportation and mapping rules for open formats.

Modelling

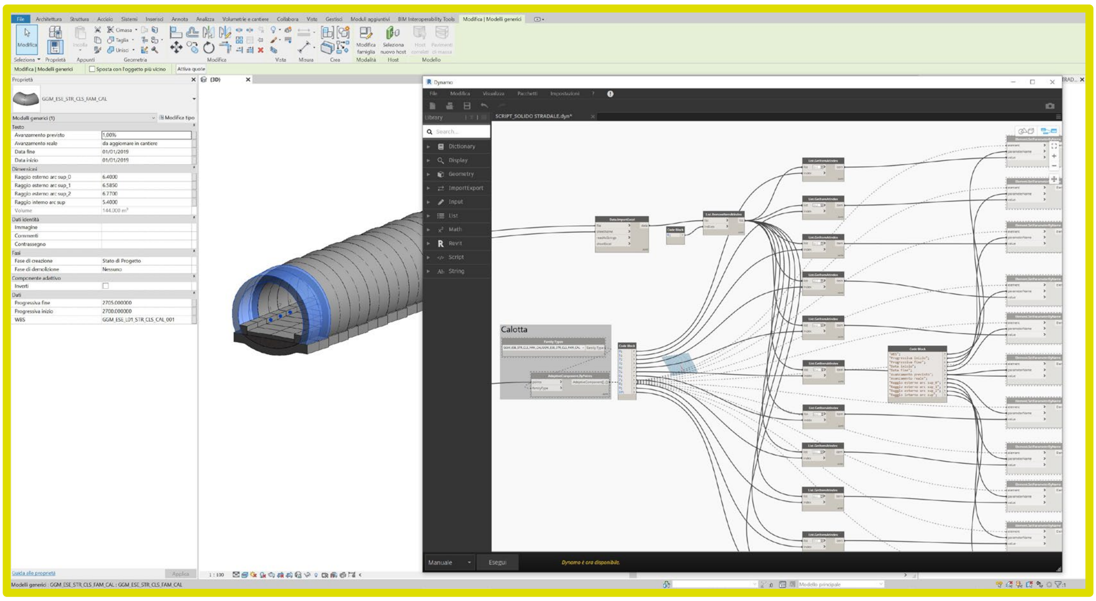


Fig. 30: BIM platform and VPL environment to model galleries

Parametric modelling requires a hierarchical structure of the elements that are often based on each other in the model; for instance, the element "hole" is usually built upon a physical component, such as a wall, slab etc. Each object is referenced and placed in a category characterized by specific properties and features and manages interactions with other elements in the project file. Within the InfraBIM environment, the common BIM platforms lack commands to be efficiently used for all the purposes of the infrastructural design, even if in the last years they are implementing new categories and tools for a more efficient use in that domain. For this reason, VPL is commonly used to overcome the limits of the platforms. An example of a gallery modelled following such an approach is reported in Fig. 30.

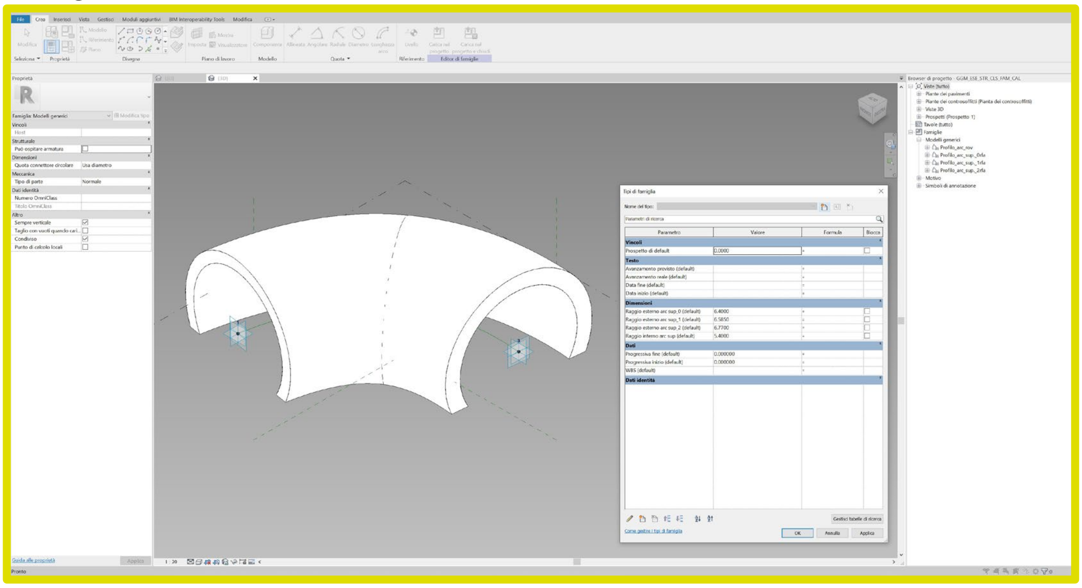


Fig. 31: Adaptive family based on three adaptive points

From one side it is necessary to collect all data related to the alignment, by discretizing it into points, whose coordinates must be reported in an excel file; on the other hand, the components of the gallery are modelled as "adaptive" elements (Fig. 31), which means that they can adapt and be extruded along two or more points. At this point the VPL make the integration and the location of such adaptive components along the previously discretized alignment. In general, some factors that negatively affect the performance of models are the following: complex geometries, multiple parametric relations, multiple constraints, views with complex graphics and linked files make it expensive to process objects. Therefore, analyzing a model and its components and understanding these criticalities allows to optimize its performance. The modelling should avoid all redundant elements that would only increase the heaviness of the file. Therefore, among the main operations there is the reduction of geometric details that will not be visible in the chosen output scale, in order to ensure an overall size of the project file that does not exceed a specific limit, depending on the BIM platform used. Other operations to make the workflow as smooth as possible are the following:

- Minimize the use of joined geometries;
- Avoid extending walls over multiple levels, as this can cause relationships between levels with a significant increase in model update time;
- Avoid storing unnecessary groups and unused objects;

– Limit the visibility of complex elements to fundamental views;

– Limit the creation of parts and assemblies to the necessary elements to avoid overloading the model with unnecessary details;

– Remove unnecessary raster images, as they result in large files and reduce performance.

Output

As previously discussed, the modelling phase have several types of output. The BIM/InfraBIM methodology is based on the fact that the information model is also a database, where information is collected and retrieved as required. Thanks to this connection, the database enables the extraction of views, sheets, different types of formats, schedules that are all connected and represent the updated version of the model.

5.2.4 Coordination and verification

Withing InfraBIM implementation the coordination and validation of the produced information is fundamental and strictly connected to the collaboration processes. This section describes the main levels of coordination and verification analysed and developed during the research activity. In an ideal context, in which the sharing of the project and its data involves all the actors of the process, it is necessary to highlight first the actors involved in the different phases, as well as the

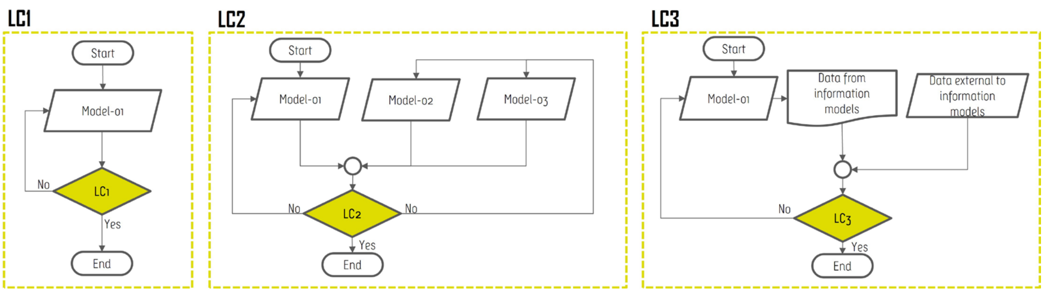


Fig. 32: Coordination levels
Source: Adapted from UNI 11337-5:2017

responsibilities related to them. Therefore, the responsibility and the details on how to organize reports for coordination and verification levels are usually given by the appointing party within the CI and confirmed by the appointed party in the oGI/pGI.

Coordination levels identify the different moments in which the coordination of information models happens, through an iterative process of analysing and solving interferences/inconsistencies inside a single model, between models and between models and external data/information/information content not generated by information models. According to the UNI 11337-5, there are three main coordination levels (UNI 11337-5:2017):

LEVELS	ACTIVITIES	OUTPUT	FOLDER IN CDE
LC1	Analyses on the interferences among objects within a single model and their resolution	**Interferences report LC1:** interferences matrix, interferences list, ways of resolution	Within the sub-folder "5.0 Submissions" under the relative WBS code folder of the macro-work Example: 12_GA_SERVIZIO > 12.9 > 5.0 Submissions > Reports LC1
	Analyses on the inconsistencies among objects within a single model and their resolution	**Inconsistencies report LC1:** parameters presence and accuracy	
LC2	Analyses on the interferences among objects included in several single models and their resolution	**Interferences report LC2:** interferences matrix, interferences list, ways of resolution	Within the sub-folder "25_Coordination and Verification Reports" under the sub-folder "LC2" the folders with the indication of the macro work of the models subject to coordination are contained. Example: 25_Coordination and Verification Reports > LC2 > 13_14
	Analyses on the inconsistencies among objects included in several single models and their resolution	**Inconsistencies report LC2:** parameters presence and accuracy	
LC3	Analyses of interferences between data/information/information content generated by information models and data/information/information content not generated by information models	**Interferences report LC3:** summary sheet of interferences encountered and the explanation of their resolution	Within the sub-folder "25_Coordination and Verification Reports" under the sub-folder "LC3" the folders with the indication of the macro work of the models subject to coordination are contained. Example: 25_Coordination and Verification Reports > LC3 > 13_14
	Analyses of inconsistencies between data/information/information content generated by information models and data/information/information content not generated by information models	**Inconsistencies report LC3:** parameters presence and accuracy	
LV1	Internal, formal verification of the data, information and information content of single and federated models	**Verification report V1:** Completeness of the parameters used with reference to Annex A, correctness of these parameters, compliance with production standards and model delivery times	Within the sub-folder "25_Coordination and Verification Reports" under the sub-folder "V1" the folders with the indication of the macro work of the models subject to coordination are contained. Example: 25_Coordination and Verification Reports > V1 > 13_14
LV2	Internal, substantial verification, meaning a verification that data and information content in single or federated models is legible, traceable and consistent	**Verification report V2:** accuracy of reports produced during the LC1 and LC2 coordination checks, correct compilation of the parameters used with reference to Annex A, information consistency between models and what is extracted from the models, information consistency between the federated model and what is extracted from the federated model, achievement of the level of development (LOD) of the objects, models and their extracted outputs	Within the sub-folder "25_Coordination and Verification Reports" under the sub-folder "LV2" the folders with the indication of the macro work of the models subject to coordination are contained. Example: 25_Coordination and Verification Reports > V2> 13_14
LV3	Independent, formal and substantial verification of the legibility, traceability and consistency of the data and information included in models, outputs, sheets and objects in the CDEs	**Verification report V3:** interferences and inconsistencies of single, federated, elaborated models, etc., the list of detected interferences and how to solve them, the checklist for checking the quality of the models, the complete and correct compilation of the parameters used with reference to Annex A, achievement of the level of development (LOD) of the objects, models and extracted elaborations, correspondence of the matrix of responsibilities	Within the sub-folder "25_Coordination and Verification Reports" under the sub-folder "LV3" the folders with the indication of the macro work of the models subject to coordination are contained. Example: 25_Coordination and Verification Reports > V3 > 13_14

Table 2: Example of a table for coordination and verification levels, activities, reports and related folder in the CDE

- LC1: The first level is oriented to the coordination of data and information within a single information model. It includes analyses on the clashes and inconsistencies among objects within a single model and their resolution;
- LC2: The second level is the coordination of data and information between several single models. This means that also the analyses on the clashes and inconsistencies are performed and solved between elements included in several single models;

- LC3: The third level is defined as the control and resolution of clashes and inconsistencies between data/information/information content generated by information models and data/information/information content not generated by information models.

Furthermore, data, information and information content must be verified through three verification levels:

- LV1: internal, formal verification of the data, information and information content, by checking their compliance with the Appointing party's requirements as reported in the CI;
- LV2: internal, substantial verification, meaning a verification that data and information content in single or federated models is legible, traceable and consistent;
- LV3: independent, formal and substantial verification of the legibility, traceability and consistency of the data and information included in models, outputs, sheets and objects in the CDEs.

Table 2 shows an example of how to organize activities and reports for each level of coordination and verification; in this case it is also indicated the folder of the CDE where that specific report is located.

5.1 Summary of proposed steps for implementation

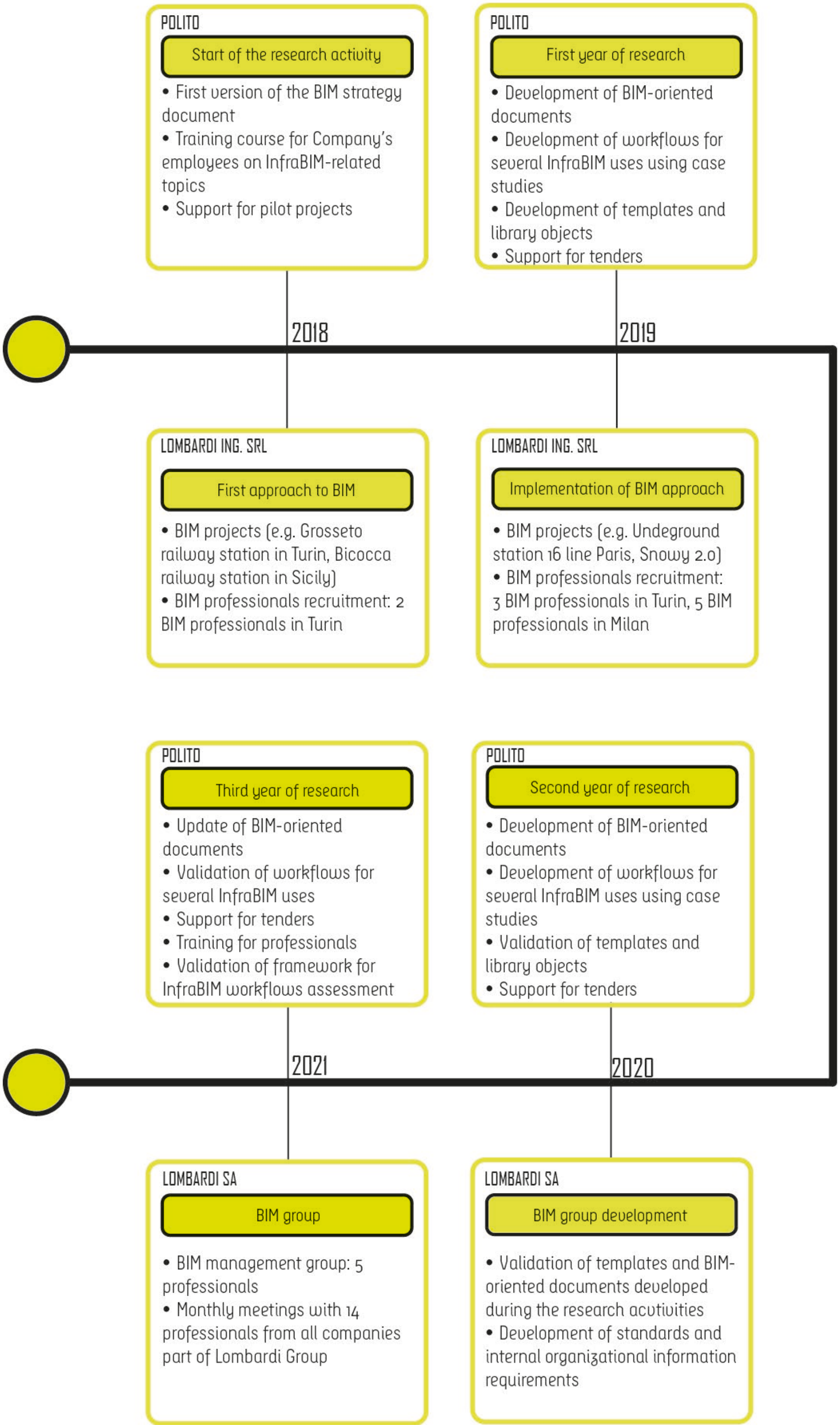


Fig. 33: Timeline of the research activity

The previous sections analysed the different processes considered and studied for the implementation of the InfraBIM methodology within the business procedures. To summarize, the proposed steps for implementation can be grouped under three main categories:

– **Strategy**, in terms of planning how to approach the implementation itself. For this purpose, the first part of the research activity focused on understanding the company and its employees' needs. This phase of analysis was fundamental for the customization of the subsequent production of InfraBIM oriented documentation. Fig. 33 shows the main activities carried out thought the whole research, also integrating the progress made by the company over the three years.

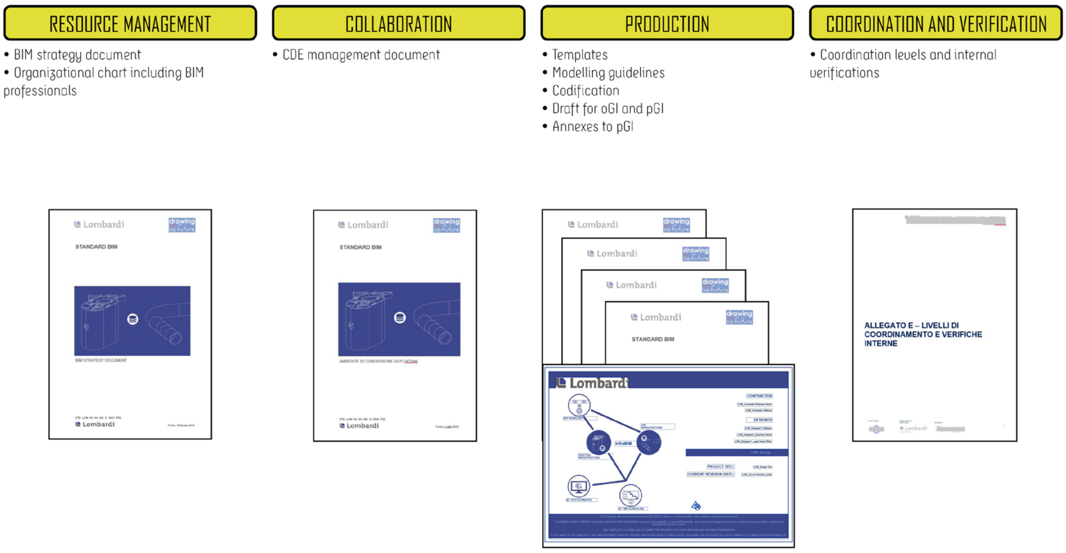


Fig. 34: Documents

– **Documentation**, which refers to the production of specific documents useful as guidelines for activities and processes. Fig. 34 reports some

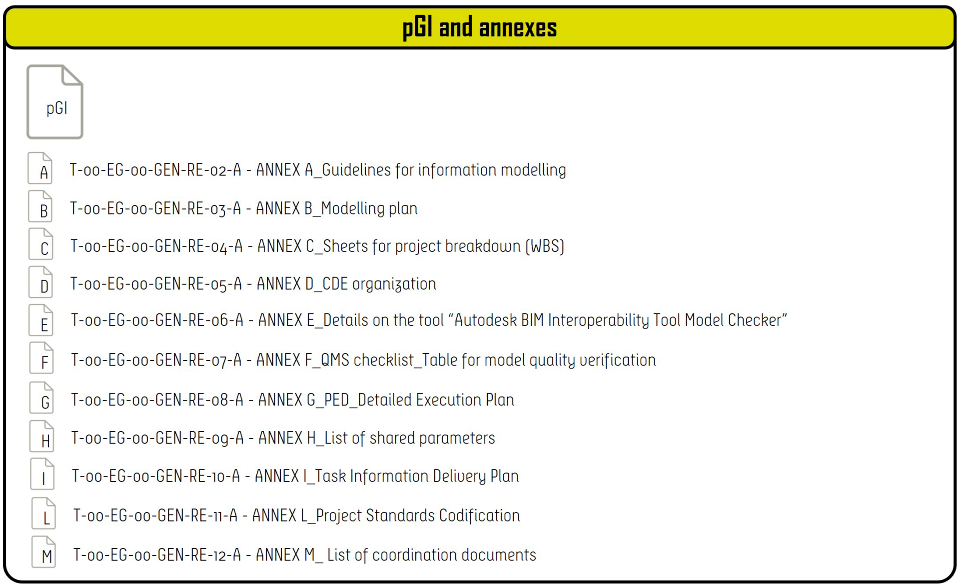


Fig. 35: Example of pGI and its annexes

examples of such documents; some of them are exclusively for internal use within the company, others are drafts for the production of specific documents to be delivered during a call for tender, such as the pGI. An example on how to organize a pGI is shown in Fig. 35. It includes not only the document itself, but also several annexes useful to better detail specific sections of the pGI.

- **Training,** which results fundamental to guide professionals to the transition from CAD based processes to InfraBIM. Training has taken on a variety of forms during the research activity: (i) presentations on specific topics; (ii) webinars for update on new regulations in the BIM environment; (iii) direct consulting on activities/workflows.

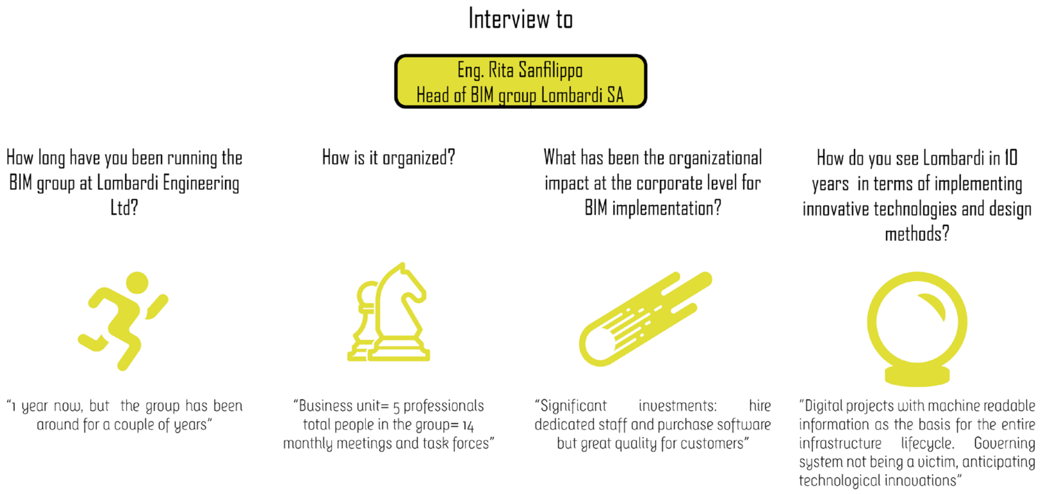


Fig. 36: Summary of the interview

To conclude, in order to get feedback on the overall implementation that the company has undertaken, not only at the level of Lombardi Ingegneria but also considering the developments of the Lombardi Group, the Head of BIM Team of Lombardy Group, Eng. Rita Sanfilippo, was interviewed. Eng. Rita Sanfilippo is a civil geotechnical engineer with sixteen years of experience in the design of galleries and geotechnical infrastructures. She attended the BIM Manager Master of Politecnico di Milano; from that moment onwards, she started her career in BIM working as BIM Manager and business development Manager. She is the Head of BIM Team since March 2020, when the BIM team of Lombardy Group was established.

How is it organised and what are the core objectives of the BIM Team?

The BIM Team consists of fourteen people located in the different Lombardi companies around the world; each of them is specialized in a specific discipline. The operative unit is made up of five people in the Head Quarter in Giubiasco (TI), Switzerland. The core objective of the team is to develop standards at company level and train people both within the team and to spread knowledge among all the professionals. The BIM Team was constituted about two years ago, but in the last year and a half it achieved its highest development. The team meets about once a month, and it is divided into task forces oriented to specific topics within the BIM *environment. Furthermore, several professional training courses are organized to support the team in their activities.*

In which contexts does Lombardi SA work most in BIM?

Lombardi SA works both at national, having national customers such as the managers of Swiss infrastructures, but also international level, because its several companies all over the world. Currently, the international project Snowy 2.0 in Australia is involving several Lombardi companies, who are showing a good level of BIM maturity.

What was the organizational impact at company level for the implementation of BIM?

The investment was significant. The Board of Directors saw opportunity to introduce this method, even if in some countries is not compulsory yet, but benefits are evident. It was diffused the awareness that is not just a question of tools and software, but a design method to be understood and developed over time throughout the Group. The introduction of such a disruptive method requires investment but produces great quality for the customers.

How do you see Lombardi in 10 years in terms of implementing innovative design technologies and methods?

Nowadays, we are experiencing a faster change than those in the past, because of the rapidity and quantity of innovation technologies. The basics to build on are mainly two: a strong know-how and digital innovation for the development of future applications in ten years' time. Currently, attention should be paid to: IA, machine readable data and IoT. As a company digitalization will be a tool to be managed to offer customers the opportunity to provide a digital project with machine readable information as a basis for facility and asset management. What should pass is the opportunity to lead and not to be a victim of the system, but to anticipate the technological innovations to achieve a higher optimization of the process.

Chapter 6

InfraBIM workflows development and assessment

After having discussed the results of InfraBIM implementation methods within company processes, the focus of the research is now on the **development** and subsequently the **assessment** of **InfraBIM workflows** for specific applications. Such workflows have been developed and applied to the case studies previously described. The results obtained through the "interoperability tests" performed during the research helped in the decision process of what tools and strategies to implement in order to achieve the best outputs.

6.1 The concept of workflow

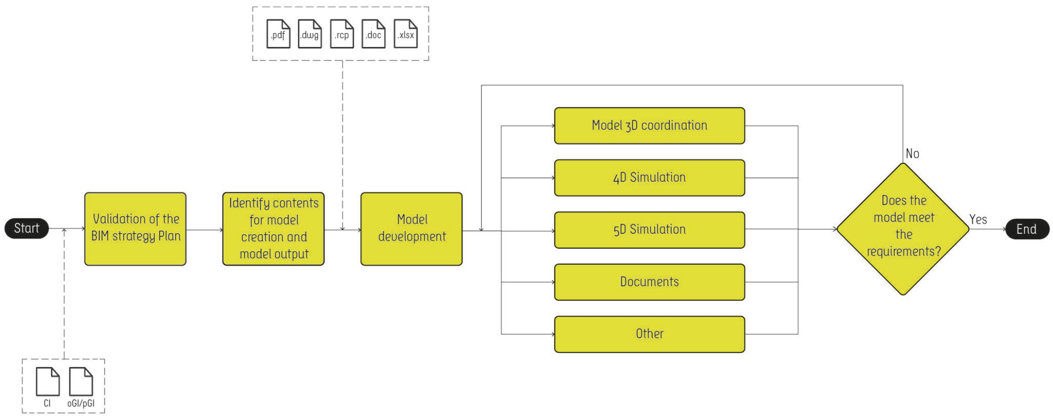


Fig. 37: Example of a workflow framework

The concept of "workflow" is of paramount importance for the aim of the thesis, because it is necessary to identify the different steps to perform and ensure interoperability both among software platforms and professionals. The term was conceived independently from the BIM methodology, but within this environment it acquired a specific meaning, offering a solution for the organization of the work, including the integration among different tools and the management of heterogeneous file formats and sources of information. The Cambridge Dictionary describes a workflow as "the way that a particular type of work is organized or the order of the stages in a particular work process" (Cambridge Dictionary, 2020), highlighting the breakdown of processes into several stages useful to deal with one issue at a time. This definition is confirmed by the Merriam-Webster Dictionary, where workflow is referred to as "the sequence of steps involved in moving from the beginning to the end of a working process" (Merriam-Webster Dictionary, 2020). In this definition the focus is on the time of process, while less attention is paid to the organization and hierarchy of the working process. On the other side, the definition given by Benjamin Brendall takes into account another important factor determining the meaning of workflow and therefore the people involved within processes. From his point of view "workflows are the way people get work done and can be illustrated as series of steps that need to be completed sequentially in a diagram or checklist" (Brandall, 2018). Within this definition another fundamental aspect is represented by the use of diagrams or frameworks to explain and put into practice the sequence of steps within a workflow to achieve a specific result (Fig. 37). Finally, the BIM Handbook defines the workflow as "the sequences of task-related communication among people -normally the project team- to accomplish sequences of tasks and the needed data flows to support those sequences" (Sacks, Eastman, Lee, & Teicholz, 2018), integrating all the concepts present within the previous definition. The use of workflows diagrams within BIM processes has greatly simplified the description and comprehension of the different activities to be carried out, to the point that the use of such diagrams has been implemented within Common Data Environment (CDE) platforms. Indeed, commercial CDE often gives the chance to create virtual gates for information containers within folders by saving an "approval workflow" that has to be performed in order to analyse and approve the transit of such information container from one area to the other of CDE. In this framework, it is useful to explain the concept of "interoperability test", which expresses the necessity to verify that two systems guarantee the possibility to "operate" among each other ed eventually the bidirectionality of data exchange. The scope of such tests is to verify that the interchange among platforms and tools is complete, highlighting any critical issues that, without an iterative process of control and validation, could lead to unreliable and incorrect operations. In addition, these tests allow us to become familiar with the tools, in order to avoid as much as possible errors dictated by weak experience; the objective to be set, especially initially, is not the complete passage of data but to avoid the uncontrolled loss of such data. This procedure is very useful to confirm the truth of what has been stated in the literature and, if necessary, to contribute to the state of the art. When carrying out interoperability tests, it is possible to define and follow a "network" of associations and links existing between the different platforms and tools; the evaluation of these operations can take place on the basis of KPIs (Key Performance Indicators), i.e. parameters defined and characterized by different "weights" according to the priority level assigned. This process can lead to an objective evaluation of **which strategy is the most effective** according to the requirements explained in the definition of KPIs.

6.2 A framework for workflows assessment

The idea of defining a framework of assessment including a benchmark and comparison of workflows derived from the fact that during the research activity several BIM users expressed the **need to assess the most efficient workflow** to

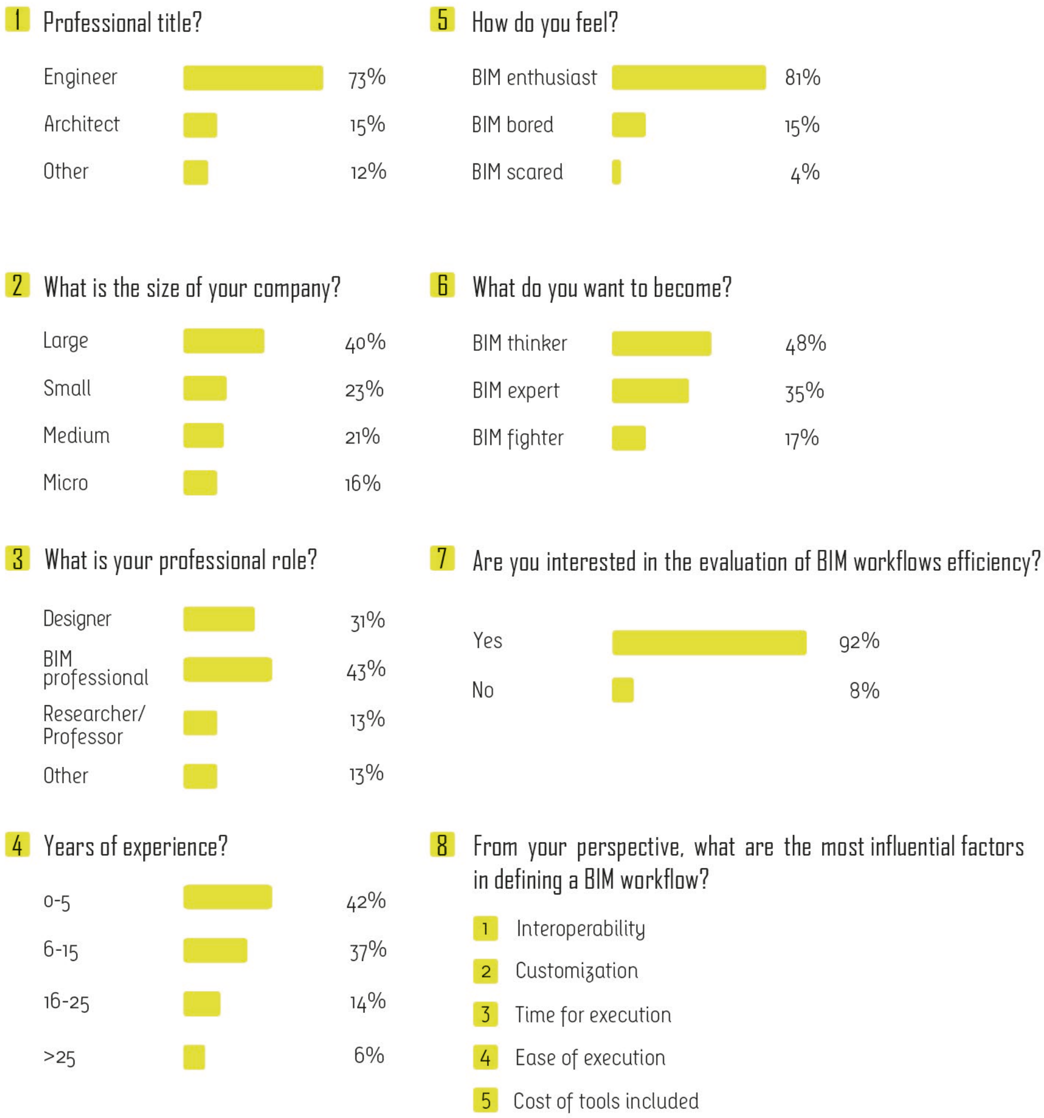


Fig. 38: Results form the survey

achieve specific **BIM uses**. However, such needs differed from user to user, mainly in relation to the size of their company and their role within it. For this reason, in order to better understand the real needs of different kind of BIM users a campaign was conducted to test the need for different professionals to evaluate a BIM workflow that includes different methods and tools. In general, it is evident that large companies are more digitized than SMEs thanks to their economic resources and human capital. This does not mean that SMEs cannot stay abrest of times in terms of digital transformation, but the way technologies are implemented is charaterized by different investments. Indeed, questionnaires were submitted, and users were asked, in addition to some basic information, if they were interested in assessing the efficiency of BIM workflows by comparing them and which factors, from their point of view, had the greatest impact on the actual choice of one workflow over another.

The campaign was conducted among engineers and architects currently working in Italian companies developing infrastructural projects where BIM methods and tools are already implemented and used in daily practice. Indeed, in this case it was of paramount importance to consider people having already some knowledge on BIM, because they are aware of strengths and difficulties towards the implementation of BIM processes. The output of the campaign is summarized in Fig. 38; it included 48 answers of which 73% given by engineers, 15% by architects and 12% by professionals with another qualification. The survey revealed that 40% of people works in a large company (> 250 Staff headcount and Turnover > € 50 millions), 21% works in a medium company (≤ 250 Staff headcount and Turnover ≤ € 50 millions); 23% works in a small company and 16% works in a micro enterprise. An interesting output is related to roles of people who answered the survey in their companies; indeed the 43% of answers shows the BIM acronym in the description of the role such as BIM manager, BIM coordinator, BIM expert, BIM specialist etc. highlighting different possible professional figures strictly related to the BIM environment. This specification for the title is greatly link to the professional figures characterized by BIM-related competencies and knowledges developed during time, but is it true that those people are only dedicated to BIM processes? Are those new competences required to work within BIM processes replacing the skills acquired by architects and engineers during their degree programs? Of course, the answer is no, but then why should we use a different professional role? The truth in this case is in between, because from one side such figures are joined by traditional roles to support them towards this transition, on the other side, the risk is to over-sectorialize activities, separating those who design from those who represent and model what is designed. To the question "How do you feel?" with the possible answers "BIM enthusiast", "BIM bored" and "BIM scared", 81% answered the first one option, 15% the second one and 4% the third one, showing the great interest towards the BIM environment. In terms of future development, to the question "What do you want to become?" the possible answers were the following: "BIM thinker", "BIM expert", "BIM fighter"; 48% answered BIM thinker, 35% BIM expert and 17% BIM fighter. Both questions, obviously in an ironic form, aimed at giving motivations for the following part of the survey. The core of the survey is represented by the seventh question, which regarded the possibility to evaluate the efficiency of a BIM workflow; the 92% of people answered yes to the question "Are you interested in the evaluation of BIM workflows efficiency?". The result confirmed the necessity of BIM users to establish a method to compare several different methods and tools among each other. Furthermore, among the most influential factors for evaluating a BIM workflow the first one resulted to be the "Interoperability among the software included", the second the "Possibility to customize the workflow", the third was related to the "Time to perform the workflow", the fourth "Easy to use software included in the workflow" and at the end "Cost of software included in the workflow". This survey helped in the definition of the criteria to be used in the assessment and in the assignment of the weights for each criterion. The interoperability tests performed on the workflows presented in section 6.3 managed to create a database of values of performance towards the BIM use selected. Therefore, at this stage of the research, it is possible to select some of the previously described workflows to be compared to each other within the same BIM uses. In this case, the metrics used for the assessment are represented by Key Performance Indicators (KPIs) evaluated during the interoperability tests previously performed. The selection and use of metrics are strictly related to the research activities developed along the three years of PhD, the same applies to the values of the assessment included within this Chapter.

6.2.1 KPIs and MCDA

METHOD	ADVANTAGES	DISADVANTAGES	AREAS OF APPLICATION
Multi-Attribute Utility Theory (MAUT)	Takes uncertainty into account; can incorporate preferences	Needs a lot of input; preferences need to be precise	Economics, finance, actuarial, water management, energy management, agriculture
Analytic Hierarchy Process (AHP)	Easy to use; scalable; hierarchy structure can easily adjust to fit many sized problems; not data intensive	Problems due to interdependence between criteria and alternatives; can lead to inconsistencies between judgment and ranking criteria; rank reversal.	Performance-type problems, resource management, corporate policy and strategy, public policy, political strategy, and planning
Case-Based Reasoning (CBR)	Not data intensive; requires little maintenance; can improve over time; can adapt to changes in environment.	Sensitive to inconsistent data; requires many cases.	Businesses, vehicle insurance, medicine, and engineering design.
Data Envelopment Analysis (DEA)	Capable of handling multiple inputs and outputs; efficiency can be analyzed and quantified	Does not deal with imprecise data; assumes that all input and output are exactly known.	Economics, medicine, utilities, road safety, agriculture, retail, and business problems
Fuzzy Set Theory	Allows for imprecise input; takes into account insufficient information.	Difficult to develop; can require numerous simulations before use.	Engineering, economics, environmental, social, medical, and management.
Simple Multi-Attribute Rating Technique (SMART)	Simple; allows for any type of weight assignment technique; less effort by decision makers.	Procedure may not be convenient considering the framework.	Environmental, construction, transportation and logistics, military, manufacturing and assembly problems
Goal Programming (GP)	Capable of handling large-scale problems; can produce infinite alternatives.	It's ability to weight coefficients; typically needs to be used in combination with other MCDM methods to weight coefficients.	Production planning, scheduling, health care, portfolio selection, distribution systems, energy planning, water reservoir management, scheduling, wildlife management.
ELECTRE	Takes uncertainty and vagueness into account.	Its process and outcome can be difficult to explain in layman's terms; outranking causes the strengths and weaknesses of the alternatives to not be directly identified.	Energy, economics, environmental, water management, and transportation problems.
PROMETHEE	Easy to use; does not require assumption that criteria are proportionate.	Does not provide a clear method by which to assign weights.	Environmental, hydrology, water management, business and finance, chemistry, logistics and transportation, manufacturing and assembly, energy, agriculture.
Simple Additive Weighting (SAW)	Ability to compensate among criteria; intuitive to decision makers; calculation is simple does not require complex computer programs.	Estimates revealed do not always reflect the real situation; result obtained may not be logical.	Water management, business, and financial management.
Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS)	Has a simple process; easy to use and program; the number of steps remains the same regardless of the number of attributes.	Its use of Euclidean Distance does not consider the correlation of attributes; difficult to weight and keep consistency of judgment.	Supply chain management and logistics, engineering, manufacturing systems, business and marketing, environmental, human resources, and water resources management.

Fig. 39: Summary of main MCDA methods
Source: Adapted from Velasquez & Hester (2013)

Key Performance Indicators (KPIs) have been broadly used in several fields of application as metrics for assessments: "An indicator provides information on the state or conditions of a phenomenon; it is a simplified way to explain a complex concept (Astleithner, Hamedinger, Holman, & Rydin, 2004)". Furthermore, indicators are divided into quantitative and qualitative ones. Quantitative indicators give numeric information on a specific topic and are calculated from metered data; on the other hand, qualitative indicators are used to measure aspects related to user behavior and social issues, so they cannot be estimated in quantitative terms but are important to assess the benefits related to the development they are used for

(Fonsati, 2021). Indicators are widely used as metrics of evaluation within the Multi-Criteria Decision Analysis (MCDA) methods. MCDA represent a set of assessment approaches for decision-making in complex contexts to make a comparative assessment of alternatives (Watróbski, Jankowski, Ziemba, Karczmarczyk, & Zioło, 2019). Several methods are available, as shown in Fig. 39; each one is characterized by advantages and disadvantages and used for specific areas of application. Therefore, such assessment methods usually produce operational advice or recommendations for future activities, so, for instance, they lend themselves well to their application within smart cities context (Fonsati, 2021). Furthermore, the approaches present differences also in terms of the results that could be obtained. For instances, some approaches have as a result a ranking of alternatives, from the most to the least preferred ones, such as the AHP or PROMETHEE methods, or give the final choice, excluding all the other alternatives. The quality of the assessment depends on many factors: (i) the quality of the information available; (ii) the indicators chosen, as representation of the reality used and the interests taken into account; (iii) the direction of each indicator, in terms of deciding if maximizing o minimizing the indicator itself on the basis of its positive or negative effect; (iv) the relative importance of the chosen indicators, indicated by the weighting factor attached; (v) the ranking method used (Munda, 2005).

Indicator	Description	Measurement method	Unit of measure
N. formats for import/export	The total number of possible file formats for import plus the total number of possible file formats for export	Quantitative	[N]
Information content share	Information content share, as the percentage of information preserved through interoperability	Qualitative	[%]
Customization share	Percentage of customization of the selected workflow according to specific user's needs	Qualitative	[%]
Time for workflow execution	Time spent to carry the whole workflow out	Quantitative	[min]
User-friendliness share	How easy it is to carry out the workflow	Qualitative	[%]
Overall cost of workflow	Total cost of software included in the workflow	Quantitative	[€]

Table 3: KPIs used for the assessment

As previously enounced, the KPIs used were selected on the basis of the answers to the survey presented in section 6.2. Due to the fact that KPIs to assess the efficiency of workflows in InfraBIM environment represent a novelty, the author introduced and develop specific indicators for the evaluation, providing for each KPI its description, measurement method and unit of measure, as reported in Table 3. The selection of indicators had the scope to define easy-to-measure metrics, so that the assessment could be easily applied autonomously by any interested BIM user. The values of indicators result from the author's subjective experience on workflows because the values are estimated through the interoperability tests performed on the case studies for the different workflows. However, the strength of the assessment relies on the fact that the framework itself can easily adapt on the basis of the values chosen; this means that changing the value of indicators the result of the assessment could change. The indicators chosen and estimated are the following: (i) Number of formats supported for data import/export, which refers to the total number of file formats allowed for import plus the total of file formats allowed for export; (ii) Information content share, as the percentage of information preserved through interoperability; (iii) Customization share, a percentage of the capability of the selected workflow to be customized according to specific user's needs, for instance, the capacity to produce different views (3D, cross-sections, etc.) or the ability to reach an objective through different methods; (iv) Time for workflow execution, which refers to the time spent to carry the whole process out; (v) User-friendliness share, which refers to the possibility to easily apply the workflow; (vi) Overall cost of workflow, which considers the total cost of software included in the workflow.

6.2.2 AHP and pairwise comparison

The AHP approach was originally developed by Prof. Thomas L. Saaty (1977), in order to deal with complex systems related to making a choice among several alternatives, providing a comparison of the considered options (Saaty,

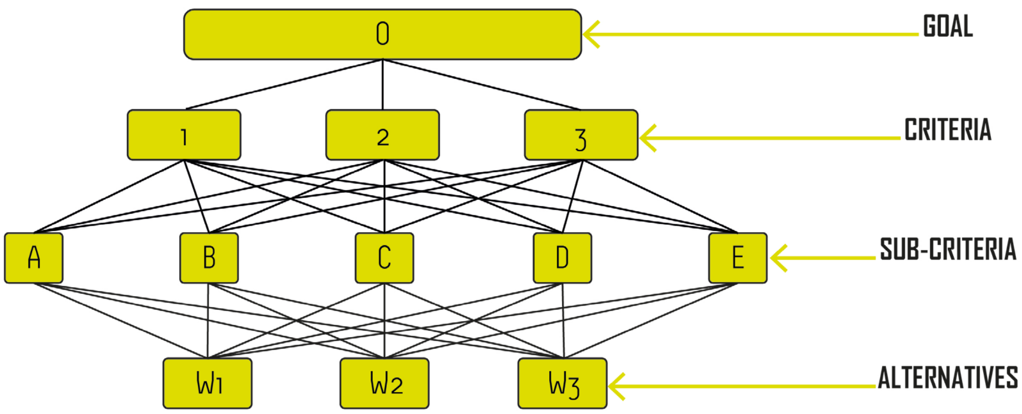


Fig. 40: Breaking down the problem

1980). The analysis is based on four main phases: (i) breakdown of the problem from the top to the bottom, defining a hierarchy with unidirectional hierarchical relationships between levels (Fig. 40); (ii) pairwise comparison in which weights are assigned for each of the criteria to reflect their relative importance to the decision using the "Saaty's Fundamental Scale" is used; (iii) synthesis of judgements to obtain the weights for each decision element; (iv) evaluation and check of consistency of judgements. The Saaty's Scale is a 9-points scale determining the relative importance of an alternative when compared with another one; each numerical value has a definition and an explanation as shown in Table 4.

Value	Definition	Explanation
1	Equally important	Two decision elements equally influence the parent decision element.
3	Moderately more important	One decision element is moderately more influential than the other.
5	Much more important	One decision element has more influence than the other.
7	Very much more important	One decision element has significantly more influence over the other.
9	Extremely more important	The difference between the influences of the two decision elements is extremely significant.
2,4,6,8	Intermediate judgment values	Judgment values between equally, moderately, much, very much, and extremely.

Table 4: Saaty's scale for weighting

Therefore, the assessment of workflows developed within the research activity was performed using the AHP method through the use of the presented in section 6.2.1. The choice fell on this MCDA for the following main reasons: (i) this method is easily applicable, so users interested in evaluating their workflows can easily understand how to perform the assessment; (ii) the method is quite flexible, so it could be adapted on specific needs of evaluation, changing for instance the values of indicators or the weighting of criteria; (iii) the approach is scalable, so it could involve a lot more indicators than those considered in this study (iv) it is particularly adapted to evaluate technology choices, that in this case are fundamental part of the assessment. In this framework, the assessment has been developed as it follows:

- Definition of the **hierarchy structure**, which presented the following key components: (i) **Goal** refers to the assessment of InfraBIM workflows in order to find the most efficient one for the specific field of application (GeoBIM, 4/5D etc.); (ii) **Criteria** are the key factors considered relevant to analyse the efficiency of workflows, on the basis of a campaign of submitted to BIM users through an online questionnaire as explained in section 6.2; (iii) **Sub-Criteria** are the indicators representing the characteristics of each workflow to be compared to the others; (iv) **Alternatives** are represented by the different possible workflows proposed in chapter 6 for each BIM use.

- **Estimation** of the values of indicators for all the workflow alternatives to compare. After that, the indicators have been maximized or minimized depending on their activity towards the overall goal. For instance, "Time" and "Cost" criteria were minimized, because a higher value of such KPIs implies lower efficiency of the workflow alternatives;

- **Pairwise comparison** among alternatives for sub-criteria using the Saaty's scale in order to assign weights to criteria. In general, the point of view adopted for the weighting took into higher consideration the exchange of information, both in terms of geometrical and alphanumerical data, and the possibility to customize the workflows rather than time, user-friendliness and cost. This means that first two criteria were considered more influent over the others in the assignment of weights;

- **Normalization** of the **indicators**; the resulted column-normalized matrix was multiplicated by the Weights column vector to yield the priorities column vector. At this stage, the workflow alternative with the highest score is the "preferred" one.

The assessment has not been performed for all BIM uses, but only for some of them, and specifically those workflows that could have been compared among each other by applying the developed method of evaluation: GeoBIM, structural analysis and 4/5D. However, the **framework** is **replicable**, so the assessment can be implemented for all InfraBIM uses. The calculations of final priorities are included in the Annexes attached to the thesis. However, the alternatives developed for the other areas of application have been compared qualitatively by using the same criteria of the assessment.

6.3 InfraBIM workflows

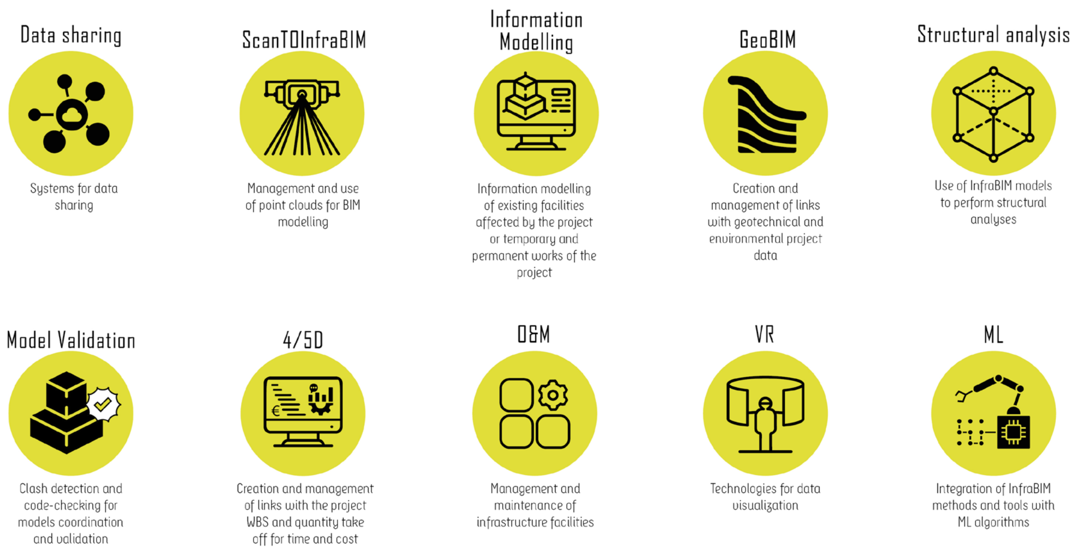


Fig. 41: InfraBIM areas of application selected for the present study

The development of case studies enabled the application of workflows involving specific methods and tools for the selected InfraBIM areas of application (Fig. 41). On the basis of the literature review analysed in Chapter 3 and considered the needs of the company towards the development of workflows the following InfraBIM applications have been identified:

- **Data sharing:** Systems for data sharing;
- **ScanTOinfraBIM**: Management and use of point clouds for three-dimensional modelling;
- **Information modelling:** Information modelling of existing works affected by the project or temporary and permanent works of the project;
- **GeoBIM:** Creation and management of links with geotechnical and environmental project data;
- **Structural:** Interaction with structural analysis tools for structural models validation;
- **Model validation:** Clash detection and code-checking for models coordination and validation;
- **4/5D:** Creation and management of links with the work program, organized according to WBS and quantity take off for connection with cost estimate documents;
- **O&M:** Management and maintenance of infrastructure works;
- **VR:** Technologies for data visualization;
- **ML:** Machine learning to broaden InfraBIM opportunities.

Each use involved the integration among different tools and approaches, each of them aiming at developing a specific result in terms of objectives. The following sections provide details on the development of the workflow alternatives for the different fields of application. Some workflows have been analysed and tested more deeply, for this reason more details are given. As previously enounced, all the results are based on the experience acquired during the research project, which also includes activities developed by students in their Master theses. The final priorities of workflow alternatives reflect the necessity to understand how to optimize production processes in terms of information modelling, giving priority to specific criteria. Therefore, it represents a very subjective result which does not in any way mean that one tool is better than the other, but rather more efficient in achieving a given objective, based on the author's experience.

6.3.1 Data sharing

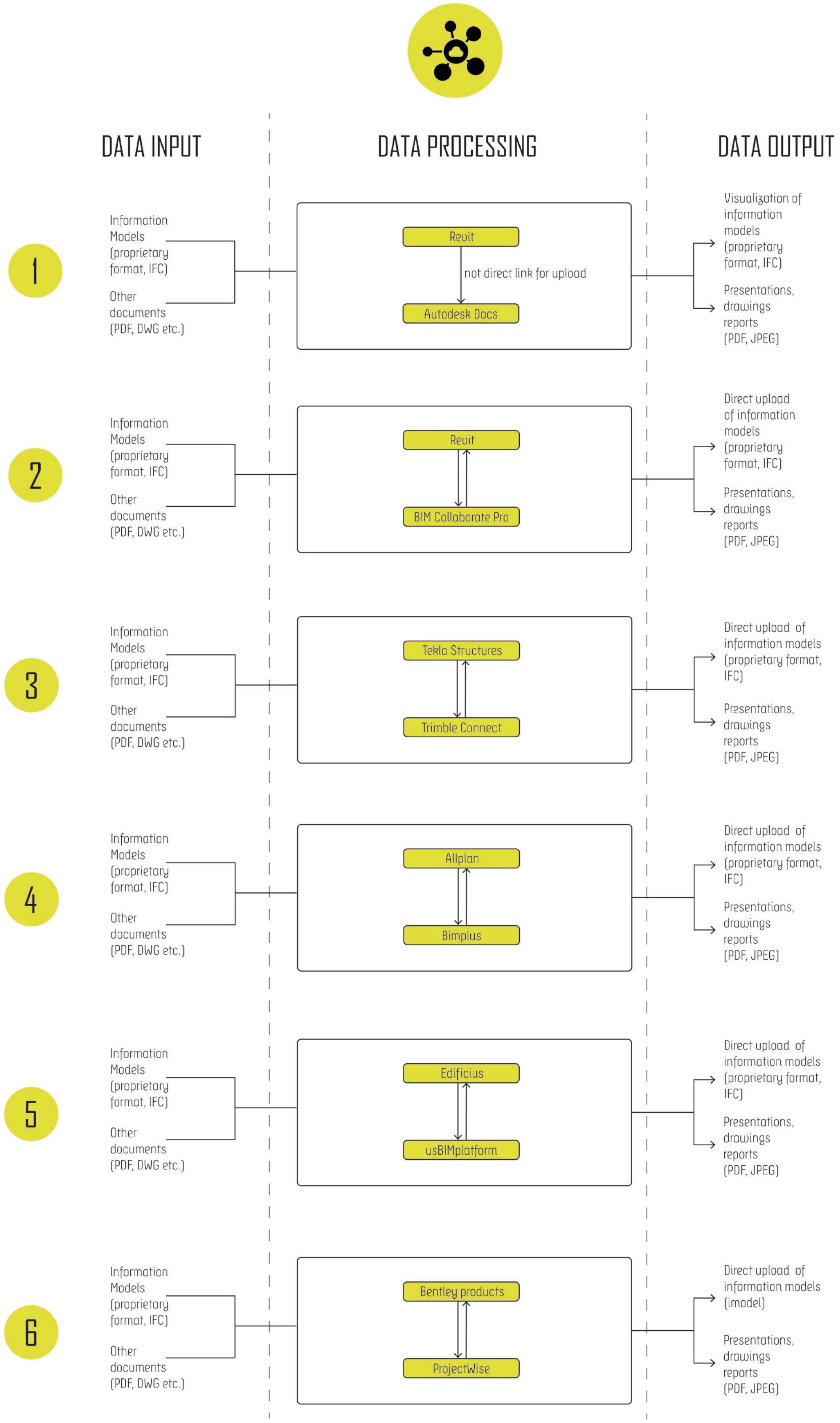


Fig. 42: Possible workflow alternatives for Data sharing

Data sharing is a key concept in InfraBIM methodology. Indeed, within the information modelling environment the data exchange results very important and at the same time challenging because of the possible data losses. In this case, the proper organization of a Common Data Environment is fundamental to guarantee the traceability and accuracy of data exchange. For this reason, six main workflows have been analysed in this study, trying to understand main advantages and disadvantages. In this case the assessment is not performed but the workflows are compared to each other. These workflows include only some of the available CDEs software but represent the most used ones. Indeed, all software houses which owned a BIM platform also produced platforms for CDE, in order to guarantee the best interoperability and information exchange. This resulted into a "forced" approach to use of commercial tools that come from the same software house, to avoid interoperability issues. However, working with tools from the same software house does not always avoid all issues, but it is true the data flow offers more guarantees. In this framework the first two workflows in Fig. 42 present an information exchange between the BIM platform Autodesk Revit and two modules of the commercial platform CDE produced by Autodesk: Autodesk Docs and BIM Collaborate Pro. The former is mainly used to store documents and models, without the possibility to edit the models, while the second one represents the full version of Autodesk collaboration platform, which also works as server to manage and validate submitted models. Both give the chance to define a project folder and to organize sub-folders and permissions to enter the CDE, in order to manage the roles and activities of stakeholders. Autodesk Docs is now included in the Autodesk AEC Collection, so it is not part of the BIM 360 modules for data management anymore. This means that users owning the AEC collection can also use Docs as an ACDoc, where documents are uploaded, visualized and could be the object of issues from users with the permission to do that. This workflow does not involve a real CDE platform, because models are not submitted but uploaded, which means that the automatization of the process is not complete. On the other hand, the second workflow includes the BIM Collaborate Pro platform, which presents a lot of additional functionalities than Docs. Indeed, the platform includes the *Design Collaboration* module which enables the direct upload of "information packages". An information package is a container that allows to be grouped together models, views, tables and supporting documents produced by a team and shared with other teams. This control over data sharing ensures that what is shared is ready to be reviewed by users outside the team in question. Teams that receive the package for approval view its contents and can decide whether to transfer it to their design environment (through the Consume activity) or not. This reduces the interruption of constant change and allows all teams to 'freeze' products in a given version before approval. When information is consumed it means that it is ready to be shared with the other teams and eventually submitted to the appointing party. These operations are controlled using the function *Approval Workflows* which allows document managers to facilitate, control and automate the distribution of documents to project members. Members designated as reviewers can then review and comment on the documents and members designated as approvers can give final approval for the documents to be used. The third workflow concerns the proposal from Trimble software house, Trimble Connect, which is very useful to manage models, even large ones, and to perform checks, leave comments and organize folders in the data environment to collect documents. The CDE is organized under five main sections: (i) *Data*, where models and documents are collected and uploaded using several exchange formats; (ii) *Activity*, where all the activities performed within the platform are registered and displayed; (iii) *ToDo*, which is a tool to launch, manage, review and approve comments and evaluations from other users; (iv) *Team*, which manages the users' invitations to collaborate, permissions etc.; (v) *Settings*, to modify the general settings of the project. Also, in this case it possible to define the possible users' activities on the basis of their role and responsibilities. The fourth workflow includes the use of BIMPLUS in integration with Allplan BIM-platform. BIMPLUS, as the previous ones, is an online dashboard organized in four main sections: (i) *Projects*, where all users' projects are stored; (ii) *Project members* (ii), for the users' permissions management; (iii) *Models*, where models are uploaded; (iv) *Documents*, for the storage of data. BIMPLUS has a direct connection with Allplan, models can be directly saved in one of the folders. The platform also gives the possibility to add modules for the direct import of the RVT (Autodesk Revit project file) file format; using the *BIM Explorer* tool models are visualized, properties of components are accessible, clashes are possible, and it is also possible to import and export the BIM Collaboration Format (BCF) format, to exchange issues and directives on specific components of the models. The fifth workflow includes the usBIMplatfom from the ACCA software house; compared to the previously ones this platform is realized by an Italian software house, therefore it is specifically designed to fulfil the requirements from the D.lgs. 50/2016 and the standards UNI 11337. The whole system is based on the cloud and since 2021 it evolved into an integrated system called usBIM which includes both collaboration tools and interoperability tools. In this case also, the platform is divided into several sections. The *BIM Project*, where the hierarchical structure of folders is included. As in the other platforms, the permission to access to the various folders is determined by the role of the user. This structure also contains a *BIM Share* folder, where information useful to all projects are contained, such as templates, regulations etc. The *Documents* section, where all types of documents and models are stored. Documents could be assigned to a specific status linked to a workflow in order to manage that document following specific steps of its validation and verification, these workflows are very similar to the *Approval Workflows* of the BIM Collaborate Pro. Another interesting functionality is represented by the *#TagBIM*, which is useful for an advanced search among documents. Indeed, it assigns one or more tags with structured alphanumeric strings to documents in order to be able to retrieve specific information from documents and use these tags as filters for information. The platform was specifically developed to work mainly with IFC opens standard, but it enables the visualization of other file formats such as EDF, RVT, RFA, OBJ, 3DS, DWG, SKP etc. Furthermore, it is also possible to associate documents within the CDE to specific components of the IFC model, using external links and *#TagBIM*. The last workflow involves the use of

ProjectWise developed by Bentley software house, which represents one of the most used commercial platforms within the information modelling of infrastructures, mainly in large companies also because of the big investment to acquire the license. This system is probably the most advanced among the systems taken into consideration; it is divided into ProjectWise Administrator (PWA) and a ProjectWise Explorer (PWE). The former manages: (i) *Users' roles*; (ii) *Approval states*, which represent control points on information (models and documents) for the moving to the next stage of the process; (iii) *Workflows*, which represent a sequence of approval states to which a document has to be submitted; (iv) *Environment*, which is a container of attributes (parameters) to be associated to the generic project file; information is linked to the document and can be queried via the graphical interface in the properties. On the other side, the Explorer is similar to a Microsoft resource explorer, but the graphic interface also includes a list of documents and a preview panel for models. Another characteristic is presented by the introduction of the i-model concept, which enables the opening of models coming from several applications in different file formats together, for a fast and easy coordination of information contents and visualization of properties.

Alternatives	Interoperability	Customization	User-friendliness	Cost
1	It is possible to import several different file formats, but only RVT files can be visualized in the viewer	It is not possible to customize the workflow, only in terms of the organization of the CDE	100%	Included in the AEC Collection
2	It is possible to connect the BIM platform Revit to save the models directly within BIM Collaborate Pro	It is not possible to customize the workflow, only in terms of the organization of the CDE	70%	1250 €/year (not specified n. of users)
3	It is possible to connect the BIM platform Tekla Structures to save the models directly within Trimble Connect	It is not possible to customize the workflow, only in terms of the organization of the CDE	90%	250 $/year/user
4	It is possible to connect the BIM platform Allplan to save the models directly within BIMPLUS	It is not possible to customize the workflow, only in terms of the organization of the CDE	70%	380 $/year/user
5	It is developed to work woth the open standard IFC	It is not possible to customize the workflow, only in terms of the organization of the CDE	80%	120€/year/user
6	It uses the i-model to manage several different activities, such as the federation of models	It is not possible to customize the workflow, only in terms of the organization of the CDE	50%	Very expensive

Table 5: Comparison of alternatives for data sharing

In general, all systems provide a section for administrative purpose, where only administrators, for instance the CDE manager, can enter and where the whole project must be organized in terms of management, functionalities, activities on documents and models, workflows, permissions etc. and an operative section, accessible to all stakeholders with their specific roles. Each application provides all the requirements for data traceability, management and retrieval from regulations and standards. However, each of them present characteristics related to the specific target they are directed to, large companies or small ones etc., implementing functionalities and using different approaches. Table 5 shows a qualitative comparison among the presented platforms, highlighting each of them have weaknesses and strengths.

6.3.2 ScanTOInfraBIM

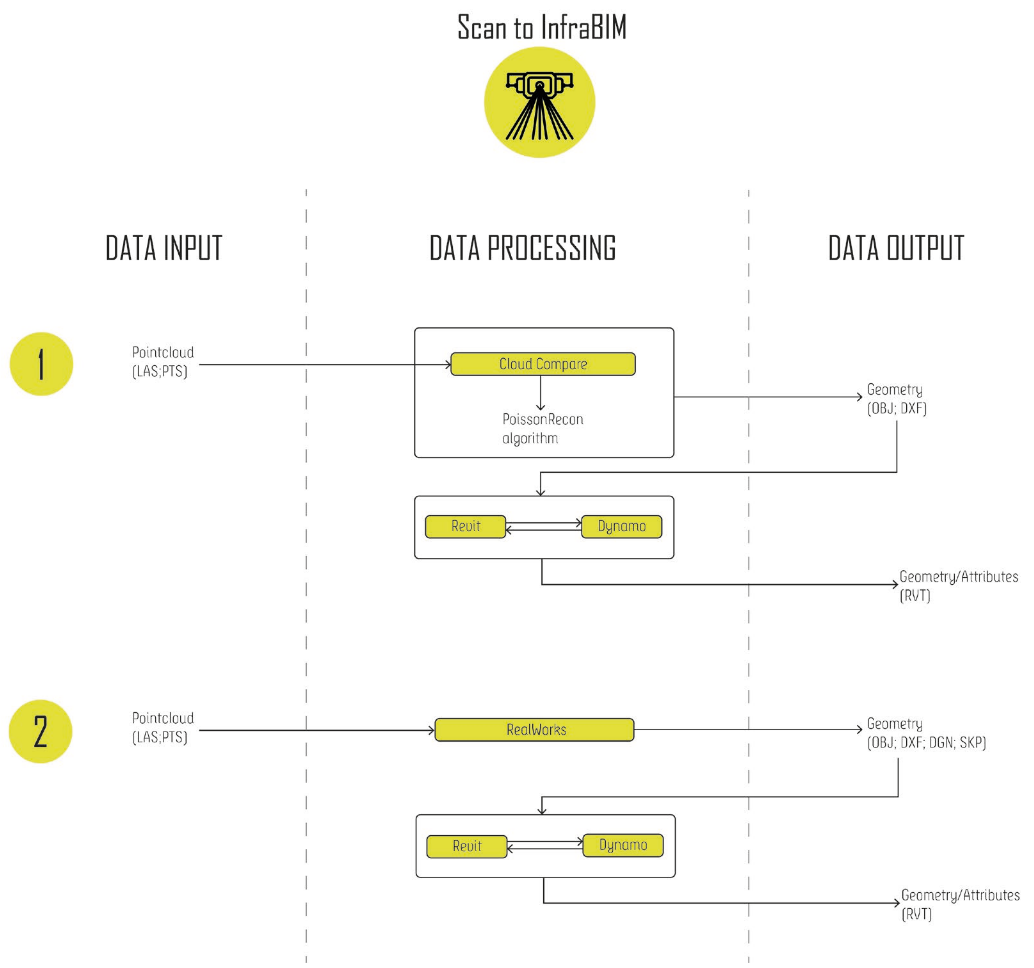


Fig. 43: Possible workflow alternatives for ScanTOInfraBIM

The Scan to InfraBIM techniques have been deeply analysed within the literature, showing several possible approaches towards the use of point clouds for BIM at different design phases, both for new projects and to work on existing infrastructures for maintenance. Within the context of the research, the workflows identified for this specific BIM use had the objective to start from an existing survey performed through laser scanning surveying technique of an existing gallery and develop the meshes to be used as reference for further development in a model-authoring platform. Two workflows have been tested (Fig. 43); the former used the open-source software for point clouds processing Cloud Compare, the latter included the use of the commercial software Trimble RealWorks. The starting point was the same for both workflows, the point cloud used for the elaborations was in standard format LAS, a file format designed for the interchange and archiving of lidar point cloud data. The first workflow involved the use of PoissonRecon algorithm for the creation of the mesh (Fig. 44) and further filtered to reduce the noise reduction and cancel outliers at a distance greater than one meter. After that the mesh can be exported as geometry in OBJ or DXF file format, after having cancelled the leftovers from the mesh creation.

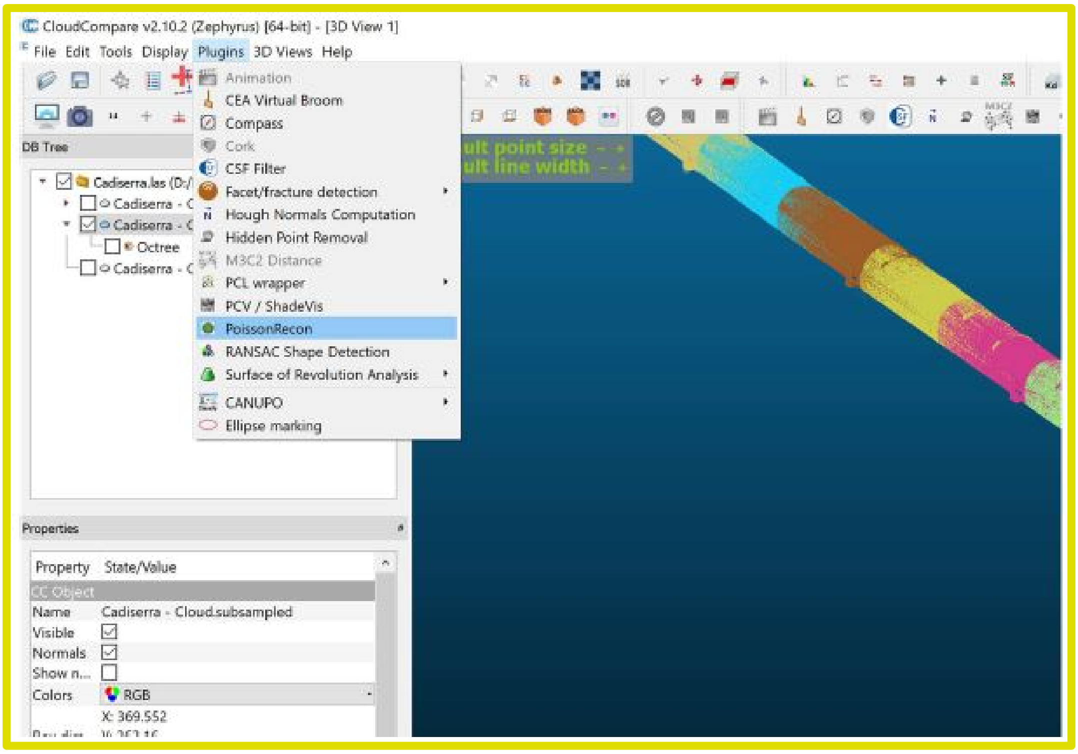


Fig. 44: PoissonRecon algorithm for point cloud processing in CloudCompare

The second workflow instead involved the use of Trimble RealWorks for the creation of the mesh (Fig. 45). Within this workflow firstly the point cloud must be fragmented and then merged in order to define the mesh. Within this phase of "cleaning" activity it is important to eliminate those elements, in this case the MEP systems, that appear in the point cloud but are not useful for the creation of the mesh. After that it is possible to simplify the point cloud by using the "Autoclassification" method, using the "spatial sampling", where the distance among point to consider must be defined. At this stage, it is possible to export the

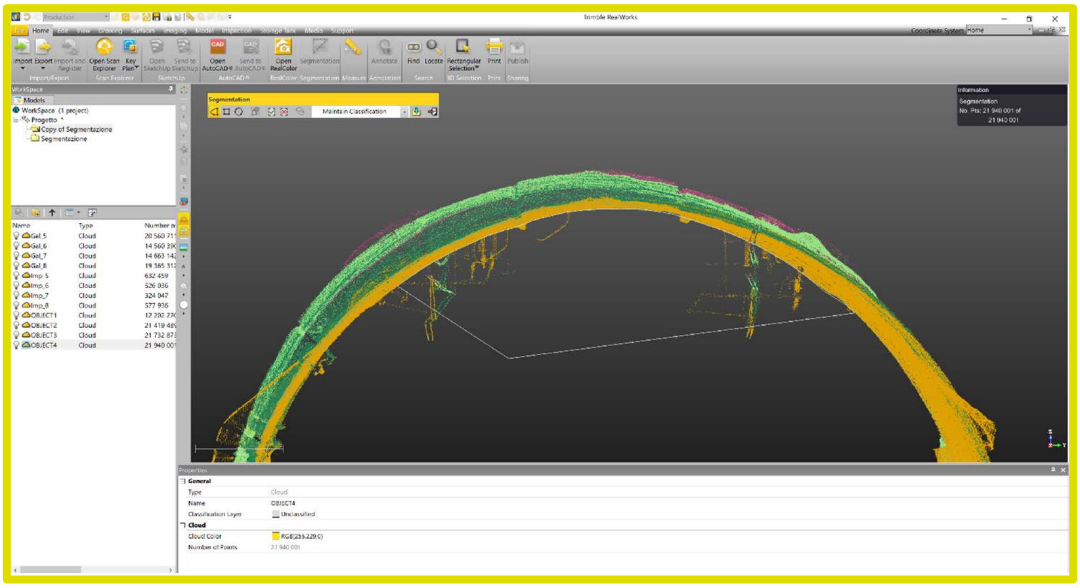


Fig. 45: Point cloud processing in RealWorks

mesh as geometry as in the previous case, using the file format. The second workflow results more accurate in the processing of the point cloud, but a good result is obtained also using the open-source software Cloud Compare. Both workflows merged in the use of the VPL plugin Dynamo from Autodesk to connect and use the mesh for further elaborations within the BIM-authoring platform Autodesk Revit. The workflow included the following steps:

- Export the alignment of the galley into points with their specific coordinates to use as reference in Dynamo, where the alignment is divided in a regular range of about 1 meter;
- Import previously modelled meshes with different points densification degree;
- Divide the meshes using perpendicular planes to the alignment at a regular step;
- Choose which mesh to use for each segment from section to section, on the basis of the degree of approximation for each segment;
- Merge all the meshes to have as a result one mesh with different degrees of approximation;
- If necessary, use adaptive families to re-model the shell where it is necessary to have a greater detailing.

Alternatives	Interoperability	Customization	User-friendliness	Cost
1	The exchange of information in mainly related to geometries	The workflow is highly customizable since Cloud Compare is a free source tool and another BIM platform could be used	40%	Cloud Compare is an open-source software, while Revit and Dynamo are part of the Autodesk AEC Collection
2	The exchange of information in mainly related to geometries	The processing of the point cloud is not customizable because it is linked to the specific functionalities of the software itself	80%	Commercial product by Trimble

Table 6: Comparison of the alternatives for Scan to InfraBIM

Table 6 shows a qualitative comparison between the two workflows on the basis of four main criteria. In terms of interoperability in both cases only the geometry is exchanged. On the other side, differences are highlighted in terms of customization, user-friendliness and cost.

6.3.3 Information Modelling

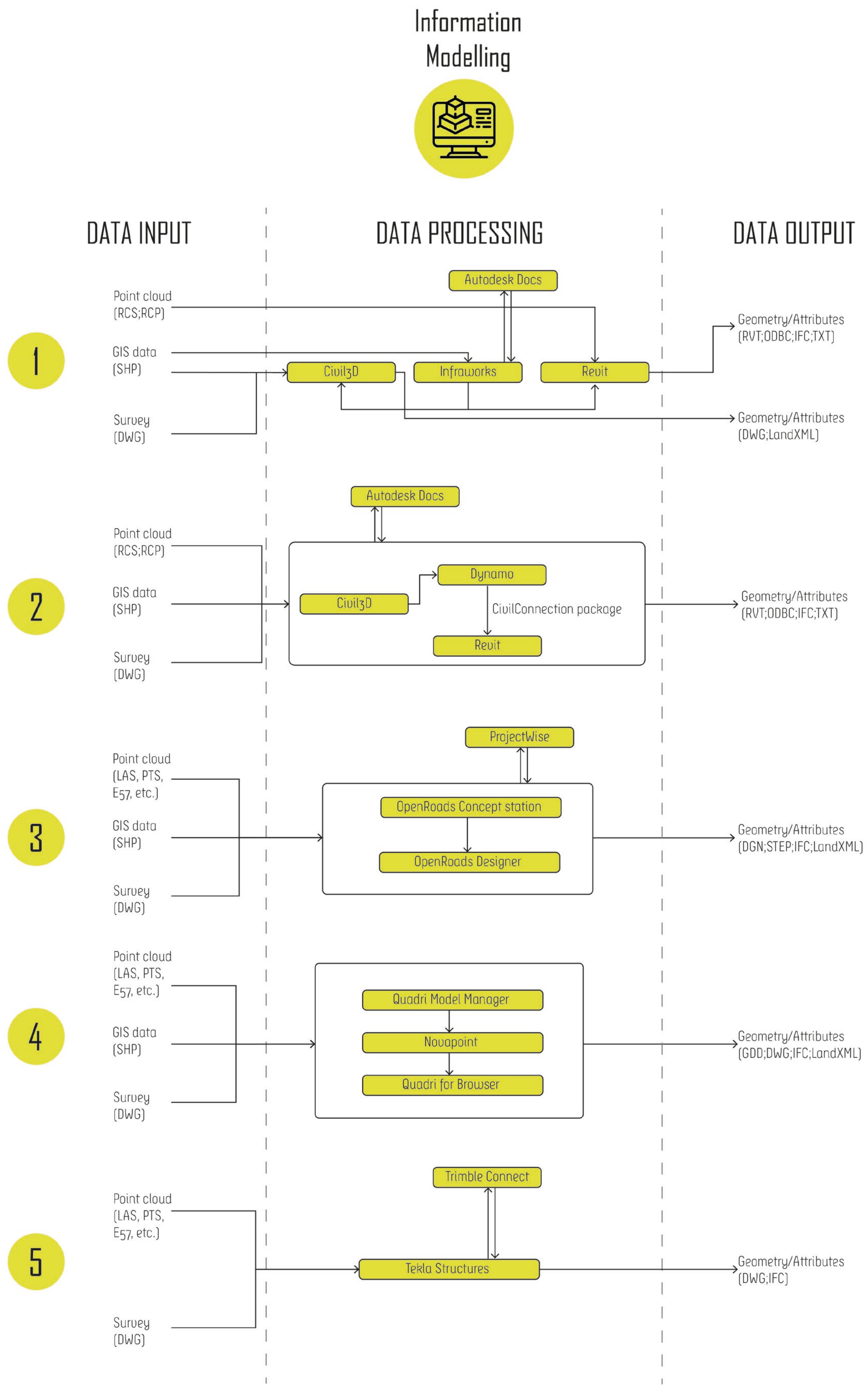


Fig. 46: Possible workflow alternatives for Information Modelling

In terms of modelling infrastructures, several different approaches and related workflows have been developed and applied to case studies within the research activity (Fig. 46). The first workflow is suggested by the software house Autodesk itself, in which the tool Infraworks is used to make the other main tools Civil 3D and Revit communicate with each other. The idea behind such a workflow is that conceptual modelling performed in Infraworks can be further detailed in terms of civil works within Civil3D and in terms of facilities and works of art in Revit by adding components, parameters etc. In this framework, the Autodesk Docs platform for data sharing is used to exchange information among the tools. For instance, the element topography, which is usually created in Civil3D, could be published from Civil3D to Autodesk Docs to the import it into Revit by using the *Desktop Connector* tool.

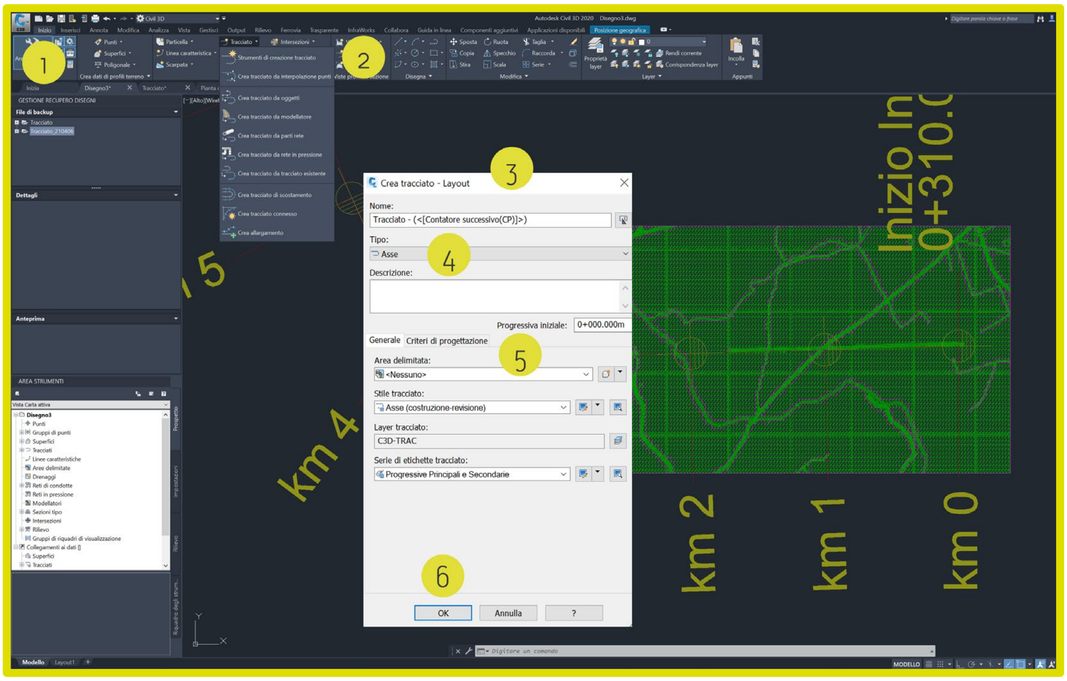


Fig. 47: Alignment definition within Civil 3D

The design process in Civil3D consists of the following main phases:

– Alignment; the alignment is modelled as a sequence of different types of segments (Fig. 47). After the creation of the object "alignment", it is possible to associate properties such as speed of travel useful for the extraction of the speed diagrams rather than setting alarms if the drawn/selected track does not comply with Italian regulations. This function is enabled by the Country Kit Italy plug-in, which is a useful tool for checking road elements in the project geometry definition;

– Altimetric profile; the altimetric profile is modelled on the basis of the alignment previously modelled to determine the horizontal development of the of the specific component (road, railway etc.). In this case, to proceed with the definition of the profile both the alignment and the surface (topography) have to be defined. Indeed, the ground surface profile is used as “guide” to draw the altimetric profile; once having finished the values for all elevations can be changed;

– Assembly/Subassembly; the section of the corridor is defined by using sections from the library of the Country-Kit Italy, called *Assemblies* or customized sections using the *Subassemly Composer* module, included within the installation of Civil3D. The Assemblies, once uploaded, can be used in the modelling of corridors by selecting the desired alignment and profile;

– Corridor; the corridor represent the extrusion of the selected Assembly along the selected alignment and profile on the selected surface. For this reason, the previous elements have to be defined before starting the creation of corridor. After having specified this data, the object properties can be modified through the appropriate menu or through the "Contextual tools" - i.e. a series of tools that allow modifications without having to enter the properties window. In any case altimetric and planimetric constraints can be inserted so that the road actually corresponds to what is foreseen by the survey and the plan. Roads and railways do not have always a constant width so using the properties to assign widening or narrowing constraints is necessary to obtain an accurate model; for this reason, Corridors are easily editable.

	FAMILY	CATEGORY	FAMILY TEMPLATE (RFT)	NOTES
1	Pile footing	Structural foundation	Metric structural foundation	Nested family in «Foundation» family with the option «sharing» active
2	Foundation	Structural foundation	Metric structural foundation	
3	Column	Structural column	Metric structural column	
4	Cap	Structural framing	Metric structural framing	Nested family in «Column» family with the option «sharing» active
5	Beam	Structural framing	Metric structural framing	
6	Abutment	Wall	Structural wall	

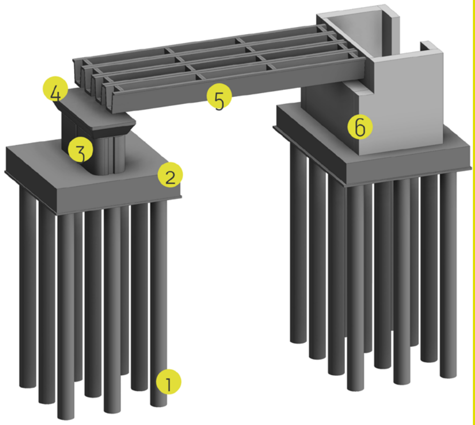


Fig. 48: Bridge components definition using Revit features

On the other hand, Revit is specifically directed to the modelling of infrastructure facilities such as bridges, segments of galleries etc. Here components are modelled through a hierarchical structure (*Categories*, *Families*, *Types* and *Instances*). The use of Revit as a BIM-authoring tool also for infrastructural facilities led the software house to the increase of the number of Revit *Categories*, in Revit 2022 version, adding for example specific categories such as *Piles*, *Abutment*, and *Deck* for bridges modelling. However, components modelled under such categories have limitations in terms of the information that can be retrieved, for instance in terms of quantity-take off, which make the use of such categories difficult to be applied in information modelling workflows. Fig. 48 shows possible adaptation of Revit features for infrastructural components.

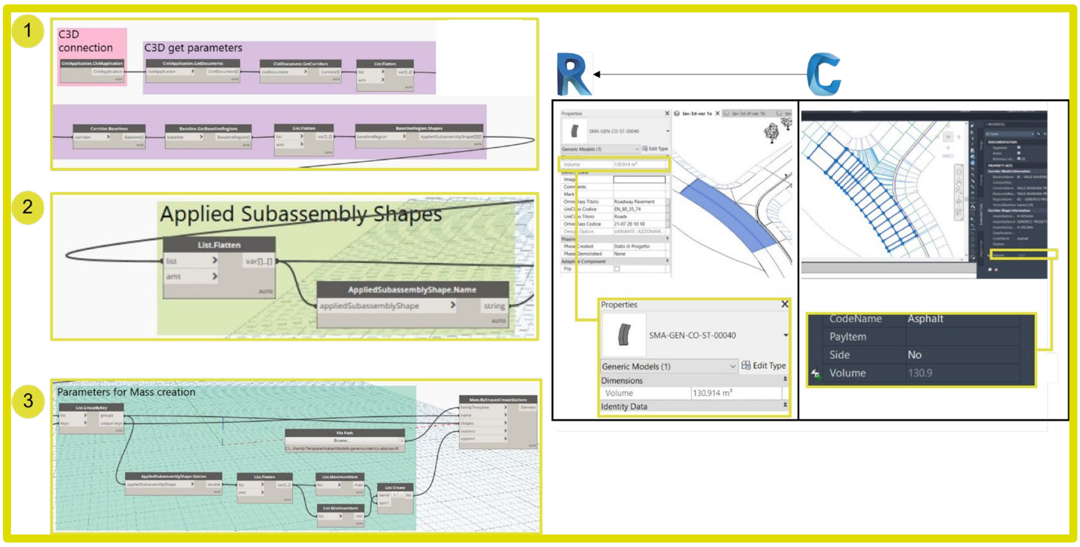


Fig. 49: Civil3D to Revit Dynamo script

The second workflow represents an alternative to what is defined from Autodesk as the preferred workflow for civil works design. In this case the aim was to test the possibility to import the geometries of corridors modelled in Civil3D into the BIM-authoring platform Revit to further proceed with the modelling of other components. This workflow establishes a direct connection between Civil3D and Revit, with the use of Dynamo, that since the 2020 version is also available for Civil 3D. The starting point is the definition of alignment, altimetric profile, assemblies and corridors as previously presented. Once the elements are modelled in Civil3D and the coordinates are acquired through the use of the same ground surface published from Civil3D by using Autodesk Docs, the connection between Civil3D and Revit is established through Dynamo. To enable such an operation the package of add-ons called CivilConnection, provided by Autodesk, was used (Di Lisa, 2020). The Dynamo script (Fig. 49) is divided into blocks consisting of several nodes, each of them performing different functions in the import process from Civil3D to Revit. The first part of the algorithm enables the connection with C3D with the "CivilApplication" node and then extracts all the necessary data to be used as reference in the reconstruction of feature lines and alignments within the Dynamo environment. Despite some modelling inaccuracies due in some cases to small errors in Civil3D and in others to the final node of the script the import result can be considered satisfactory and for further elaboration and visualization.

The third workflow involves the use of Bentley systems. As previously stated, the CDE ProjectWise is included within the workflow, but it was not tested within the research activity because it was not possible to obtain an educational version. The approach of Bentley is different from the Autodesk one because the software house developed different products for each infrastructural disciplines, starting from its basis product Microstation and developing specific tools such as: OpenRails for railways, OpenRoads for roads, OpenBridge for bridges etc.

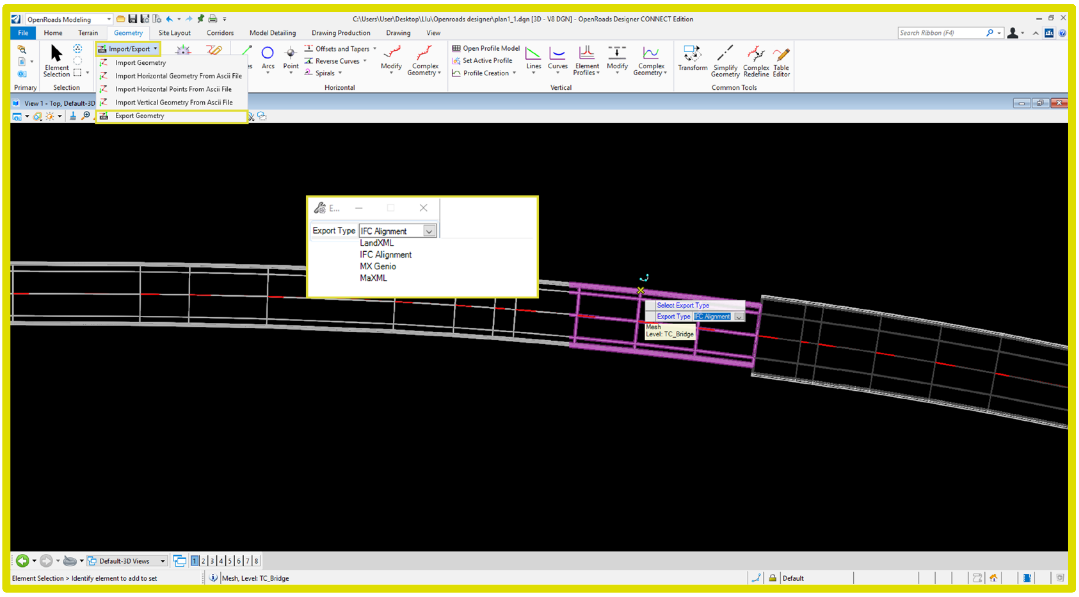


Fig. 50: IFC export from OpenRoads

The workflow presented involved the use of OpenRoads and specifically the two modules OpenRoads ConceptStation and OpenRoads Designer. The former is dedicated to conceptual modelling, Digital Terrain Model (DTM) definition, presenting a very similar approach to Infraworks. It also enables a conceptual modelling using elements called "Templates", which are typological sections extruded along alignments and correspond to the Assemblies of Civil3D. Among the file formats that can be imported there are Terrain files (TIN; DTM etc.), Raster files, Bentley project files (DGN), other supported files, such as OSM, LandXML, SHP etc. The majority of formats is also supported for export; however, the suggested workflow involves the development of the design process within the OpenDesigner module, which represents the version produced by Bentley for Civil3D, in this case specifically used for roads design. The concept of template is paramount within Bentley products because it refers to the drawing of a bidimensional section with the necessary components that is saved and can be later assigned to segments of the alignments. Also in this case, the solid extruded on the basis of the template is called "Corridor", which can be edited subsequently. Among the possibilities, customized attributes can be assigned to objects; in this case such parameters are called Items. In terms of export file data there are five main types of files: (i) open standard IFC (Fig. 50); (ii) common file types, DWG, DGN etc.; (iii) exchange file types, PDF, DAE, FBX, STP etc.; (iv) 3D modeling file types, SAT, OBJ, SKP etc. (v) visualization file types, KML, SVG etc.

The fourth workflow involves the use of Trimble products for civil works and mainly: (i) Quadri Model Manager, which is used to manage server, create models and projects and define project users; (ii) Novapoint, which represents the model-authoring platform for civil works developed by Trimble with the support of Autodesk AutoCAD software; (iii) Quadri for Browser, which is the online platform for an easier management of the project and enables the visualization of project information and updates on the model development. The ideal workflow requires the definition of the project within Quadri Model Manager as first step; the opposite process is also possible anyway, but when several users approach the modelling phase on the same project the best option is to set the environment before starting to model.

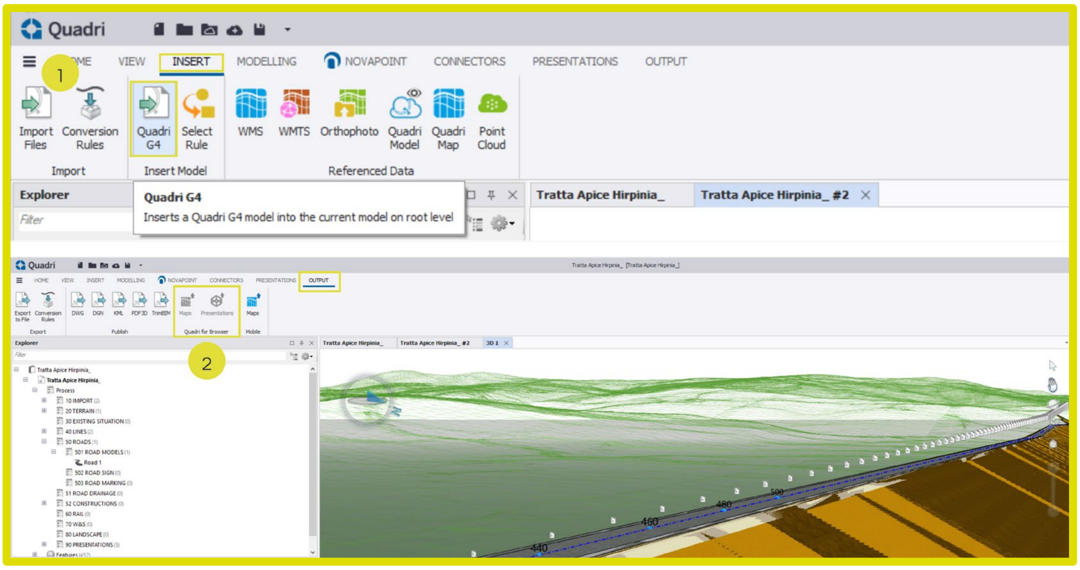


Fig. 51: Publication of the model on Quadri

Once the model is defined, within Novapoint it is possible to sign in the project by using the URL for the connection to the model server; the model can also be uploaded and published on Quadri after the modelling phase (Fig. 51). Within the Quadri and Novapoint environment some main features have to be introduced: (i) *Tasks*, represent an activity that has to be performed to complete the project. When using Quadri Model Manager to manage models tasks are characterized by a specific *status*, which highlights if that task is "owned" by another user, if it can be edited, if it is shared within the server or saved only locally; (ii) *Object*, which represents an object in the project file characterized by specific attributes but that exists in the model without being necessarily linked to a geometry; (iii) *Geometry*, which represents the real object modelled. Another key point in Novapoint is represented by *Conversion rules*, which refer to a set of rules determining how information is converted both in terms of import and export of the model. Such rules are important because they are essential when exporting the model in open standards such as IFC.

The last workflow considers the use of the BIM-authoring platform Tekla Structures, produced by Trimble and specifically developed to model steel and concrete structures, as shown in Fig. 52. In relation to Revit, it is more advanced in detailing and management of heavy, in terms of MB, models but it is only for structures, so it does not implement the possibility to model architectural and MEP components. It enables the import of drawing files and point clouds by using the tool *Reference Models*. When adding models or drawings with external references it is of paramount importance to check that the coordinate system of *Base Point* in Tekla is coherent with the coordinate system or the reference model added. One of the most important features in Tekla are *Grids*, which represent the "skeleton" of the model itself defining the position both in plan and elevation of structural components.

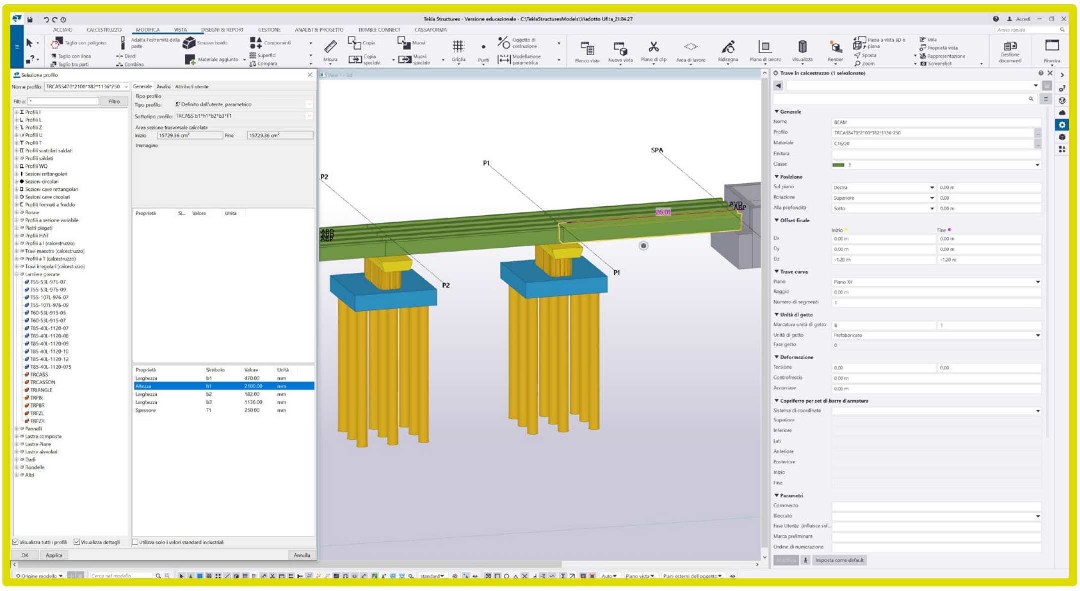


Fig. 52: Bridge modelling within Tekla Structures

This object is greatly important also for visualization purpose because views can be automatically obtained on the basis of grids. Also, in Tekla the most common used elements such as column, beams etc. are called *Parts*, which represent objects based on an extruded bidimensional profile, that can be retrieved from the standard library or customized by the user. On the other side, objects based on a three-dimensional shape are called *Items*. When more parts are linked together to define structural connections, for instance, such groups of parts are called *Components*, that work as "blocks", editable by exploding them. Also in this case, attributes are associated to objects, each type of part is characterized by specific properties. Furthermore, user-defined attributes (UDA) can be added and customized on the basis of requirements. All workflows implement the possibility to start from surveys both in terms of drawings and point clouds, while not all of

Alternatives	Interoperability	Customization	User-friendliness	Cost
1	High level of interoperability both in terms of geometries and information	Not customizable	80%	Autodesk AEC Collection 4136 €/year/user Free educational version
2	High level of interoperability both in terms of geometries and information	Highly customizable	60%	Autodesk AEC Collection 4136 €/year/user Free educational version
3	High level of interoperability both in terms of geometries and information	Not customizable	70%	- Free educational version
4	High level of interoperability both in terms of geometries and information	Not customizable	50%	5000 €/year/20 users
5	High level of interoperability both in terms of geometries and information	Not customizable	80%	- Free educational version

Table 7: Comparison of the alternatives for information modelling

them enable the communication with shapefiles from GIS systems. Workflows number 1,3,4 and 5 are suggested workflows from software houses, which means that customization on the basis of users’ needs is difficult because the data flow is organized in a fixed way; on the contrary, workflow number 2 is customized with the aim to overcome the limits of data exchange between the two main tools Civil3D and Revit, so it is characterized by higher flexibility and adaptability (Table 7).

6.3.4 GeoBIM

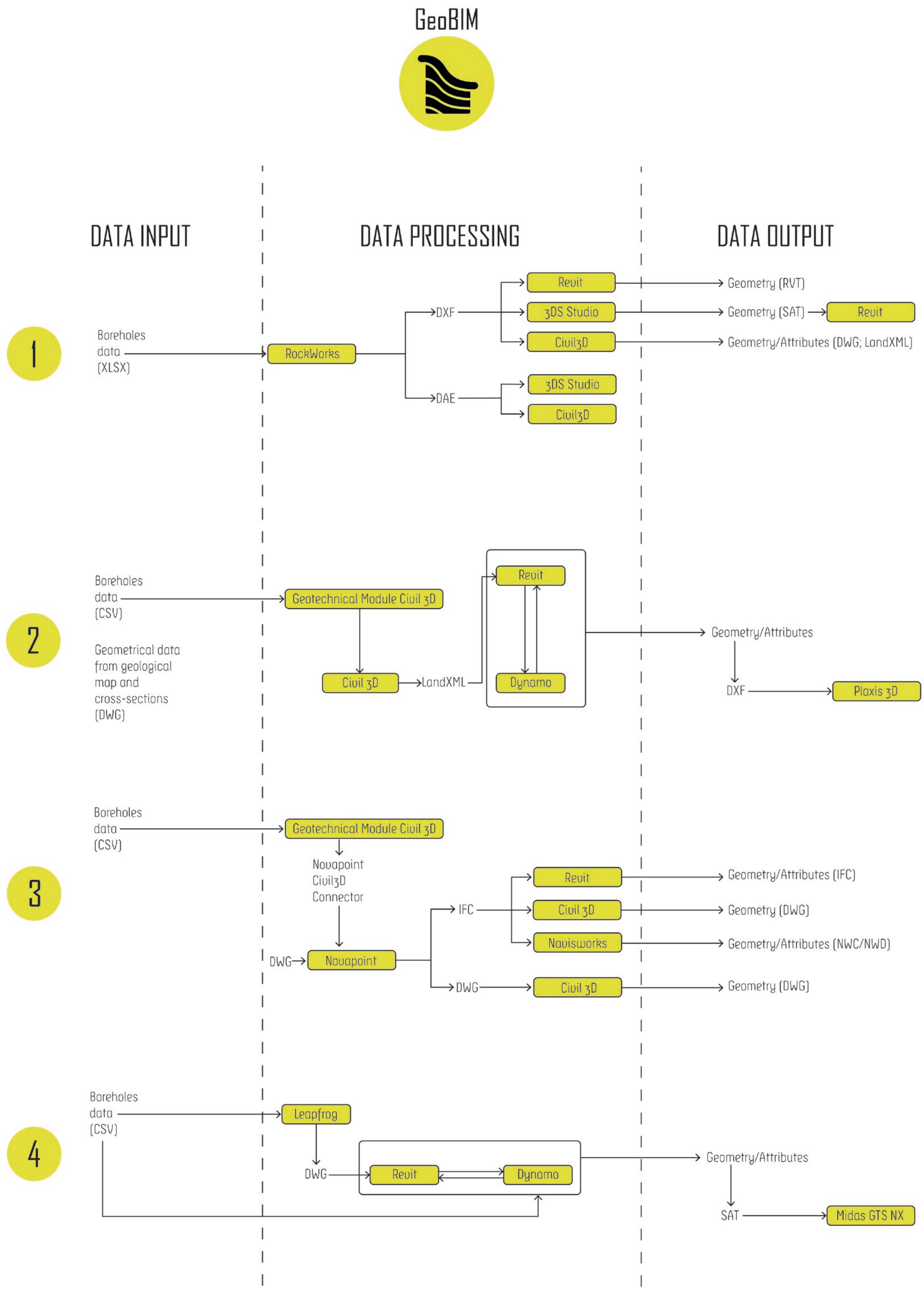


Fig. 53: Possible workflow alternatives for GeoBIM

The GeoBIM approach has been introduced within the literature review, highlighting attempts on including of geotechnical and geological data from survey within a BIM process. The four workflows in Fig. 53 represent possible alternatives for a GeoBIM integration developed over the research.

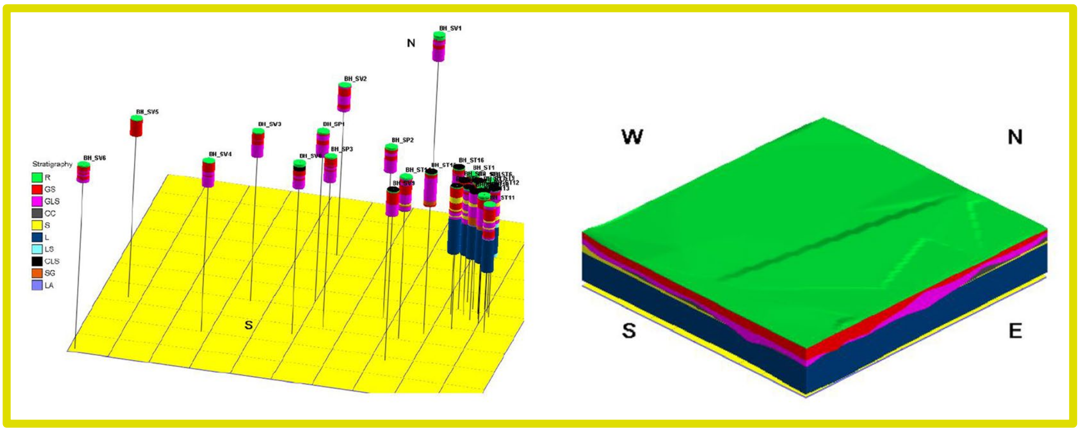


Fig. 54: Modelling results with workflow n. 1
Source: Fonsati et al., 2021

The first workflow is based on the use of the software RockWorks for the data processing. Starting from importation functionalities, the software supports geotechnical data in XLSX, but it is necessary to format the Excel file in a specific way. Indeed, the data must be divided into three excel sheets: (i) Location (with Borehole ID, X and Y coordinates, elevation and total depth); (ii) Stratigraphy (with Borehole ID, top and bottom elevations and stratigraphy type); (iii) Lith type (with different parameters of geotechnical characterization). The geotechnical information is managed with a "Borehole Manager", which allows to geolocalize the boreholes, to set parameters and update details at every stage of the project. The 3D visualization of boreholes is accurate and detailed, so the lithographic layers are clearly recognized. The whole stratigraphy of the area can be obtained immediately through an automatic procedure; the output is shown in Fig. 54. The software makes use of interpolation to create the stratigraphic volumes and several interpolation's algorithms can be chosen, according to the nature of data and soil. The most important limit of the procedure consists of the impossibility of customizing the modelling process, so the three-dimensional model cannot be modified by the user and complex stratigraphies are not represented. In fact, if a lithographic type compares several times at different depths in the same stratigraphy, the tool elaborates it as a singular layer, losing the real soil configuration. About the interoperability with BIM environments, the RockWorks model can be exported as DXF file and imported in Civil 3D preserving its geometry and the assigned attributes. The model can be imported also in Revit, but without attributes. The software allows to export collada files, too, but it does not bring to successful results.

The second method involved the use of a plugin within the software Autodesk Civil 3D and namely the Geotechnical Module. This addon has been specifically designed for terrain modelling, with data from *in situ* boreholes as input. The procedure of data import, processing and production of the model is quite standardized, so it does not present major issues. The important limit of this tool is related to the inaccuracy of the software in the realization of the stratigraphic surfaces, including the visualization of the cross-sections, where there are several points of discontinuity that lead to the need to fix errors manually. Moreover, model updating is not possible through the plugin; a further step forward could be the integrated use of Civil 3D and the HoleBASE SI database, specific database for the collection and organization of data from environmental surveys.

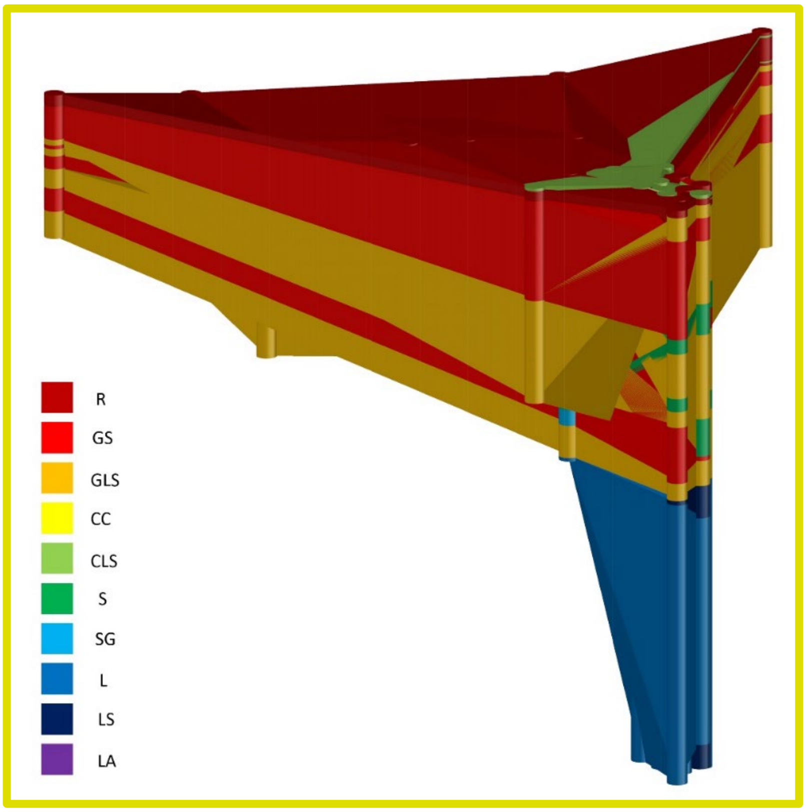


Fig. 55: Modelling results with workflow n. 2
Source: Fonsati et al., 2021

The data necessary as input for the Geotechnical Module is represented by a CSV file, including three different tables: (i) "Location Details" including information such as Location ID, Location Type, Easting, Northing, Ground Level, Final Depth (the maximum depth of boreholes); (ii) "Field Geological Description" contains all information related to the sequential stratigraphy of each individual borehole; (iii) "Orientation and Inclination", where information on the orientation and inclination of boreholes is included. Once such data is imported, the georeferenced boreholes are located within the modelling environment; the processing phase involves the modelling of surfaces based on the terrain stratigraphy through the generation of Triangular Irregular Networks (TIN) surfaces. After having defined the upper (Top) and lower (Base) surface for each stratigraphic unit, it is then possible to model the three-dimensional solids, as shown in Fig. 55. Because of its belonging to the sets of BIM-oriented tools, Civil3D enables the export of the model through three main types of formats: CAD files (DWG/DXF), which export the geometry only, IFC and LandXML, which are open standard formats that exports also attributes and properties, the first one mainly used for vertical infrastructures and the second one, mainly used for horizontal ones. In this case, a collaborative platform able to read the exported file and link it to other BIM models is represented by Navisworks Manage, in which information on the classification of material is maintained through the color of solids, based on the previous classification of stratigraphic layers.

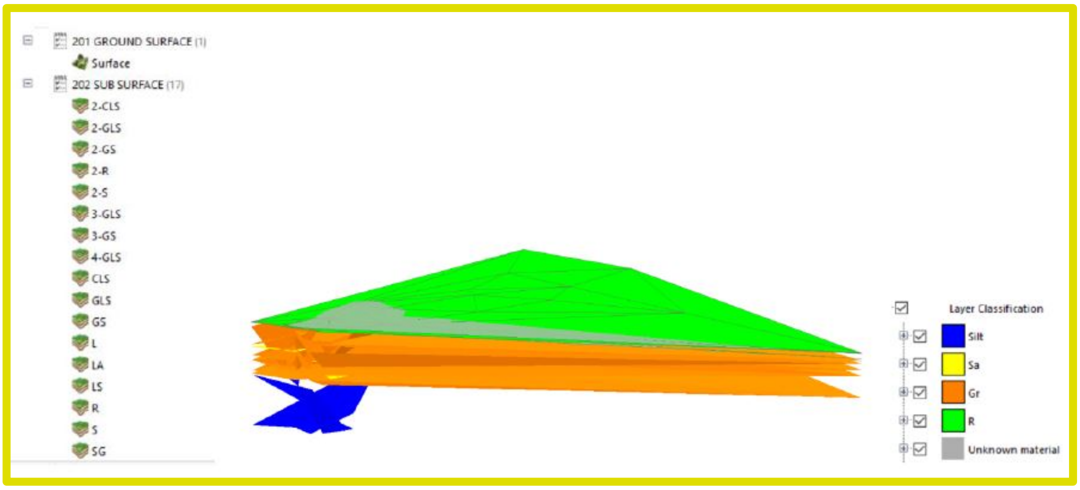


Fig. 56: Modelling results with workflow n. 3
Source: Fonsati et al., 2021

The third workflow another followed method concerned the use of the software Novapoint by Trimble. Unlike the previous cases, this method attempts to create the geotechnical model directly in a BIM platform. As far as the data import process is concerned, the software user guide reports the possibility to import data in XLSX, but it does not specify the data input format, so it is not possible to test this way. Another chance is constituted by the use of Civil 3D Connector of Novapoint, which is a tool for data exchange between the two softwares. Thus, the boreholes properties are imported in Civil 3D and then shifted in Novapoint. Anyway, the best way to import geotechnical information in Novapoint (in order to represent the complete stratigraphy) is to organize the data in DWG files. In every file, each borehole is discretized in points, with different materials assigned to different depths and geolocated in the reference system WGS84/UTM32N. After importation, the 3D soil modelling is not automated, so a strategy was conceived to customize the existing functions of the software. First, points with the same lithographic type were linked by generating surfaces, which represented the interconnection between close layers. As interpolation method the tool supports triangulation, so layers with less than three points disappeared. After that, consecutive surfaces were related, creating stratigraphic volumes (Fig. 56). It is not possible to discern volumes according to materials, but the tool allows only two differentiations, Cut volumes and Fill volumes, as a function of the manner of their generation. Consequently, it is difficult to visualize the stratigraphy, but the information can be added in the model. From the points imported from the CAD file is not possible to extrude a 3D model of the boreholes, so the general model can be completed importing them from another geotechnical software, such as RockWorks. The stratigraphic model can be exported as file DWG or IFC and imported in other software BIM-based, like Autodesk Revit (with its geometry and its attributes) and Autodesk Civil 3D (only geometry). To conclude, Novapoint can be used as a collaboration platform for the coordination among BIM models, for instance the structural or architectural disciplinary model of infrastructures can be federated with the model of the subsoil previously described.

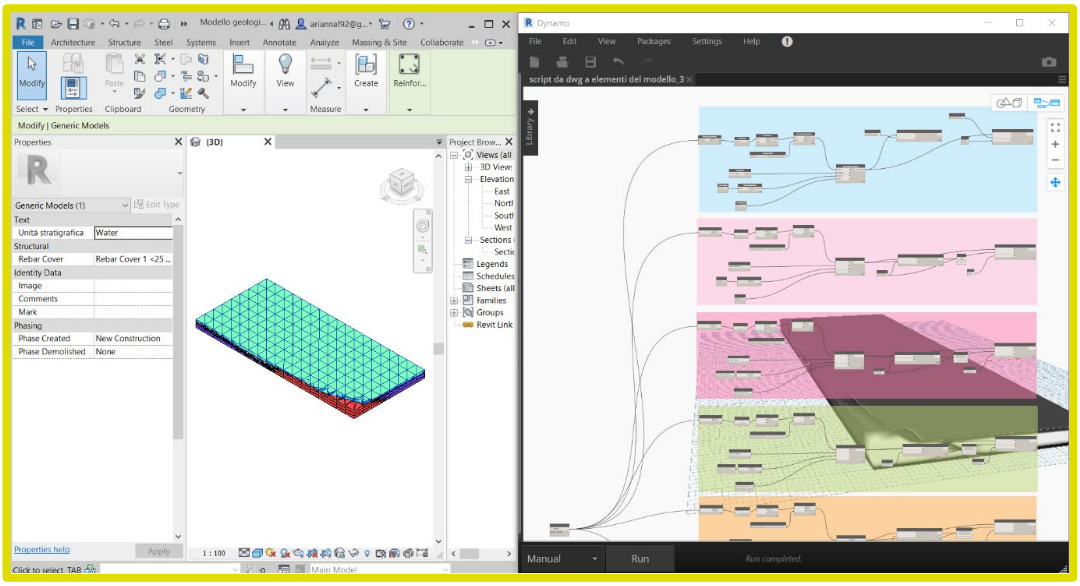


Fig. 57: Geometries conversion and parameters association using Dynamo

The fourth workflow involves the use of the software Leapfrog. The geotechnical data from boreholes are imported using the CSV file format with a specific formatting, elaborating three different files: (i) *Collar*, to define the position of boreholes; (ii) *Survey*, defines the orientation of excavation for the different depths; (iii) *Interval Table*, which specifies the stratigraphy from boreholes already interpreted and classified and its depth. Once having imported data from boreholes and having checked the whole process did not encounter issues, a new *Geological model* can be created, considering that a topography already exists in the project file to define the limits of the model. At this stage, five sub-folders are available for the modelling of surfaces and solids: *Boundary*, *Fault System*, *Lithologies*, *Surface Chronology* and *Output Volumes*. In particular, the folder *Surface Chronology* collects the tools for the definition of surfaces starting from the data input retrieved from boreholes. With such an information, the software generates 'contact points' between different units using radial basis functions (RBFs). Several different types of surfaces are available on the basis of what they have to represent; these surfaces can be easily updated because they are created directly from the borehole data. For example, if an additional borehole is supplied, the new data can be imported into Leapfrog and the surfaces automatically updated to include the new information. Once surfaces are determined volumes are modelled with the tools in the sub-folder *Output Volumes* defining the upper and lower reference surfaces. This workflow enables an easy and fast extraction of outputs, such as cross sections and models, using several formats; also the IFC can be used for the data exchange. However, to proceed with the workflow the DWG format was chosen, and the geometries were converted into Revit shapes under the *Generic Models* category using Dynamo. The model is enriched with information contents through the insertion of shared parameters, subsequently loaded as project parameters, and the compilation of the attributes through Dynamo retrieving data from Excel sheets to assign the proper values to stratigraphic units, as shown in Fig. 57.

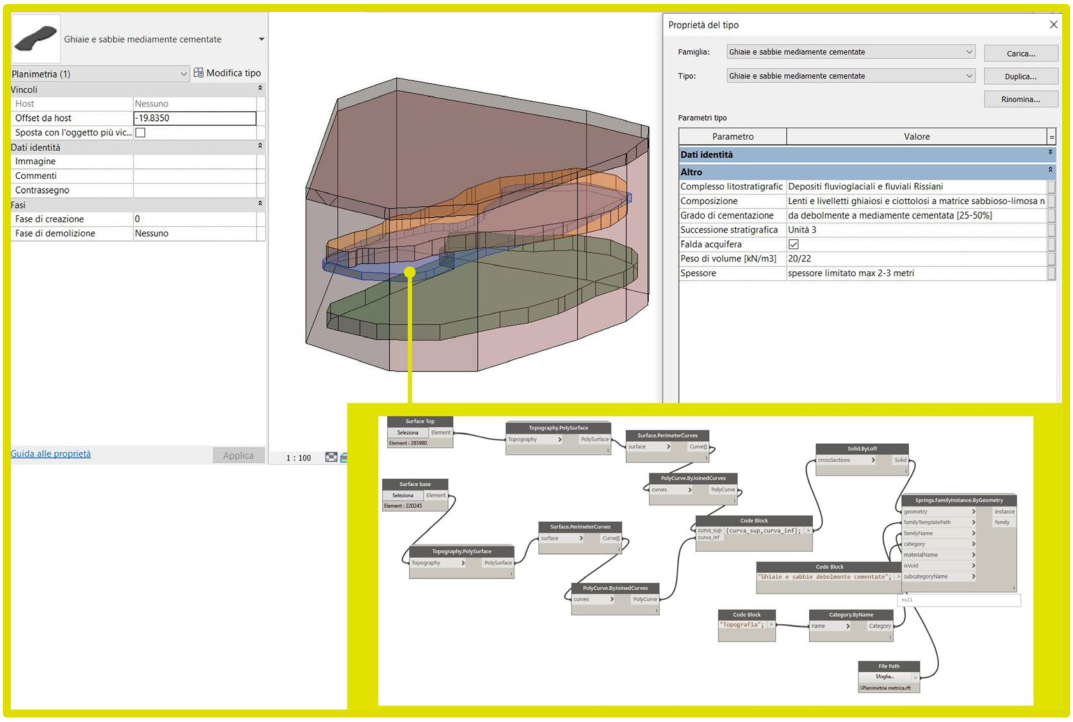


Fig. 58: Solid creation within Revit environment using Dynamo

The last workflow (De Conciliis, 2018) represents an improvement compared to the second one, because it involves the use of the Geotechnical Module, but only for surfaces generation from boreholes data. Volumes are then modelled in Revit with Dynamo by using *Solid.ByLoft* function with top and bottom surfaces as references (Fig. 58). In this case, solids are modelled within the Revit environment in a similar way to Leapfrog, but volumes are easily editable within the BIM-platform, while in the previous workflows, this did not result possible. Once the solid of the stratigraphic unit is obtained, it is possible to create the Revit *Instance* by such a geometry; in this case the *Site* Revit category was used.

On the basis of the tests described within the previous paragraphs, it was possible to get some considerations regarding the processes of data collection, processing and output that characterized each approach:

- in terms of **data input**, all approaches involved as starting point the information related to boreholes, which means that this kind of data is paramount for the purpose of integrating geological modelling and BIM processes and it means that these activities should be promoted in the first phases of analysis and performed in a way that could be as much as possible useful for further developments;

- as far as **data processing** is concerned, the different approaches use considerable different tools to define features and information, which means that the modelling methods are substantially different from each other, even if using some common techniques, such the use of TIN surface; as far as data output is concerned, all approaches presented several different outcomes, both in terms of visualization (views, sheets, geological cross-sections etc.);

– in terms of **information exchange**, in general the file formats to export the models obtained aimed at exchanging the geometry, while some open standards also implemented the exchange of alphanumeric data and information linked to the modelled features that can be integrated into specifically set databases.

In this case, the assessment framework presented and described in section 6.2 was applied and the most efficient workflow was selected. The efficiency of workflow was based on the correspondence to the highest final priorities of alternatives on the basis of the weighting of criteria established in section 6.2. Table 8 shows the final priorities for each alternative workflow.

Alternatives	Metrics	Final priorities AHP
1	Exchange formats [N] Information Modelling share [%] Customization share [%] Time for workflow execution [min] User-friendliness share [%] Overal cost of workflow [%]	0.080
2		0.097
3		0.154
4		0.262
5		0.406

Table 8: Comparison of the alternatives for GeoBIM workflows with the defined framework of assessment (AHP)

6.3.5 Structural analysis

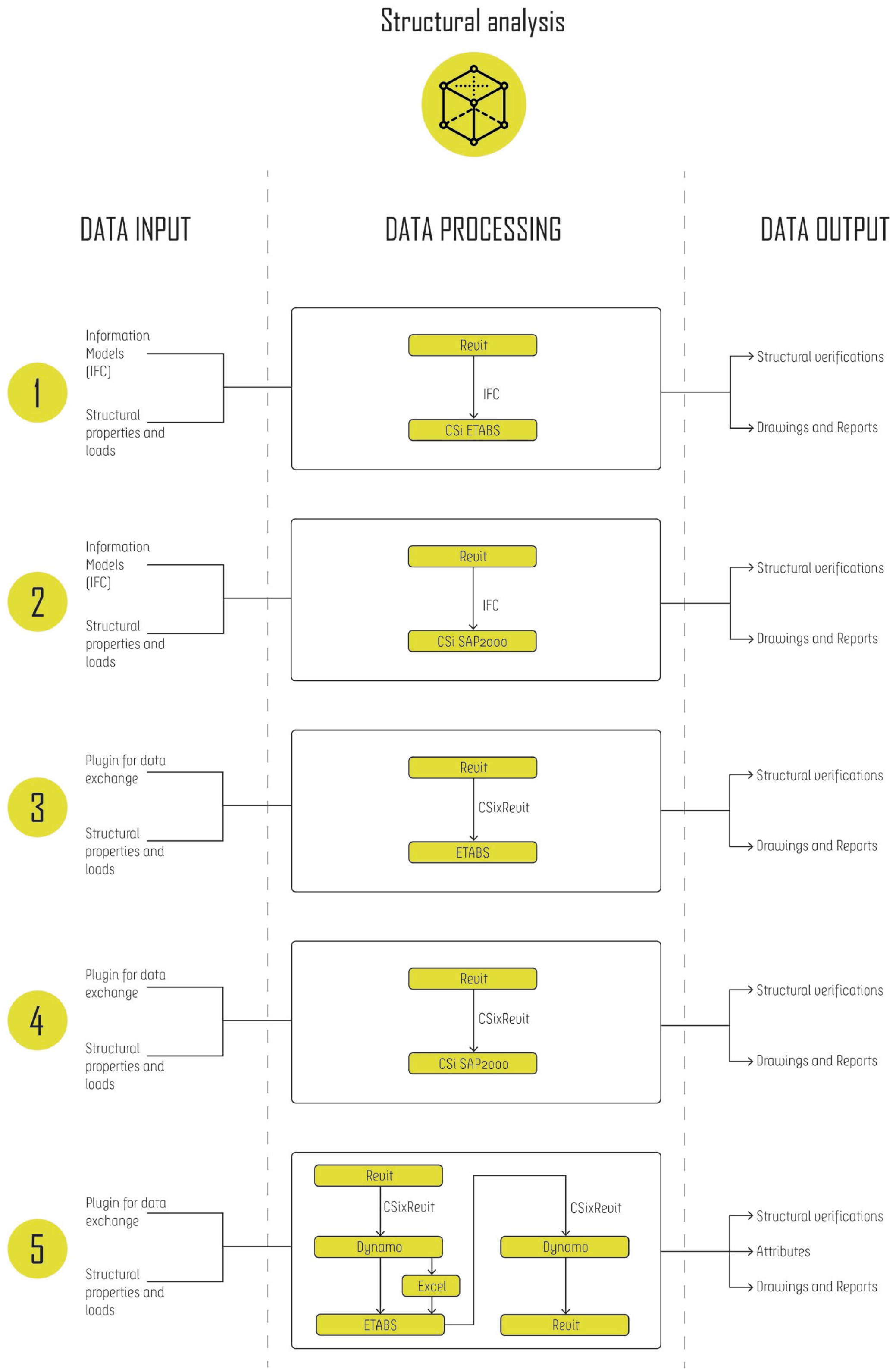


Fig. 59: Possible workflow alternatives for Structural analysis

In terms of interoperability between BIM platforms and Finite Element Method (FEM)-Based Structural Analysis Software Programs, several different workflows are available, both using the open-format IFC and plugins for a direct link between platforms. Structural analysis software boost productivity and efficiency for civil and structural engineering purposes. Based on the FEM, they include other functions such as the analysis of structural profiles, the possibility to analyze a structure characterized by different construction materials, verifications and design procedures and automatic elaboration of calculation reports and drawings. In this case the workflows have been developed starting from the BIM platform Revit and preforming the analyses within the structural software CSi SAP2000 and ETABS. The first four workflows tested the interoperability by using both the IFC and CSixRevit plugin; the last workflow aimed at improving the interoperability of workflow number four by using Dynamo in both directions, both to go from Revit to ETABS and vice versa. Within this process the exchange of information concerning structural elements such as beams, columns, walls, floors were evaluated. Furthermore, other checks related to the information exchange concerned: (i) structural typical assignations such as load cases and load combination assignments, boundary conditions, material properties, section properties, spring properties, eccentricities; (ii) the structural analysis and design results such as the reinforcement design for reinforced concrete structures. Furthermore, the interoperability test aimed at addressing differences between the use of direct links and proprietary format files because in general, direct links works when both tools are installed on the same device. On the other side, proprietary formats are used when the BIM platform and the FEM software are installed on different devices. Therefore, another investigation was related to verify the accessibility to the Application Programming Interface (API), which enables to develop integration tools autonomously for the information exchange.

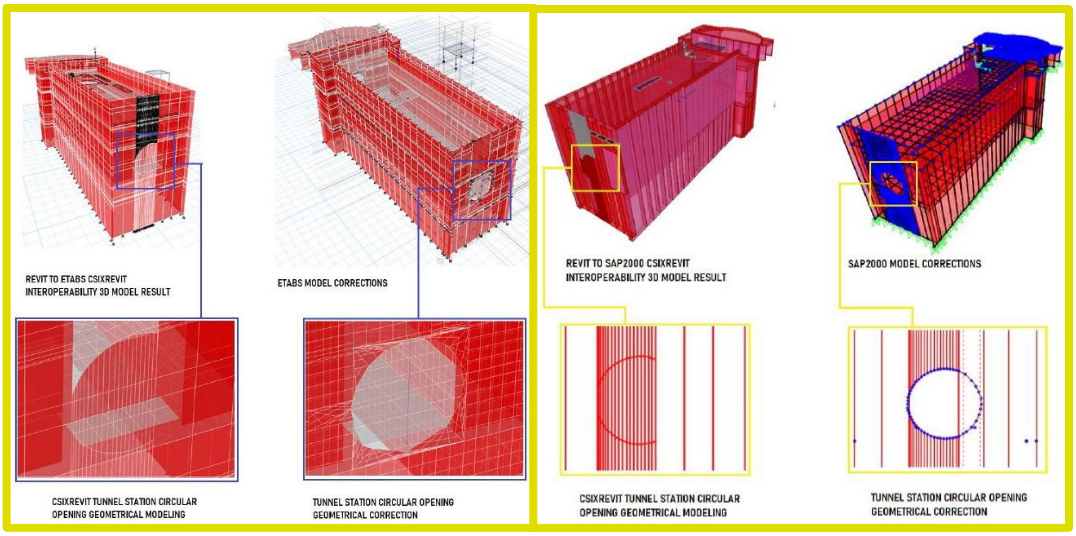


Fig. 60: Data exchange from Revit to ETABS and SAP2000
Source: Ruano Bravo, 2021

The first two workflows involved the IFC as exchange format towards ETABS and SAP2000; the first operation before exporting the IFC involves the proper mapping of IFC Classes within the BIM platform and subsequently the selection of the most suitable Model View Definitions (MVD). In workflow number one, the different tests led to state that the best configuration is the use of the IFC-MVD version 2X3 Coordination View with the default IFC Classes mapping options. This way, the model base LOG file generated when importing the IFC into ETABS reported a general good recognition of elements, however some elaboration of components, such as openings and holes intersecting walls, were not exported. The second workflow, from Revit to

SAP2000, reported an acceptable transference with the IFC2X3 Coordination View. The elements recognition resulted slightly different compared to the previous workflow, but also in this case there were some issues related to holes and elaborations of some components. In this case, problems such as corners disconnection or disconnection between structural columns and walls were encountered, and in case of complex elements the wrong section was recognized.

The workflow alternatives number three and four involved the use of the CSixRevit plugin (Fig. 60), which enabled better results compared to the use of IFC. Some general observations on the exchange for both alternatives are the following: (i) rigid links set in Revit were not exchanged, which led to the presence of disconnections; (ii) structural elements were correctly recognized, but complex structures such as vaulted elements reported several issues; (iii) Elements ID in structural software correspond to the Element ID in the BIM platform; (iv) in both ETABS and SAP2000 it was reported a deficient transference of circular openings in walls, which represents one of the main issues in all cases.

The fifth workflow aimed at improving workflow number four, by using Dynamo as a tool to improve interoperability with FEM software, in this case the software ETABS was chosen. In this framework, the algorithms intended to enhance the existing interoperability process by eliminating 'null' elements, defining and correcting boundary conditions, rigid links and area loads defined in Revit. Furthermore, Dynamo was involved also in the opposite direction of data exchange, from ETABS to Revit, with the following objectives: (i) the synchronization of elements ID name in both software; (ii) the use of Revit parameters in order to store the FEM Analytical Structural Results in the model; (iii) the transfer of frame and surface members internal forces and internal stresses; (iv) the transfer of joints/analytical nodes displacements and rotations; (v) the creation of views an filter rules to display all the FEM analytical structural information in a graphical way. The workflow enabled the development of automated processes that could substitute the post-processing operations after exportation, in order to guarantee a better information

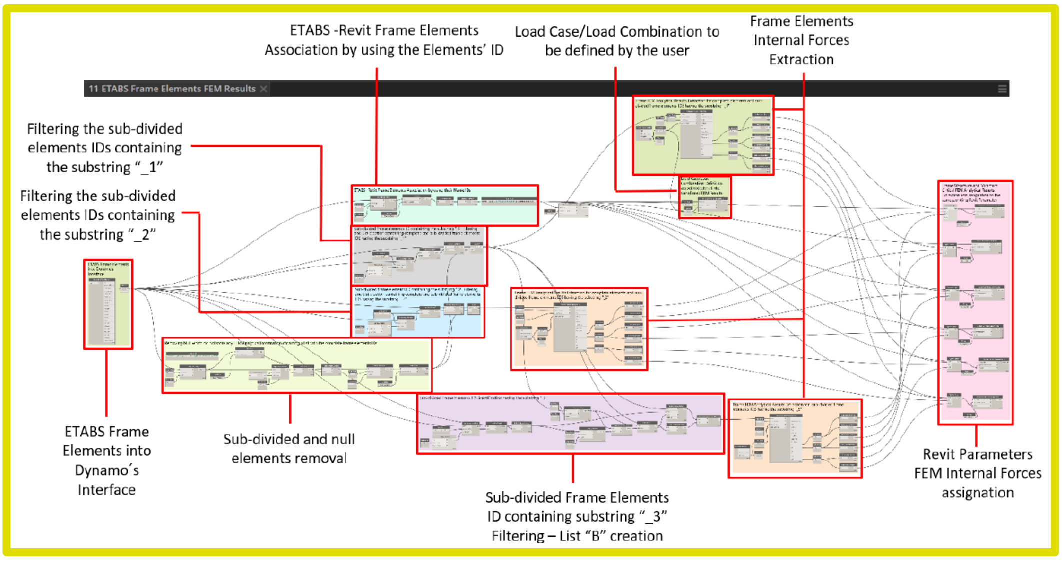


Fig. 61: Dynamo algorithm to send ETABS frame elements FEM analytical results to existing Revit frame members.
Source: Ruano Bravo, 2021

exchange, without the necessity to manually make these changes (Ruano Bravo, 2021). The workflow led to the enhancement of the interoperability in both directions, highlighting the possibility to implement communication between software by using visual programming to overcome existing limits of commercial tools.

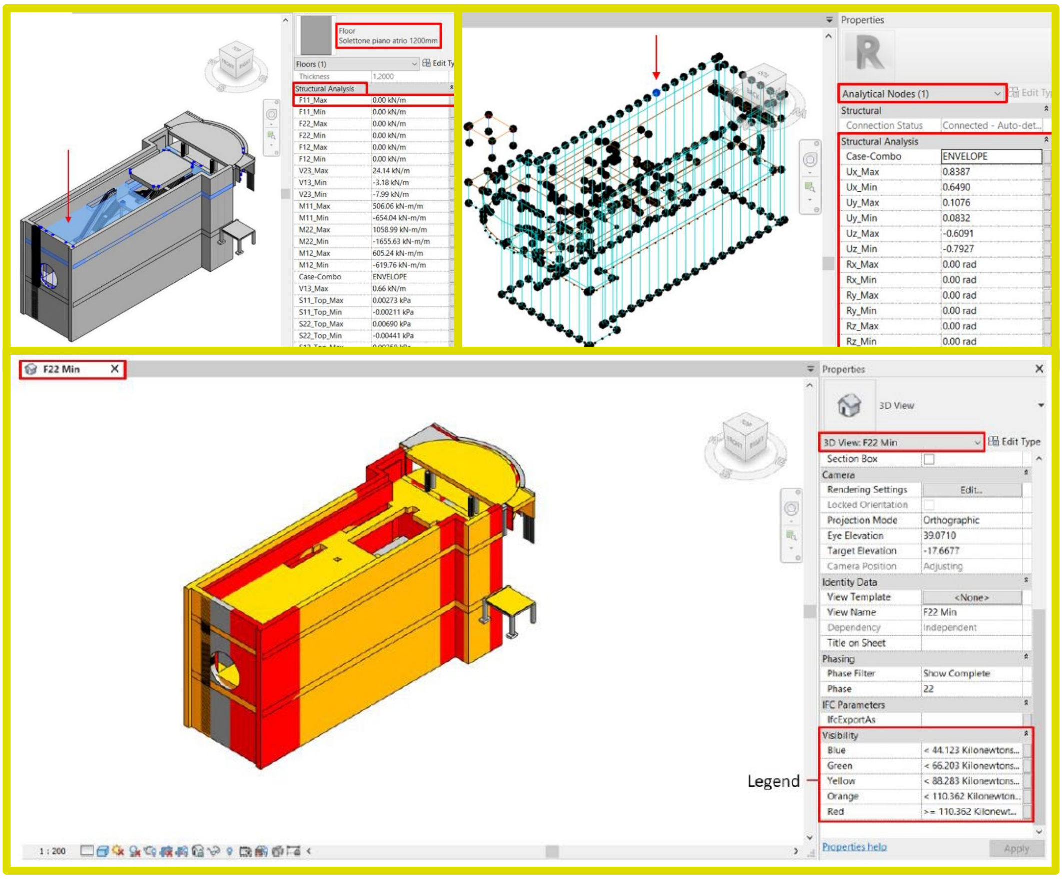


Fig. 62: Data exchange and visualization in Revit after the optimization with workflow n. 5
Source: Ruano Bravo, 2021

Fig. 61 shows the example of one of the Dynamo script specifically developed to transfer the internal forces information previously described from the ETABS frame elements (beams and columns) to the equivalent Revit BIM elements. In this example, the connection between ETABS and Revit is established by Dynamo using the elements ID. Then, ETABS Frame Elements are processed within Dynamo's interface, nulls and useless entities are removed, a list encompassing all the elements which are not subdivided is created, added with filtered lists containing the sub-divided elements. After that, the load case/combination is extracted by a Code Block node with the x[list position] syntax and it turns visible thanks to a "Watch" node type. Finally, the result is assigned to the "Case-Combo" Revit parameter that is in charge of displaying the load case/combination in Revit as shown in Fig. 62. The whole process is described within the master thesis developed by (Ruano Bravo, 2021).

Table 9 shows the results obtained from the workflow assessment performed using the AHP method as presented in section 6.2. The most efficient workflow identified is the last one. These results confirm that the interoperability processes are still not fully effective as well as not all the structural analysis software offer the same advantages in terms of tools. In the same way, the evaluation identifies the current

Alternatives	Metrics	Final priorities AHP
1	Exchange formats [N] Information Modelling share [%] Customization share [%] Time for workflow execution [min] User-friendliness share [%] Overal cost of workflow [%]	0.080
2		0.097
3		0.154
4		0.262
5		0.406 ◀

Table 9: Comparison of the alternatives for Structural analysis workflows with the defined framework of assessment (AHP)

limitation of InfraBIM and FEM integration. For this reason, further applications should propose new alternatives to enhance the exchange of information processes in both the direct link/proprietary file and the openBIM methodologies.

6.3.6 Model validation

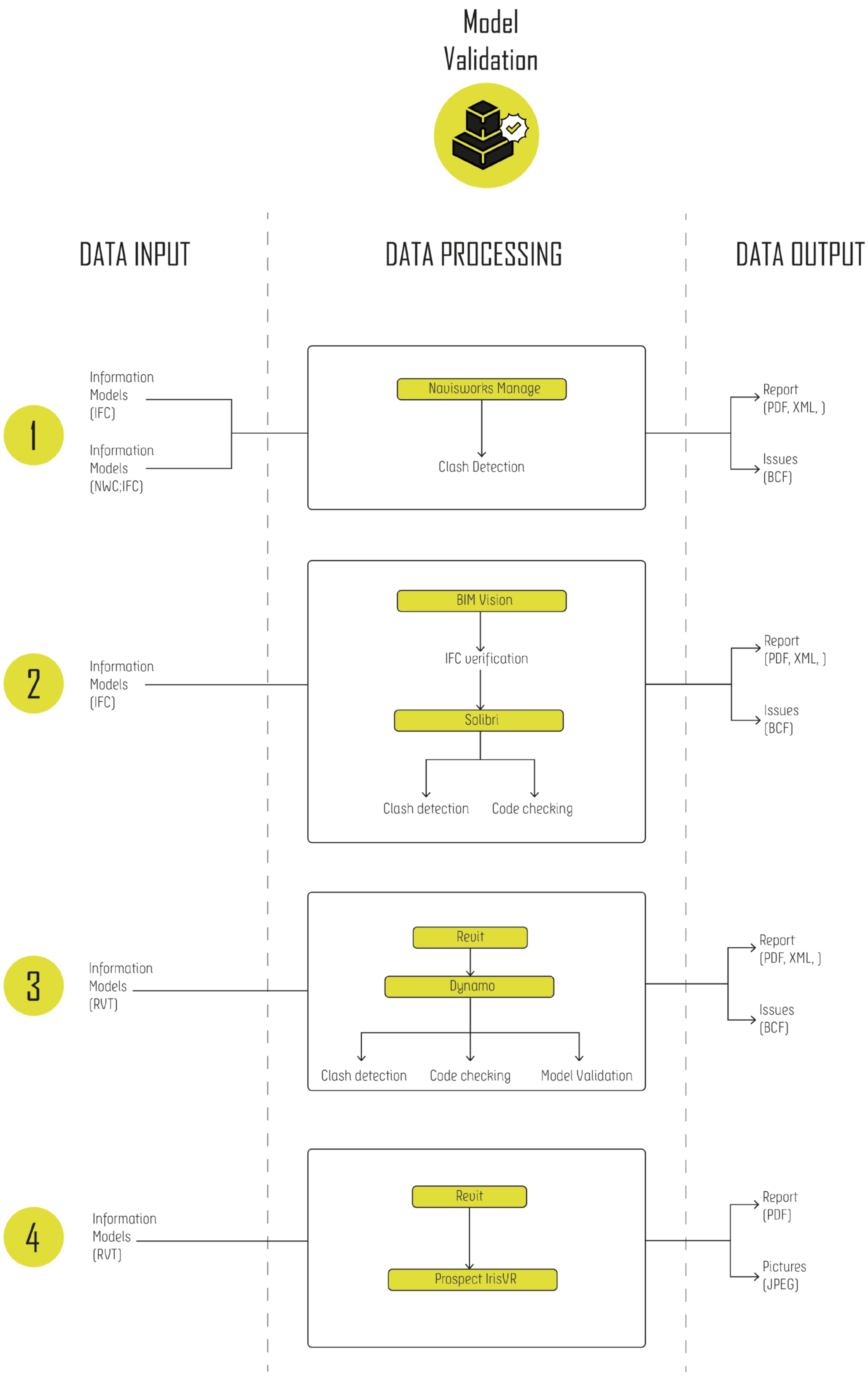


Fig. 63: Possible workflow alternatives for Model Validation

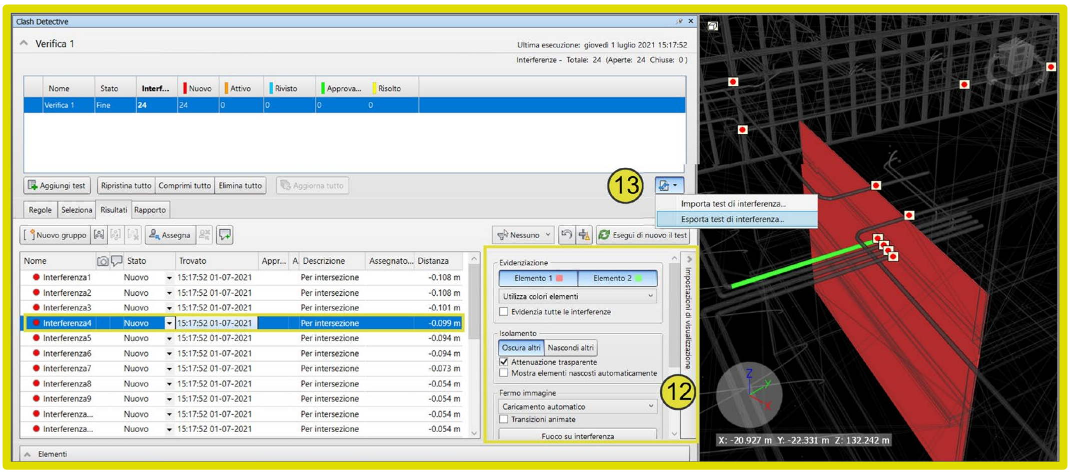


Fig. 64: Clash Detection in Navisworks

Model validation refers to the possibility to validate and verify information models and their contents on several levels, both in terms of checking the compliance of the model to the current design rules and in terms of validating the model on the basis of the pre-defined rules within the BIM process, for instance those explicated within contractual documents both from the appointing and the appointed parties. Section 5.2.4 included the explanation of the different levels of coordination and verification in terms of processes. However, for the purposes of the research activity it was also important to define possible workflow alternatives to test operational activities towards models checking and validation (Fig. 63). In this framework, four main workflows were developed and tested on case studies to search for the best approach for the different levels of coordination and verification. All workflows involved several software and specific file formats for the information exchange; the final assessment is reflecting the result of interoperability tests performed during the research activity.

The first workflow involves the use of the software Autodesk Navisworks and provides the possibility to input data both in proprietary formats (RVT, NWC etc.) and open standard format (IFC). However, the tests performed showed that the best results in terms of elements recognition is achieved by exporting the NWC format from the Revit BIM platform. This means that workflow number one has the best results when applied in integration with the Autodesk BIM platform Revit, so the customization is not possible in this case. Furthermore, within this workflow only the clash detection among models, so it is not implemented the possibility to perform code checking, which is related to the compliance to design regulation, together with checking that parameters in the models are correctly assigned and filled in. Within this coordination and validation process, it is of paramount importance to use a traceable method to store information on activities and interferences encountered (Fig. 64). The traceability is also important for future criticalities because data on the authors of specific issues and checks is stored. Within this framework, to guarantee such a traceability the BCF format was used. It enabled the exchange of issues between Revit and Navisworks; this way interferences encountered within Navisworks were reported in Revit, where the models were modified accordingly.

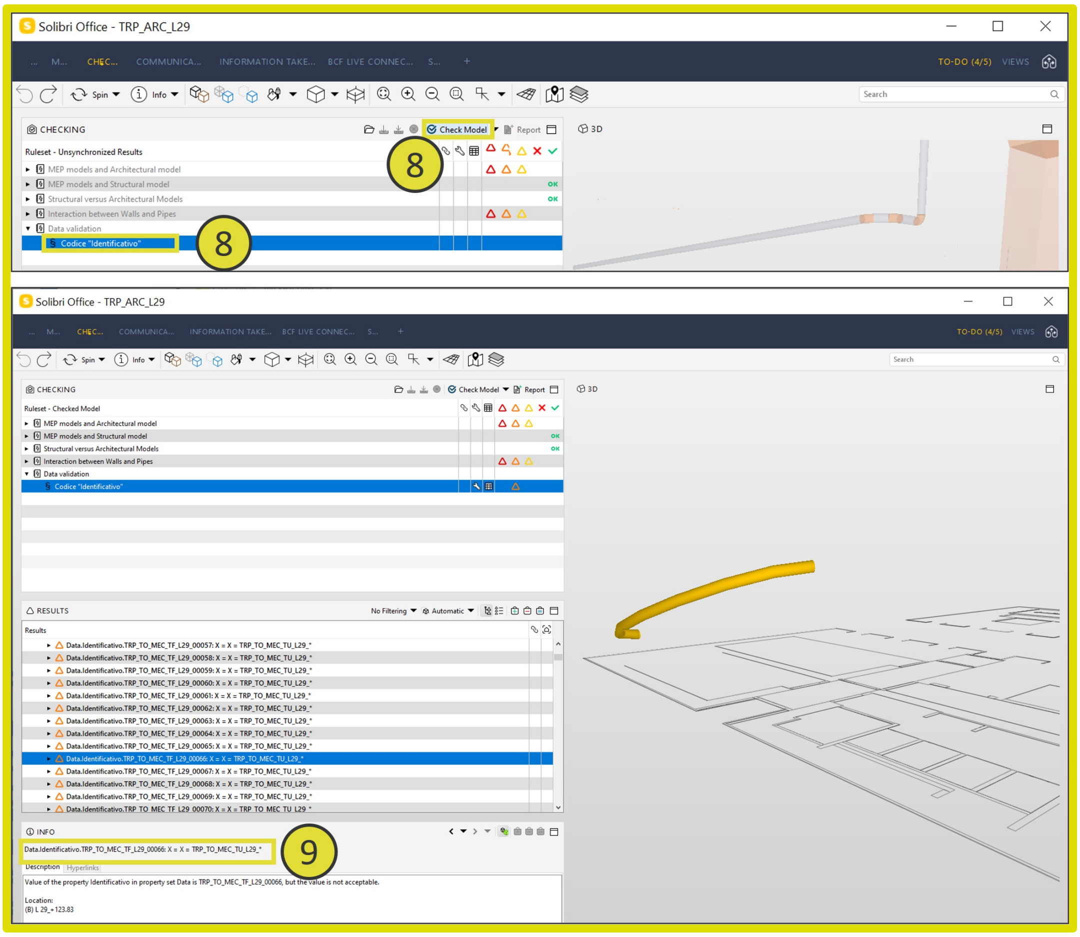


Fig. 65: Data validation in Solibri

The second workflow tested the use of the open format IFC, instead of working with proprietary formats. The first step involves the use BIM Vision tool, which is useful to verify the correct mapping of features and properties within the IFC. Then, the workflow proceeds with the use of the Solibri Office software (Fig. 65), which represents a tool specifically directed towards model clash detection and code checking, so it represents a more advanced tool in terms of checking than Navisworks. Indeed, it also implement the use of rules for model checking that can be modified and use also to validate attributes, by checking they are properly written, filled in for instance on the basis of the rules included among the Appointing party's requirements for information modelling. In terms of output, it also allows the use of BCF format for issues exchange with BIM platforms and the production of reports on the checks performed for the validation.

The third alternative in Fig. 63 involves the use of Dynamo as a tool useful to customize the model validation workflow. In this case, the data flow is not "fixed" by rules pre-defined or modified within the environment of a specific workflow, but the process is highly customizable on the basis of the necessary check to perform on the models. On the other hand, this workflow is only possible when working within Revit BIM platform. For instance, Dynamo enables the

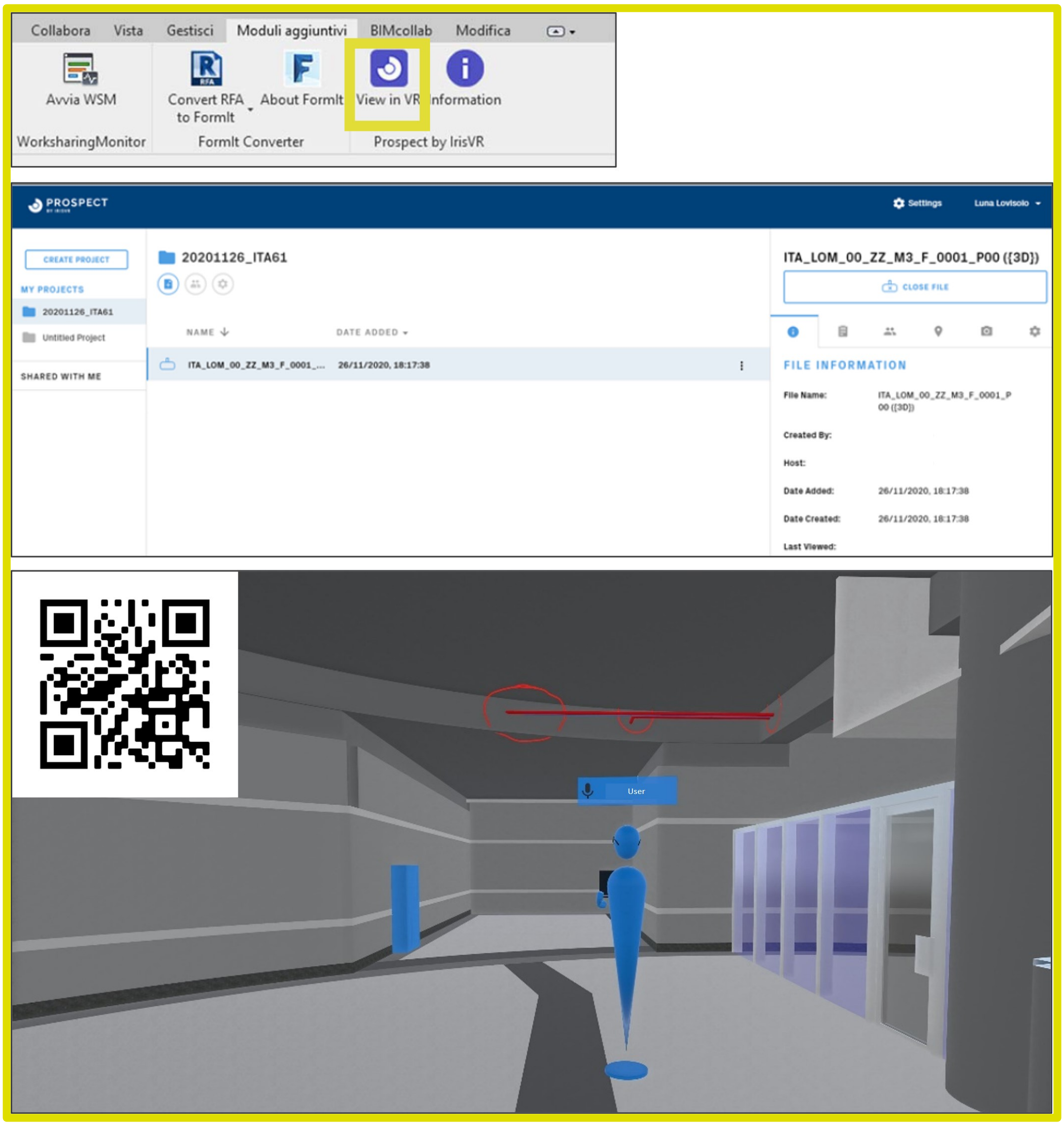


Fig. 66: VR as a tool for model validation
Source: Lovisolo, 2020

following activities related to data validation: (i) alphanumerical control of all types of parameters within Revit; (ii) different types of checks based on necessities; (iii) choice of categories or groups of categories to which checks are associated; (iv) export results obtained at the end of data validation; (v) Dynamo enables to distinguish between capital and lowercase letters.

The fourth alternative involves the use of Virtual Reality to navigate models with the specific aim to visualize clashes and model validation, because also attributes and parameters assigned to objects are visible. In this case, the IRIS VR software was used and the HTC Vive as VR headsets (Fig. 66). Such a solution is also very useful both for designers and clients, to better visualize possible design issues. However, such workflow cannot replace the previous ones, because issues encountered cannot be exchanged using BCF, which is paramount for coordination.

Alternatives	Interoperability	Customization	User-friendliness	Cost
1	High level of interoperability with all BIM authoring platforms. Possibility to use BCF format for communication of issues	Not customizable	70%	Autodesk AEC Collection 4136 €/year/user Free educational version
2	High level of interoperability, the workflow is based on IFC format. Possibility to use BCF format for communication of issues. Both clash detection and code checking	Customizable using rules for checking	50%	Solibri Office 1700 €/year Educational version
3	Workflow specific for Autodesk software, used for clash detection, code checking and model validation	Highly customizable	60%	Autodesk AEC Collection 4136 €/year/user Free educational version
4	Only visualization purpose for model navigation. Interopeability possible using several file formats, such as RVT, FBX, SKP etc.	Not customizable	100%	350$/workstation/month

Table 10: Comparison of the alternatives for model validation

Table 10 shows a comparison among the presented workflows, highlighting the essential characteristics for each of the selected criteria. Both the first and second alternatives present a high level of interoperability, because several different file formats can be used to process models and perform clash detection in the first case and both clash detection and code checking in the second case. However, while the alternative number two shows a good customizability thanks to the use of default rules to define specific checks, that can be customized accordingly to the specific check for compliance, the alternative one is not customizable because of the limitations of tools for checking that characterize the workflow. On the other side, workflow number three is highly customizable, because rules for checking are user-defined and can be created from scratch on the basis of the necessary requirements. All workflows are user-friendly, especially workflow number four, which is very easy to use and guarantees a high level of interoperability between the BIM authoring platform and the VR visualizer.

6.3.7 4/5D

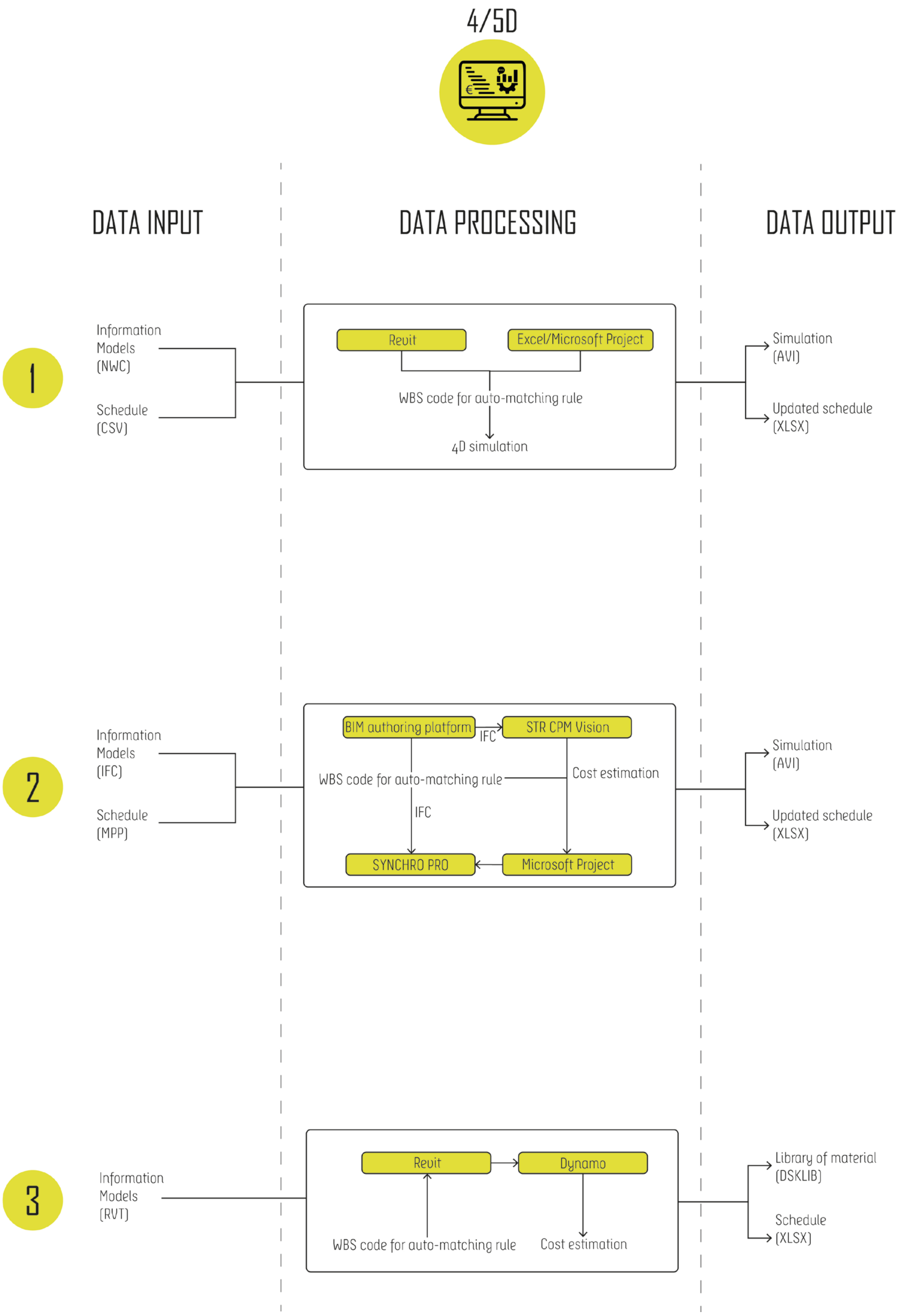


Fig. 67: Possible workflow alternatives for 4/5D

The management of time and cost dimensions involved within the BIM process in an infrastructural project is a key-concept in the future of Construction Project Management (Fonsati, Osello, & De Marco, 2021). The workflows proposed in Fig. 67 show three possible solutions to breakdown the information models in order to define the WBS and CBS; this is mainly useful to associate model components and its information content to schedules of activities and cost estimations.

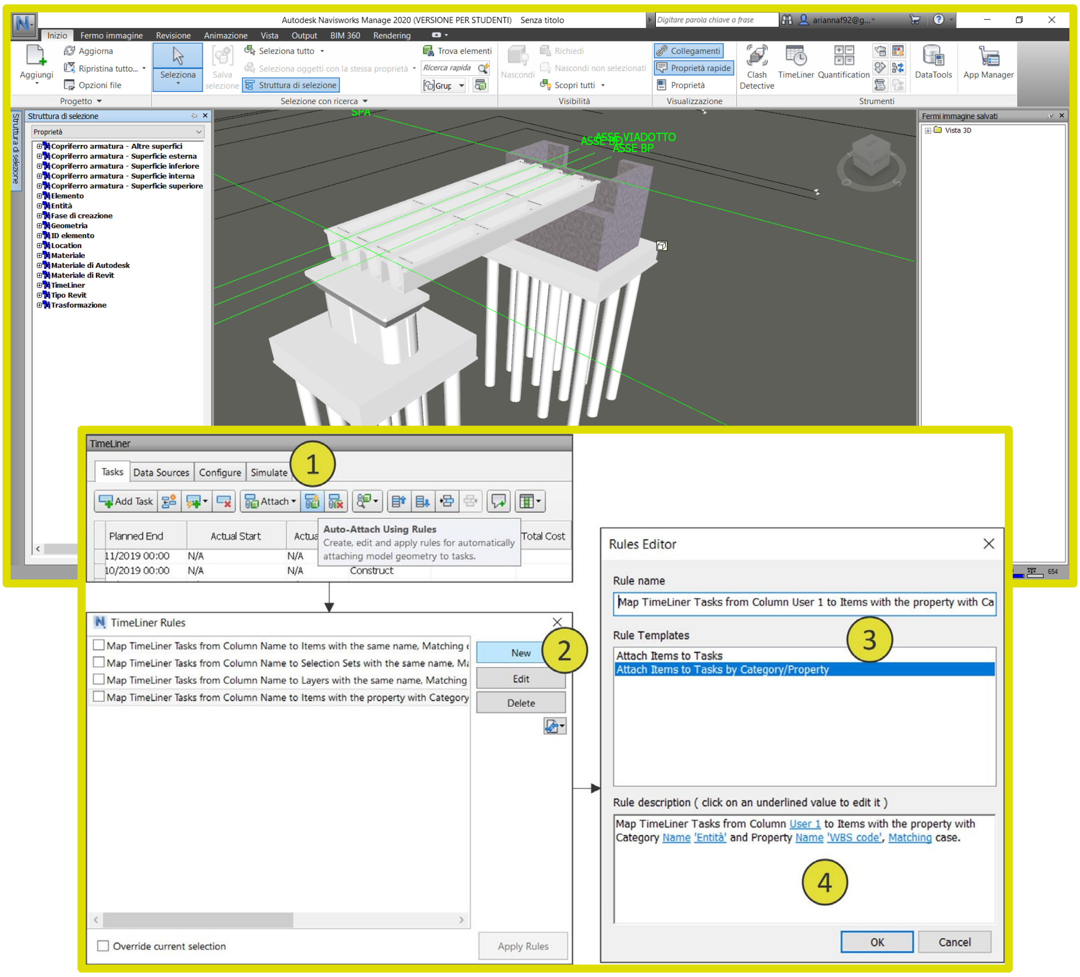


Fig. 68: Auto-matching rule to associate the objects in information model and the schedule

The first workflow involves the use of Revit as BIM platform and Navisworks as tool for 4D coordination and cost estimation. Another BIM platform could have been used, because Navisworks allows to import several different file formats. However, in terms of data input, models are imported using the NWC, the direct format to connect Revit and Navisworks, and the schedule containing sequence of activities, start and end date, working days etc. in CSV file format, that must be properly formatted to be read in Navisworks. The association between the models imported in NWC format and the schedule requires a unique identification code that links the specific modelled object to its activity within the schedule. Once the same code is shared both in the model as value of a specific attribute and in the schedule as WBS code, it is possible to define an "auto-matching" rule to associate them (Fig. 68). This operation is then followed by other activities to set the 4D animation that can also be used for a dynamic clash detection, in order to verify that during the activities included in the schedule there are no interferences and in terms of vehicles flows. Within this workflow it is also possible to extract quantities from the model itself, in order to perform a cost estimation directly within Navisworks. The possible outputs represent a 4D simulation of the construction activities and the update of the schedule of activities; this workflow allows for a continuous association between models, schedules, and cost estimations, that could evolve with the advancement of the project itself.

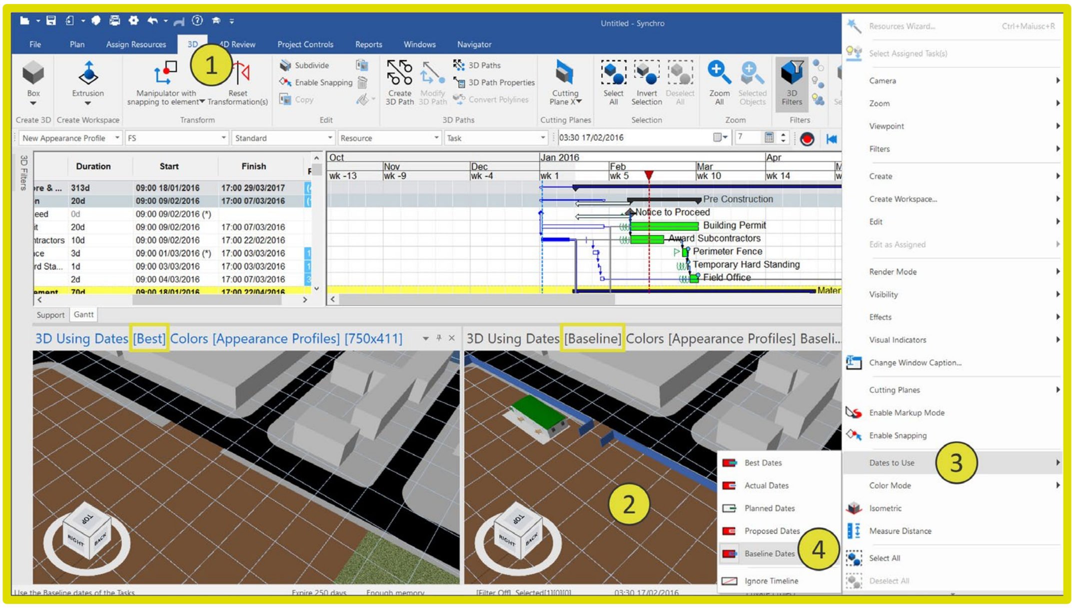


Fig. 69: Comparison of different scenarios in SYNCRO PRO

The second workflow exploits an openBIM process, by using the IFC format for the data exchange among the BIM platform and the other tools involved. The workflow involves the following steps: (i) the definition of a WBS code to classify BIM objects, based on constraints and requirements derived from the case study; (ii) the creation of the database for cost breakdown structure (CBS) and work breakdown structure (WBS); (iii) the definition of rules for the link between BIM and CBS/WBS database; (iv) the 4D simulation of the construction works and the validation of project schedule and operating spaces. The BIM model is then exchanged using IFC for the creation of a database for both the WBS and CBS; in this case the software used was the STR CPM Vision, which enabled to use the CBS as the starting point for the definition of the WBS and the relative schedule. After having developed the schedule, it was exported using Microsoft Project format to import it in the software for the development of the 4D simulation, in this case SYNCHRO PRO, where several scenarios for the schedules of activities can be compared and other analyses can be performed (Fig. 69). Also in this case, among the outputs there are 4D simulations of activities, updated schedules, and precise cost estimations performed thank to the established link between the different software used. Such a workflow represents the most customizable because using the IFC correctly exported, different BIM platforms can be used.

The third workflow represents a possible way of managing information related to the planning of construction activities and cost of materials directly within the BIM platform Revit by using Dynamo. It enables to create a more customized way to approach these topics but amplifying the functionalities of the BIM platform, extracting quantities to be further used for the development of the CBS in a spreadsheet for example. On the other side, the information related to the planning

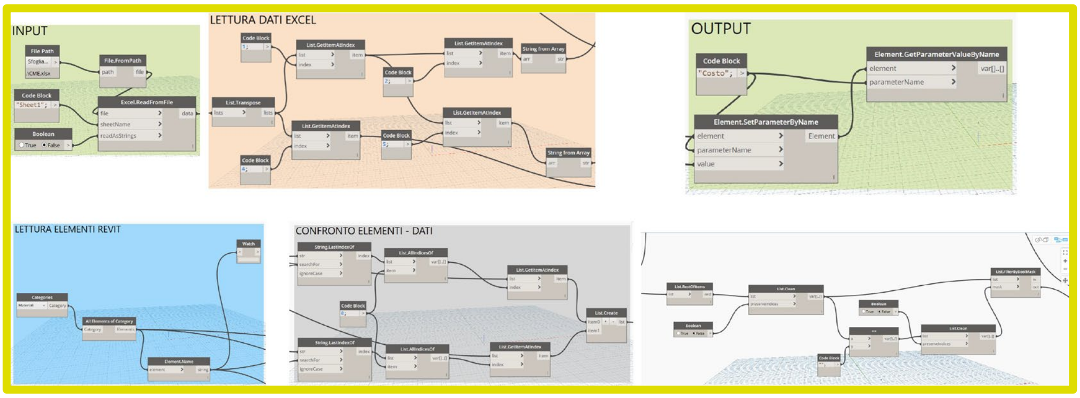


Fig. 70: Automatic import of parametric costs from external unit price list

and schedule of activities is implemented using attributes and filters associated to objects in the model. The workflow for 5D could implement several approaches: (i) creation of a bill of quantities directly in the Autodesk Revit software through the creation of a "Material Quantity" column in the materials schedule, containing the volume or surface area according to the category; (ii) possibility of automatic import of parametric costs from an external unit price list (in an Excel file) into the BIM environment (Fig. 70); (iii) automatic and direct export of Revit material schedules to an Excel file.

Table 11 shows the results obtained from the workflow assessment performed using the AHP method as presented in section 6.2. The most efficient workflow identified is the first one, even though also the second alternative achieved a good result on the basis of the evaluation parameters and weighting of criteria defined.

Alternatives	Metrics	Final priorities AHP
	Exchange formats [N]	
1	Information Modelling share [%]	0.442 ◀
	Customization share [%]	
2	Time for workflow execution [min]	0.363
	User-friendliness share [%]	
3	Overal cost of workflow [%]	0.195

Table 11: Comparison of the alternatives for 4/5D workflows with the defined framework of assessment (AHP)

6.3.8 O&M

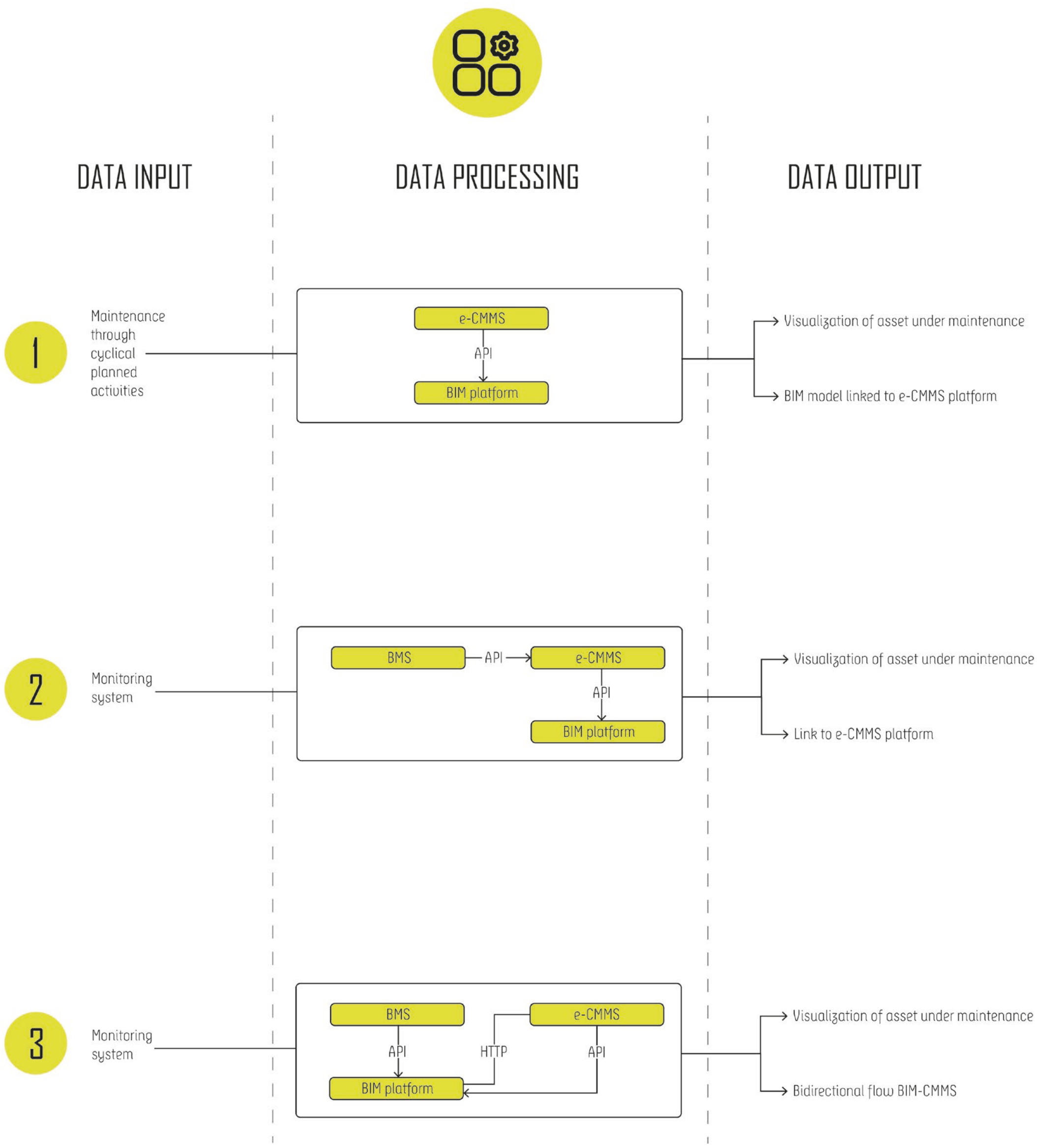


Fig. 71: Possible workflow alternative for O&M

The research activity also analysed possible integrations between InfraBIM processes and operation and management of systems components, to use the model as graphic interface for the management of maintenance activities and failures. In this case, the workflows in Fig. 71 are only proposals, aiming at integrating BIM platforms, Building Management System (BMS), that monitors physical components, and Computerized Maintenance Management System (CMMS), which facilitates and automates maintenance management processes. The CMMS system handles several types of maintenance cycles: (i) Time Division Maintenance (TDM), related to cyclical activities; (ii) Condition Based Maintenance (CBM), which refers to activity on condition and on analysis of monitored components; (iii) Breakdown Maintenance (BM), which refers to an activity based on an event. In this framework, the management of maintenance cycles would happen by analysing the assets imported from the BIM platform, ensuring that each change of stadium

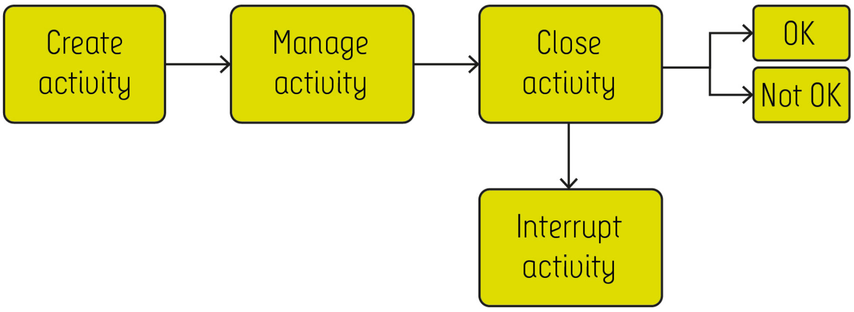


Fig. 72: Maintenance activity management

is notified in the CMMS and that the information is sent back to BIM system. The CMMS, BMS and BIM would share a common key for data exchange. However, the process of data exchange would happen in the event of a change in the asset, by updating the existing asset without modifying the whole structure. Furthermore, the CMMS would manage the users on the basis of the following main macro-categories: (i) Maintenance leader, who is the responsible for organizing and assigning maintenance cycles to other users, check the status of progress and manage maintenance teams and their turns; (ii) Operator, such as the BIM user that could ask the starting of a specific maintenance activity directly from the BIM layout; (iii) Maintenance technician/team, who are in charge of the maintenance activity and enter the output into the system, adding notes or other related documents. In this framework, the activity is created, managed, and closed, or temporarily suspended (Fig. 72).

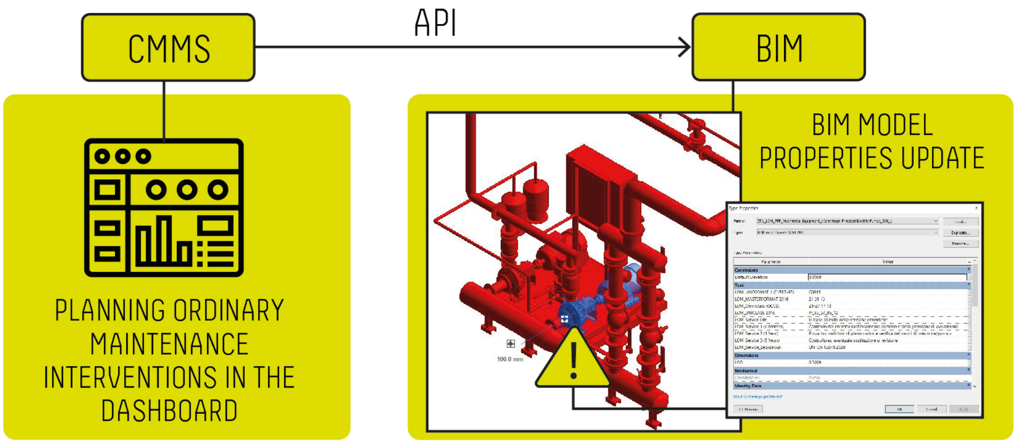


Fig. 73: Planning ordinary maintenance activities

The three systems, the BIM Model, BMS and CMMS, could communicate with each other in order to create the environment for data to be retrieved, analysed, recorded and transmitted. In this framework, data may both receive and transmit information to and from the CMMS platform or receive reports directly from the BMS system. The data flow may vary on the basis of the type of maintenance or monitoring activity; for instance, ordinary maintenance interventions can be planned directly through the CMMS platform and the related data can be transmitted and consulted directly in the BIM Model using attributes assigned to model components (Fig. 73). This type of maintenance activity is based on the anticipation of possible failures, based on the historical monitoring data obtained through the BMS system.

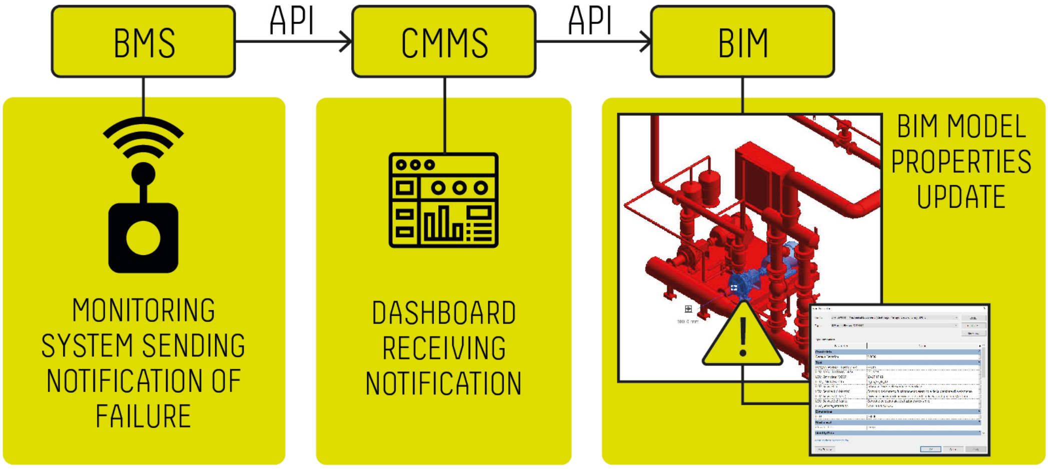


Fig. 74: Failure notification exchanged through BMS-CMMS-BIM systems

On the other hand, data collected by the sensors could be analyzed and evaluated, so that possible interventions can be planned in order to prevent failures. In this case, the data collection and archiving function of the CMMS platform is a core aspect. In case of failure or malfunction of the component, an extraordinary maintenance intervention could be planned to solve the problem. The failure signal could be produced directly by the BMS system, transmitting the alarm to the BIM model, where the affected asset is highlighted in a three-dimensional view (Fig. 74). Among the properties of the asset, it would be possible to visualize the type of failure and therefore to be able to connect directly to the CMMS platform in order to plan immediately a resolving intervention.

The transmission of data between the three systems could be guaranteed by an application installed in the BIM interface, allowing the direct data exchange from the physical asset to the BIM model and vice versa, establishing a bi-directional communication. From an operational point of view, such a bi-directional communication happens in the CMMS by receiving notifications from the BIM environment and sending from the CMMS notifications on the activity status. The data exchange could happen using the API interface, through which the structure from the BIM environment could be imported within the CMMS. In the event of a change in the asset within the BIM environment, it will be possible to make the individual changes without modifying the whole structure. Within the BIM environment, the URL parameter can be used to link the specific components to the relative web page for CMMS or BMS management; this way the BIM user will monitor the whole process from the BIM interface, without using other applications.

6.3.9 VR

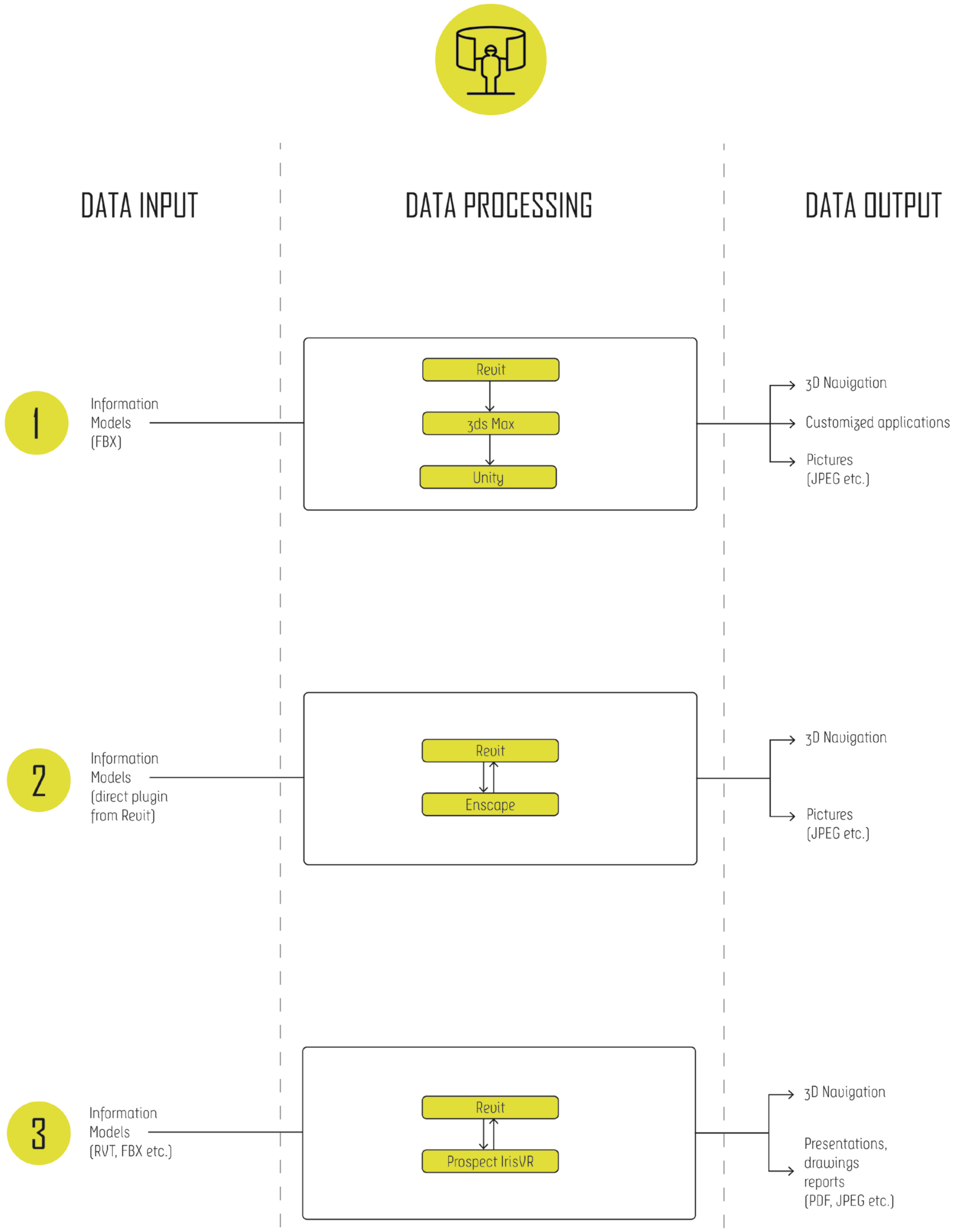


Fig. 75: Possible workflows alternatives for VR

Within the research activity three main workflows have been tested for the purpose of data visualization using Virtual Reality (Fig. 75). Each workflow was developed with different purposes, so they are not compared since the scope of the activity is not the same. However, all these workflows share the possibility to use the information models for further purposed of visualization, highlighting possible ways to integrated visualization and other activities, such as clash detection or the simulation of emergency situations.

Fig. 76: Virtual environment of the three scenarios of workflow number 1

The first workflow involves the use of the VR engine Unity, where the model is imported after having edited surfaces, textures and materials within Autodesk 3D Studio Max, due to the high complexity of models produced within a BIM authoring platform. Unity was the used to develop three scenarios where the user had to face different emergency situations (De Luca, Fonsati, & Osello, Virtual Reality for training the public towards unexpected emergency situations, 2019): the first scenario consists of the evacuation of the virtual environment in case of fire, the second one requires to offer assistance to a person using BLS techniques, the last scenario involves the interaction with a person of dubious intentions (Fig. 76).

The application was developed with the purpose to test different VR tools; for this reason, the HTC VIVE headset was used as main VR equipment, but to navigate the model the Cyberith Virtualizer was used. The Virtualizer is a locomotion platform for virtual reality, which is characterized by integrated sensors for motion detection (CYBERITH, 2021). The VR experience in this case is fully immersive and thank to sensors both in the HTC VIVE and in the Virtualizer, users’ movements within the VR environment reflect the physical ones. The idea behind the application is related to the experience of living an emergency in a safe environment because part of a virtual simulation; this way the users can train on how to behave in such a situation. Each scenario was built with the aim to make people realize what are the actions they have to perform, simulating the experience through a gamification approach, using game design elements into a non-game context to increase engagement. For this reason, each scenario was set up by giving instructions on how to behave in that specific situation.

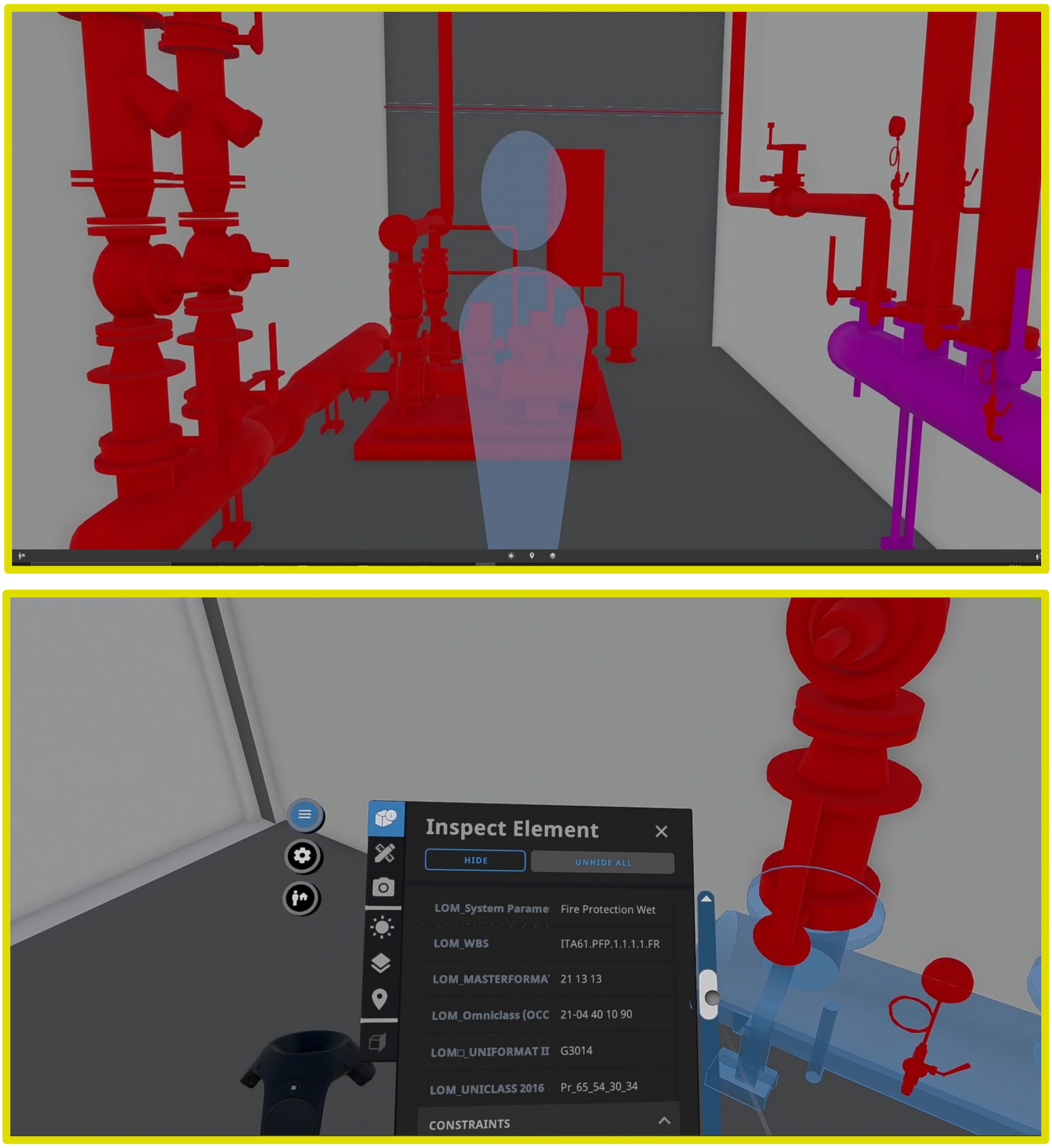


Fig. 77: Model navigation and data visualization within IrisVR

The second workflow involves the use of Enscape as a plugin of Revit; this tool is available both for non-immersive virtual navigation from desktop and for immersive experiences using HTC VIVE headset. In this case, the link between the model in Revit and Enscape is direct, so by modifying an element within Revit interface the same element is modified in real-time in the VR environment. This possibility makes VR applicable as a communication tool that can trigger social experimentation, and at the same time can also be the means through which to consolidate collaboration between professionals. The proposed scenario could represent an intermediary between the designer and the client, facilitating communication and decision making. Among the advantages of such a workflow there is not only the absence of interoperability issues, but also the ease of use that does not require special skills or standardization of procedures, such as in the case of the first workflow, where computer programming skills are required. Furthermore, the attributes assigned to modelled objects can be visualized, so in the VR environment it is not only possible to visualize geometries of objects, but also the information contents and properties associated within the design process.

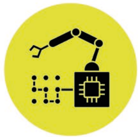
The third workflow involves the use of Prospect IrisVR as a plugin integrated within Revit platform. The same workflow was also presented in section 6.3.6 with the purpose of model validation; the software enables a set of check to perform on the model, not only in terms of clash detection, but also for data visualization (Fig. 77). Indeed, the VR environment is accessible to different users, that can use the free Prospect Viewer tool to navigate the model from desktop; on the other side to have the immersive experience using HTC VIVE the full version of the software is required. Among the functionalities available, there are the following: (i) visualization of object properties; (ii) sketching tools available to draw in the VR environment; (iii) screenshots of the VR environment to be added to the report; (iv) setting the day and hour to change light and shades; (v) visualization of the connected users and possibility to use the microphone to communicate with them; (vi) possibility to make some model categories visible or not. This workflow is very useful when it is necessary to share the VR environment with several users. However, it is not possible to have real-time modifications as in workflow number 2, because the model must be edited in Revit and then re-uploaded in the IrisVR project.

Alternatives	Interoperability	Customization	User-friendliness	Cost
1	High level of interoperability both in terms of geometries and information	Highly customizable	40%	Autodesk 3Ds Studio Max 2264 €/year/user Autodesk Revit 7245 €/year/user Free educational version
2	High level of interoperability both in terms of geometries and information	Not customizable	90%	Autodesk Revit 7245 €/year/user Free educational version Enscape 65 €/month/floating license
3	High level of interoperability both in terms of geometries and information	Not customizable	85%	Autodesk Revit 7245 €/year/user Free educational version Prospect Iris VR 350$/workstation/month

Table 12: Comparison of the alternatives for Virtual Reality

Table 12 shows a summary of differences among the three workflows presented. All workflows show high interoperability because the information exchanged is possible thanks to several different file formats. The first workflow is highly customizable because it involves the use of Unity as VR engine, which means that movements and activities can be freely defined by creator of the virtual environment. However, user-friendliness in the first alternative is low because of the complexity of building a VR environment from scratch. On the other hand, in the second and third workflows the virtual environment is already set, which means that it is only necessary to establish the connection between the digital information model and the virtual reality platform.

6.3.10 Machine Learning



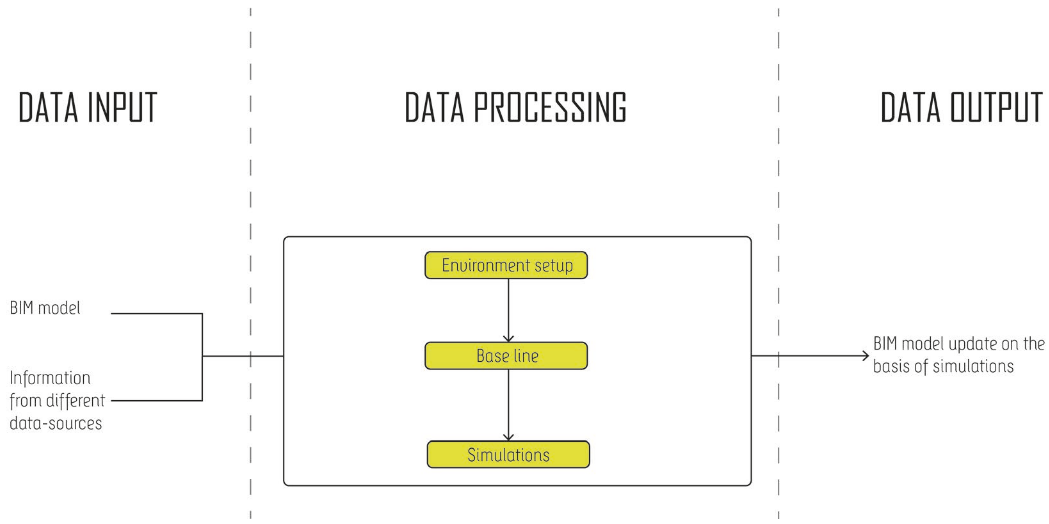


Fig. 78: Application of ML within InfraBIM context

Within the research activity, the proposal to integrate ML within InfraBIM context arose from a critical issue revealed in the field of design of highly mechanized underground tunnels realized by using TBM (Tunnel Boring Machine) machines. Indeed, within this procedure there is a gap between the theoretical alignment defined during the design phase and the operational one followed by the TBM as the construction progresses. TBM excavation method is mainly used for long tunnels projects, because of the significant costs to move, assembly and disassembly the tunnel boring machine itself.

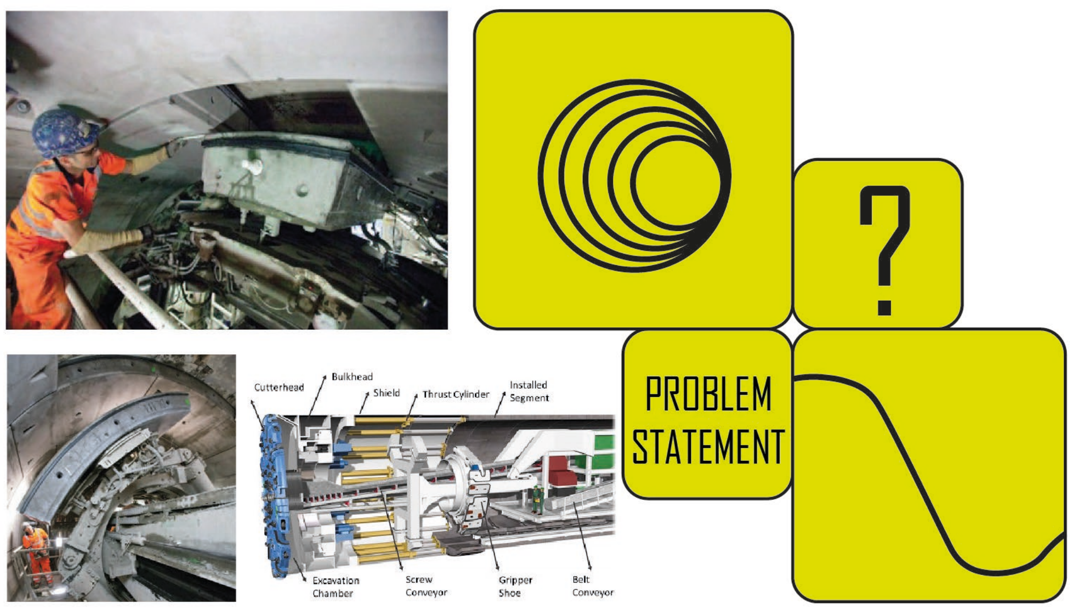


Fig. 79: Problem statement

The TBM carries the excavation out by using a cutter head to dig into the ground and rock and crush it, after that the head is pushed by jacks placed at the tail which push against the rings already placed (Pelz, 2019).

These rings represent the lining of the tunnel and are generally built by assembling precast reinforced concrete segments as shown in Fig. 79. The TBM is in charge of processing all the measurements at the excavation face and calculating the alignment to follow and any corrections due to subsidence and machine positioning. The new segments are then placed sequentially one after the other and the excavated material is then automatically disposed of. Within this context, the operational alignment is unknown until the moment of construction, when the best position of the rings to deviate as little as possible from the theoretical alignment is defined on the basis of the data collected in the process. During the construction process, the TBM guidance system monitors the correct placement of linings following the designed axis. Within this context several unexpected events could occur, such as variations in the torque of the cutting head or unexpected variations in soil density that could deviate the axis of the operational alignment from the designed one. All such possible issues depending on unkown aspects that are impossible to predict could affect the position of segments, which means that it is impossible to define a priori the exact position of the rings. For this reason, the objective of the research was to optimize, the design process that enables to hypothesize the operational alignment for tunnels by adopting an approach based on the implementation of automatic learning algorithms as tools for design. The workflow presented below was developed within the supervised Master thesis written by Rimella, 2020.

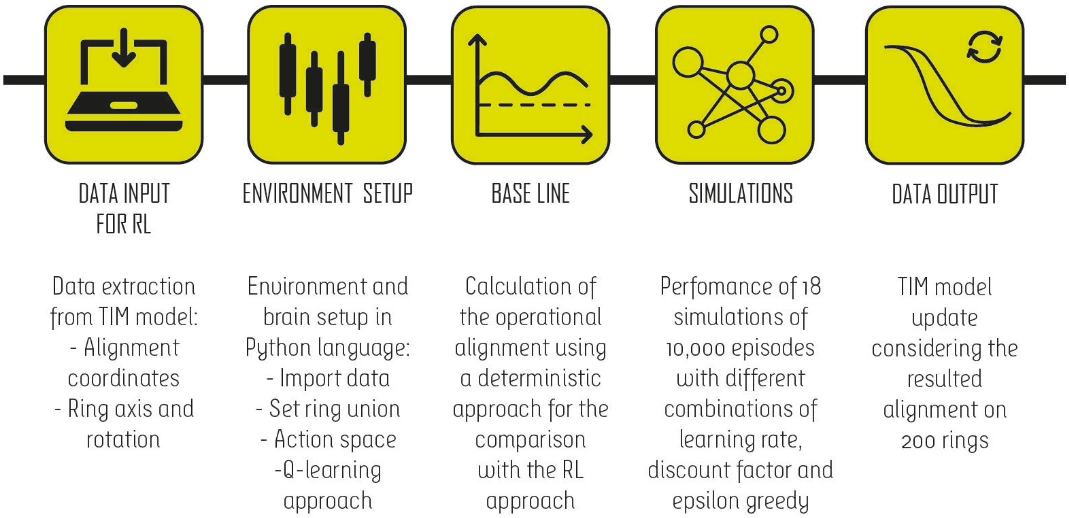


Fig. 80: Methodological workflow

The aim was to define a best practice and develop a methodological framework for the prevision of the operational alignment on the basis of the theoretical one using machine learning algorithms to choose the best combination of factors. In order to achieve such a result, the starting point of the process was the identification of the specific ML method to be applied; thanks to its characteristics the chosen method was a Reinforcement learning algorithm, which represents one of machine learning subcategories and is based on the interaction of an agent with a known or unknown environment through actions and rewards, "constantly adapting and learning on giving points" (Nandy & Manisha, 2018). This kind of algorithm is suitable to solve the proposed problem because Reinforcement learning is based on simulations that reflect real scenarios, instead of dataset analysis. The framework shown in Fig. 80 includes the following five main methodological phases (Rimella, 2020):

- **Data input for RL**: as input for the environment and brain setup later described. In this case the data input is the digital information model of the artificial gallery built using the TBM and so the Tunnel Information Model (TIM), which contained all relevant information thanks to the adoption of the InfraBIM methodology during the design phase. Indeed, using the TIM model, it was possible to analyze the structure of rings and the positions of the relative axes on the alignment;

- **Environment and agent setup**: after having extracted the relevant data from the TIM model the Environment and the Brain have been set up in Phython language, which represents a paramount phase in the definition of a high-performance RL algorithm;

- **Base line:** in order to obtain a comparison alignment to evaluate the effectiveness of the defined Reinforcement learning algorithm ,before running the simulations the tunnel operational alignment was calculated using the deterministic method;

- **Elaboration of simulations:** after having completed the algorithm based on artificial intelligence functioning and having defined a term of comparison, eighteen different simulations were carried out, each one considering different parameters. As a result, the most effective settings for the resolution of the final operational alignment were selected;

- **Data output:** the data output of the simulations was used to update the TIM operational alignment. The relative Q-Table has been extracted from the simulation carried out, containing all the information produced by the Q-Learning algorithm. Such data allowed to update the operational alignment within the TIM environment, with a maximum deviation from the theoretical alignment of 1.00 cm.

This study analysed the potentiality of an integrated use of disciplines and techniques by developing a replicable methodology. For this reason, the proposed methodology could be applied in several different other situations. Starting from analyzing the state of the art in regard with on the one side BIM and InfraBIM environment and process and on the other side Machine Learning techniques it was possible to better frame the context of the research, in order to deepen the real chances given by the proposed integration. Furthermore, the problem statement identification helped in clarifying the aims of the methodology under development, by giving details on the results to be obtained by implementing such a method. Then, the methodology was developed to specifically focus on the process of dealing with data in order to achieve the solution of the problem, through the following process on data: data collection and input definition, which included the necessity to develop a TIM model with all relevant information for the analysis; data processing, which involved several steps including the setting of the Reinforcement Learning environment and the definition of a term of comparison to evaluate the performance of results from the RL approach, and finally data validation, selecting the best combination coming out from the simulations performed, and update of the TIM model and its alignment based on the output from the training of the RL algorithm. To conclude, the algorithm adopted was able to reconstruct an alignment composed of two hundred rings with a maximum deviation from the theoretical alignment of one centimeter (Rimella, 2020). However, the management of such an alignment was difficult because of the great computational effort needed, because the number of states to explore in order to obtain the desired result were difficult to manage through a simple Q-learning method. For this reason, better results in terms of computational speed could be obtained by adopting algorithms using Artificial Neural Network (ANN), which requires strong expertise in Data Science. Anyway, the results showed that the method developed is efficient and easily replicable because of the fast extraction of the required data to run the algorithm, i.e. the coordinates of the theoretical alignment and the geometry of the ring. To conclude, this first attempt to use RL to solve a complex problem within the infrastructural domain showed the effectiveness of the use of such a technique in this field. For this reason, more applications should be implemented towards this direction, which will be useful to solve several complex problems dealing with a great amount of data.

Other applications of ML to the InfraBIM environment could involve the use of the great amount of data produced during the construction phase to perform further analyses and produce more realistic estimates in future projects, as shown in the supervised Master thesis written by Amico, 2021. Within this context, a neural network could be used in the definition of planning estimates that take into account any unforeseen events that may have occurred in previous experiences in order to build a more accurate predictive model for estimations of future projects. Once the predictive model itself is validated, it could be useful to estimate the probability of future events based on historical events (in this case the specific activities on the construction site). This makes it possible to obtain a model that provides an assessment based on what really happened in previous experiences. Therefore, machine learning algorithms allows the use of an output that, depending on the updating of the dataset, allows a reassignment of weights to the various variables in play. This way, estimations would consider a higher percentage of unpredictability based on real experiences stored within an historical dataset of related data.

To conclude, the exchange of information coming from heterogeneous data-sources and in general the integration among several disciplines and tools such as digital information modelling and ML algorithms can lead to semi-automatic decision-making procedures for further optimizations within AECO processes. Indeed, the exploitation of integration between Big Data and IoT allows to reach predictive analyses that address issues also in real time, leading to complex predictive models using specific Deep Learning techniques.

6.4 Summary of proposed workflows and assessment

The chapter summarized some of the workflows developed during the research activity for several InfraBIM uses. Furthermore, a framework for the assessment of the developed workflows was built with the aim to provide a tool for support decision towards the application of BIM processes. In this framework, some of the workflows have been compared among each other by using the assessment framework defined, which resulted easy to apply and convenient to identify the most efficient workflows on the basis of users' priorities. The assessment framework is also scalable and flexible, because the indicators used for the evaluation can be implemented and their value can be modified. One of the most important outcomes of the research is that a workflow that results efficient in one specific context could be inefficient in other situations. As highlighted within the thesis, the implementation approaches can differ substantially depending on the size of company, its hierarchy and resource management, products and services it offers etc. For this reason, it does not exist an "ideal" workflow that suits perfectly in any case, but the most important step when performing the assessment is deciding the priorities on criteria, in order to establish the most efficient workflow based on such given priorities. Furthermore, another important step is the analysis and interoperability tests phase, because it proves the real feasibility of workflows. In this case, workflows have been presented summarizing the sequence of activities to perform. However, it would be useful to describe in detail all the steps in order to standardize the workflow as much as possible, without possibility to misunderstand the tasks to perform. Another outcome is related to the flexibility of workflows; the subdivision in the three phases data collection, processing and output is useful to understand how much the interaction among the selected tools can be customized on the basis of available data. This means that no matter the elaborations, some workflows are more flexible in terms of data input/output while others result so "fixed" that is not possible to customize them on the available information. Furthermore, the context of application is also a very important aspect to consider. For instance, if working as an appointing party in public works, the use of open standard formats is fundamental, because the information cannot be submitted in proprietary version. On the other side, working in private projects the use of open standards could be secondary, because the client could require the submission of information in proprietary format. This difference in terms of context has a strong impact on the choice of the most efficient workflows, also changing possibilities of data management and exchange among interested parties. To conclude, despite the possibility of defining framework for the assessment of the different approaches towards InfraBIM implementation, the result could differ a lot when giving priority to some criteria instead of others. This means that the most efficient workflow to achieve a specific scope depends on a lot of factors, which must be defined and sorted in order of importance before performing the assessment itself.

Chapter 7

BIM decision support tool

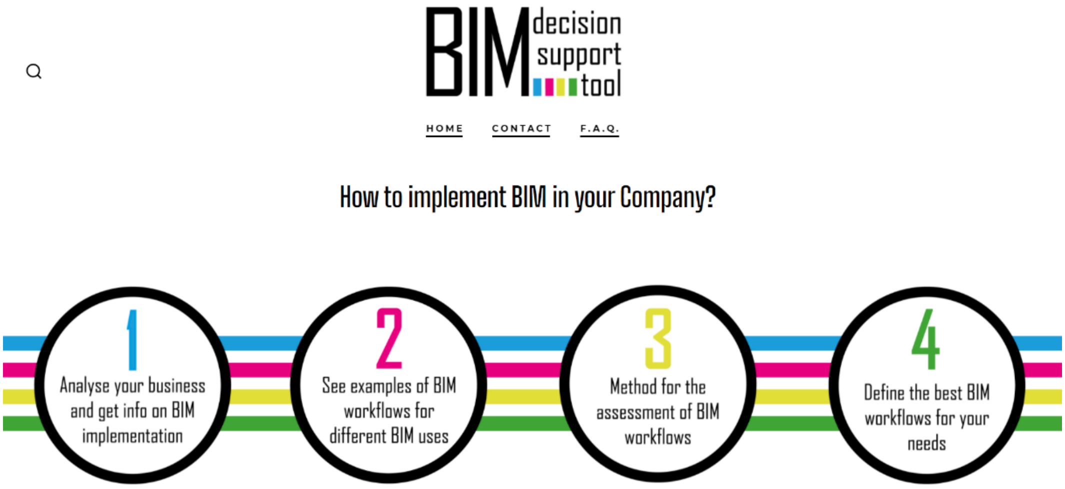


Fig. 81: BIM decision support tool home page

As part of the communication and dissemination process of the research, the **BIM Decision Support Tool** (BIMdst) website has been developed as a decision support tool for companies aiming at implementing BIM and InfraBIM and looking for the most efficient workflows. The platform is very easy to use because the homepage provides details on how to proceed with the whole process. The idea of creating such a platform was born from the desire to make the results obtained during the research activity available to different types of BIM users, showing the replicability and versatility of the workflows developed and of the methodology proposed for the assessment.

The first step is related to the analysis of users' business in terms of kind of company, size, interests etc. in order to get some basic information on how to implement BIM methods and tools, how to involve the team of employees/colleagues etc.

The second step includes the analysis of different BIM workflows examples developed for specific BIM uses and applications. This part includes the workflows developed during the research activities of the three years for several applications.

The third step is related to the explanation of the method for the assessment of BIM workflows, in which specific details on how to define the framework of the evaluation are given.

Within the fourth and last section of the guided process, users can use the assessment method developed to perform an analysis in which they can decide to which criteria they want to assign more weights, because they are more important on the basis of their needs as companies.

7.1 Analyse your business

Fig. 82: Benchmark of the company

First of all, users can analyse the state of the art of their company by answering questions related to their business (Fig. 82). The first question is related to the kind of company, the possible options are: Design firm (Architecture/Engineering), Contracting authority, Construction contractor, Supplier. The reason for this question is related to the fact that the implementation

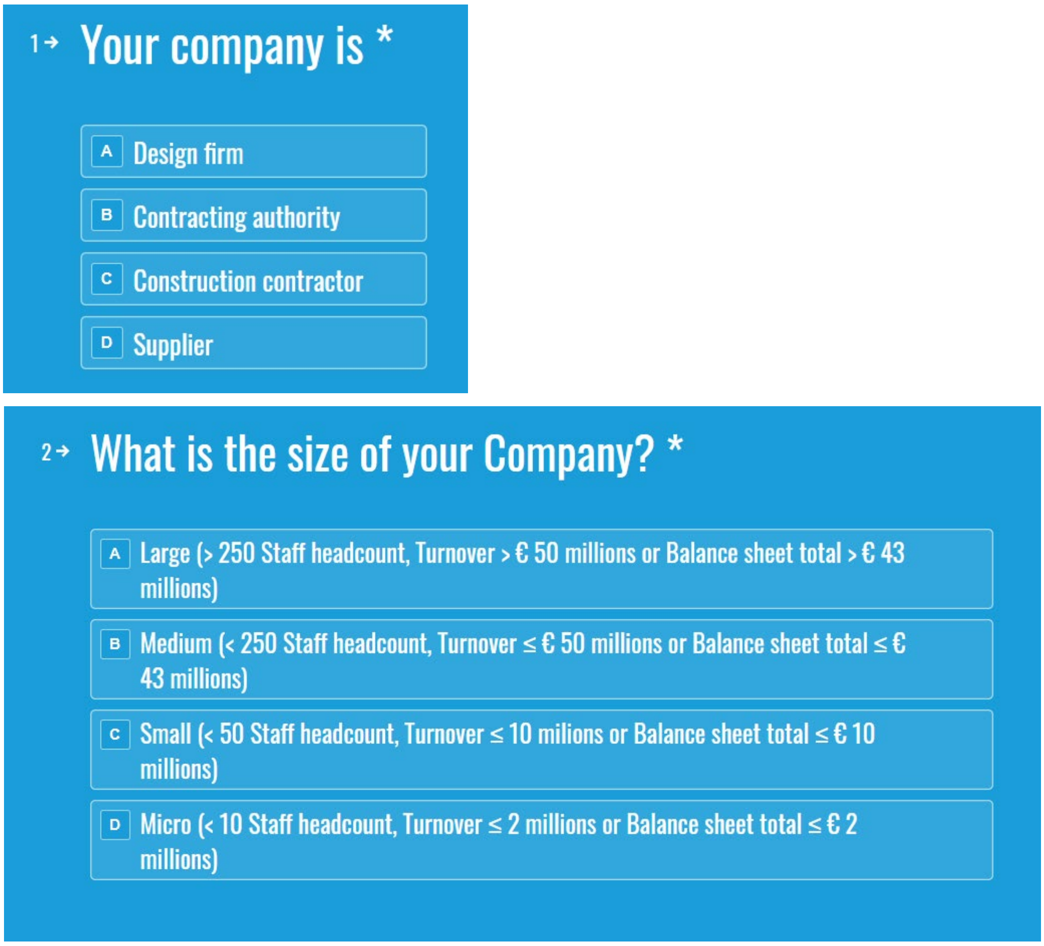


Fig. 83: Questions to benchmark the company

process changes its objectives and methods on the basis of the phase of the construction process in which the company operates. The second question is related

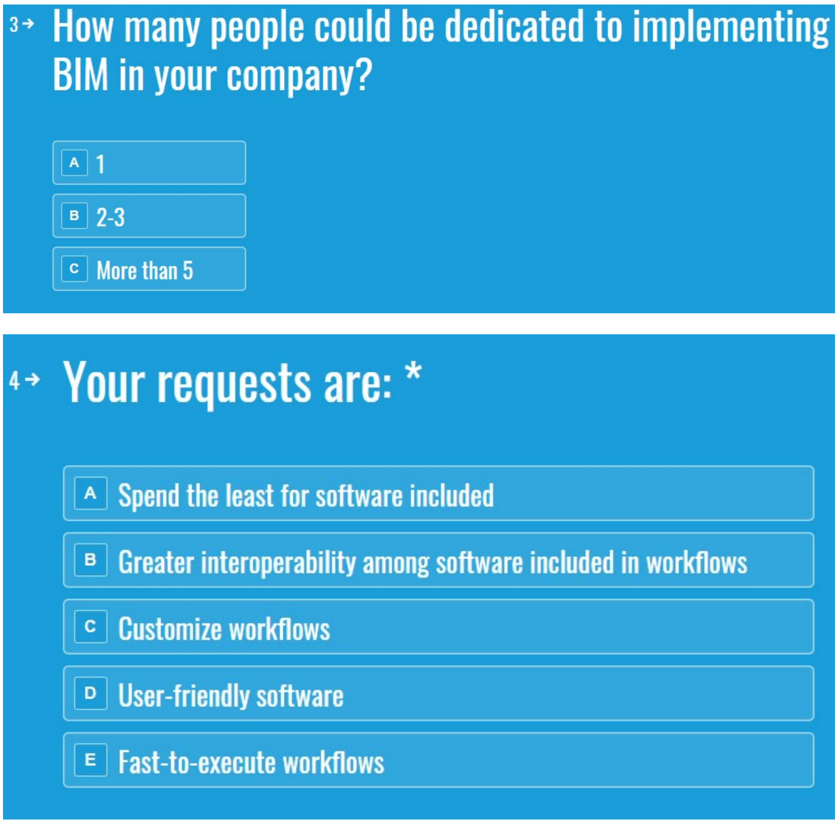


Fig. 84: Questions to benchmark the company

to understanding the company category, determining if the company is a large, medium, small or micro enterprise (Fig. 83 and Fig. 84). This part related to the business analysis is paramount in order to perform a benchmark of the company itself, which is categorized on the basis of its dimension. The reference for the categorization of business is the European Directive 2003/361/CE of European Commission, which introduces a wider definition of micro, small and medium enterprises based on the Staff headcount and the Turnover or Balance Sheet Total. From such a directive the DM 18 of April 2005 was born to adapt Italian criteria for identifying small and medium-sized enterprises to Community regulations. Within this definition the main factors determining the category of an enterprise are: (i) the Staff headcount; (ii) either the Turnover or the Balance sheet total. The third question is related to the human resources to be prepared for BIM implementation in the company; in this case it is important to understand the workload of each professional involved, in order not to put too much stress on him.

The last part of the section is useful to understand the most important factors to consider in the implementation process from the point of view of the different users. Indeed, on the basis of the company organization, focus and mission the objectives change a lot, as well as the approaches of implementation. At the end, on the basis of the answers given, users get the most appropriate ending and suggestion linked to the characteristics of their companies and to their needs. This represents the very first step to undertake a BIM implementation process, understanding the necessities and analysing the situation of the company itself, in order to start reasoning on which elements to work on.

7.2 See examples of BIM workflows for different BIM uses

This section summarizes the workflows developed for the different uses, include in Chapter 6. Each InfraBIM use is briefly described (Fig. 85). Workflows are presented and subdivided into three main phases: data collection, processing and output. This way users are provided with the necessary data to perform such workflows and being guided towards the testing phase.

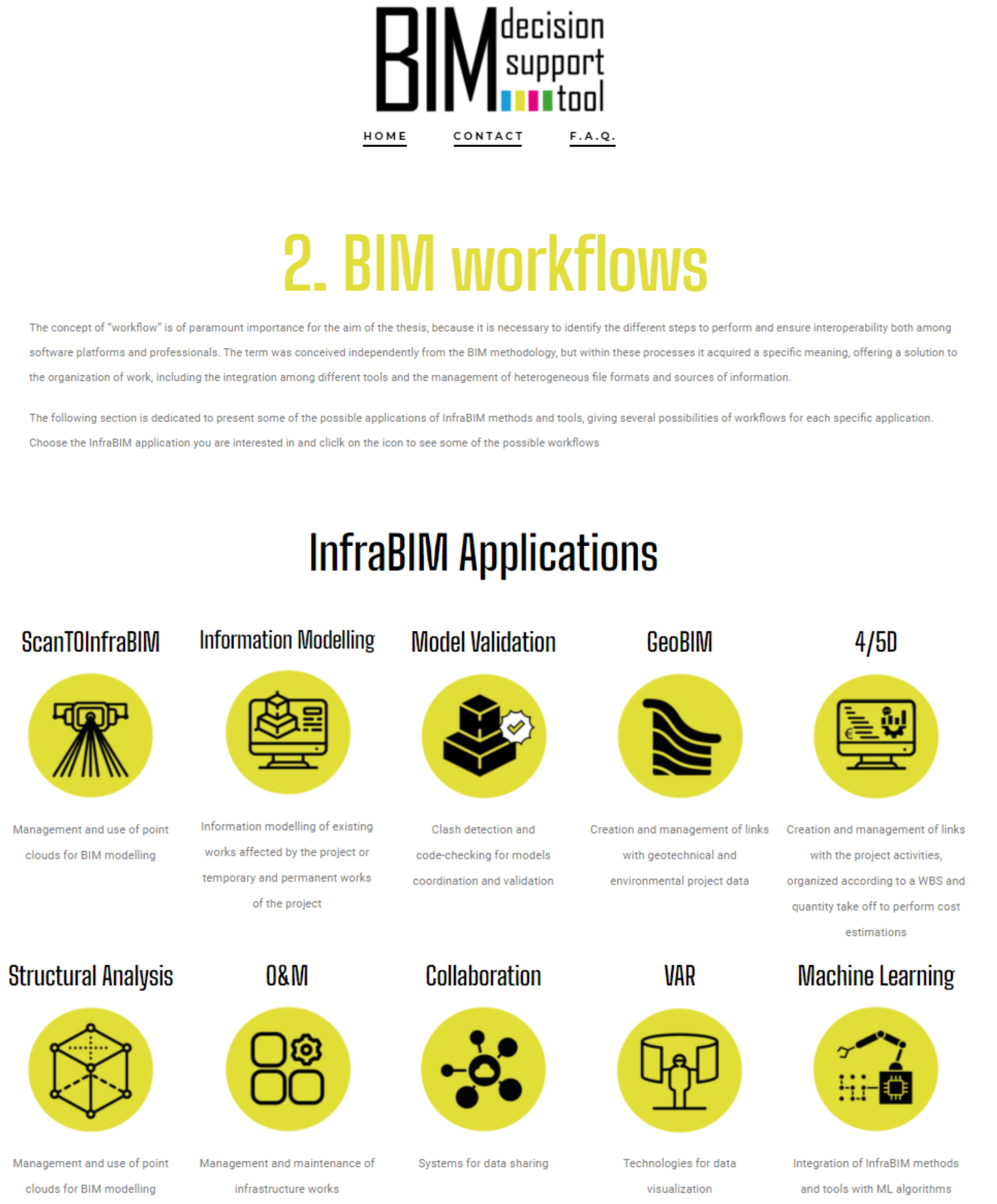


Fig. 85: Section of BIMdst related to the presentation of workflows

7.3 AHP method for the assessment of BIM workflows

Fig. 86: Section 3 - Assessment

This section explains how the assessment is performed using the AHP method (Fig. 86), highlighting the following hierarchical configuration:

– Goal of the assessment, and namely defining the most efficient workflow for a specific BIM on the basis of specific requirements;

– Macro-domain as key factors for the subdivision of criteria considered for the assessment;

– Criteria as the dimensions of each Macro-domain that influence the efficiency of workflows;

– Sub-criteria are the indicators representing general and specific characteristics of the workflows considered;

– Alternatives are the different possible workflows proposed in chapter 6 for each BIM use.

The results of assessment reflect the priorities defined by the author of the present study, explained in section 6.2. Therefore, it could work in some cases, but not in others, since the weighting of criteria change on the basis of the users’ needs and requirements. This represent a limit of the assessment, because it is subjective and can change substantially based on the decisions towards weighting.

7.4 Define the best workflow for your needs

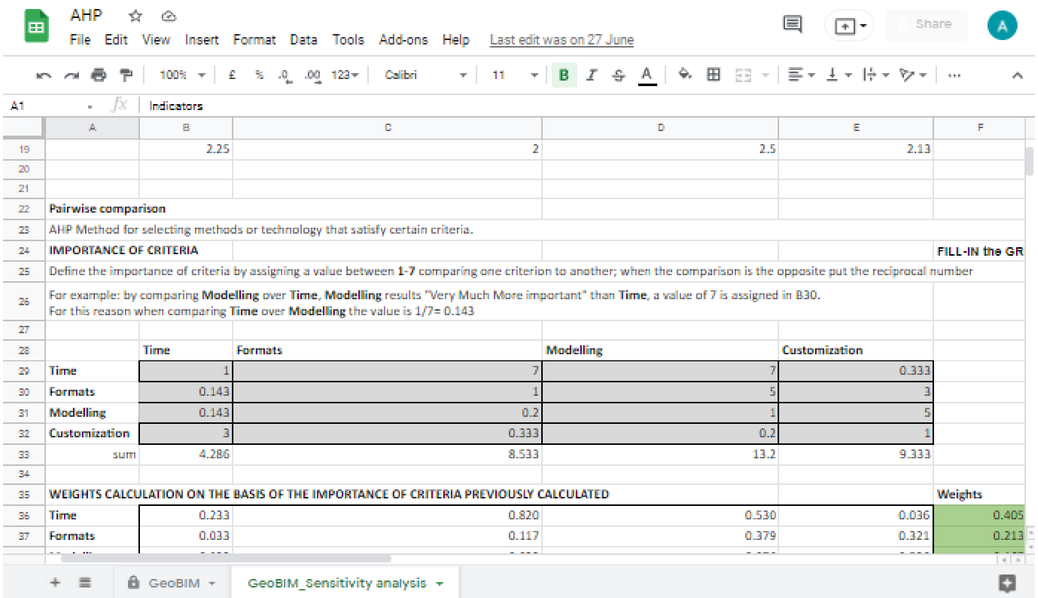


Fig. 87: The assessment framework

To overcome the limit previously highlighted, the last step of the process is related to the possibility for users to download and modify the assessment on the basis of their needs, by changing priority of criteria or the values for indicators. The assessment framework has been built in Google Drive, to give users the chance to download it and change values for indicators, criteria and weighting for the pairwise comparison (Fig. 87). The first sheet of the document is locked to show users how the calculation was performed. In the second sheet, instructions on how to proceed to use the framework for the assessment are provided.

Chapter 8

Results

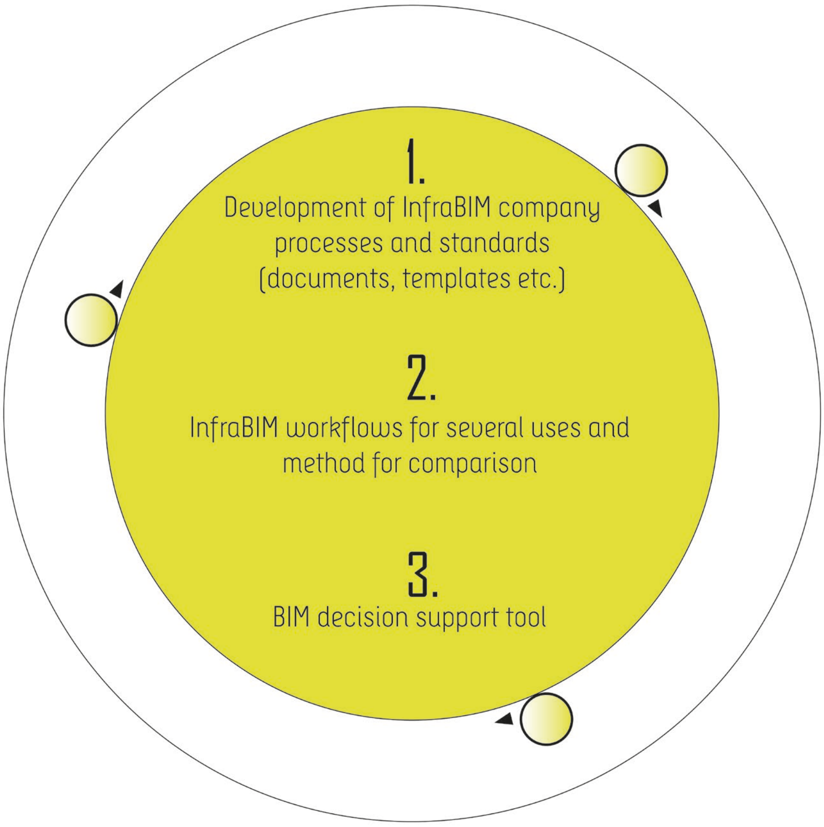


Fig. 88: Three levels of results

The present research activity highlighted the challenges and current implementation strategies of BIM at infrastructural domain. Several issues still must be overcome not only in terms of interoperability between software applications but also related to the transformation of different types of processes. The fast application of BIM methods and tools to infrastructural projects represented a direct consequence of international and national regulations. In Italy, the current procurements are increasing the requirement on the production of information models. This is inevitably leading to a progressive increase of awareness towards InfraBIM processes, both in contracting authorities and contractors. In this framework, contractual documents and, in particular Exchange Information Requirements (EIR) documents produced by contracting authorities, are rapidly increasing their quality, showing a growing ability to manage information models and all their possible analyses and uses.

The research findings suggest that it is paramount to study and develop specific processes for InfraBIM implementation to better manage the production of information models and awareness in terms of methods and tools to use.

Furthermore, the development of specific workflows to be compared to each other is essential to understand criticalities and strengths, in order to select the most efficient on the basis of the specific requirements. The tests carried out within this study shows the variety of approaches and tools that can be used to achieve specific purposes to use InfraBIM information models within the design, construction and asset management phases.

In this framework, the research activity achieved "different levels" of results Fig. 88. Indeed, the first level of results was obtained at company level, through the proposal of specific processes for BIM implementation and the elaboration of drafting template documents. Within this context, in the timeline of the research activity presented in section 5.1 the starting point involves the necessity to define a strategy towards the implementation process. This is not valid only for BIM, but it could be applied to further methodologies to implement in the future. At company level, four main processes have been developed to detail the resource management, collaboration, production, coordination and validation, leading to the development of specific documents useful to coordinate and manage the pre-defined processes from an operational point of view. Three main types of documents have been produced with the aim to update them on the basis on further evolutions both in terms of technical issues and procedures: (i) BIM Strategy Document with the purpose to give a basic knowledge on methods and tools by presenting examples from pilot projects; (ii) templates for contractual documents such as oGI, pGI etc. to start from for future calls for tenders and procurements; (iii) specific documents explaining the development of workflows for different InfraBIM uses, such as those previously presented, in order to give possible ways of achieving a desired result. The production of such types of documents had a two-fold meaning; on the one side to train and educate professionals to follow the procedures pre-defined through previous experiences and tests, and on the other side to prepare drafts that could be useful for future procurements, to be updated on the basis of requirements and needs.

The second level of results was obtained in terms of workflows, to integrate different InfraBIM methods and tools for specific BIM uses. Such development, specifically the data processing phase, was guided by the available data input and the required data output. The definition of uses was based on the possible aims and objectives of information models for infrastructures in the different design, construction, and management phases. Once having defined different workflows to fulfill the InfraBIM uses identified, a framework for the assessment based on one of the multi-criteria methods, the AHP, has been developed to compare different alternatives of workflow. The assessment was developed by defining values of indicators through interoperability test performed on the cases studies. The types of KPIs used for the assessment reflected the necessities emerged by the survey performed on a sample of professionals using BIM. Furthermore, the assessment had the scope to use metrics that could be easily applied autonomously by any BIM user interested in assessing specific workflows. For this reason, the strength of the assessment relies on the fact that the framework itself can easily adapt on the basis of the values chosen; changing the value of indicators and the priorities assigned to each parameter of evaluation, the result of the assessment could change. To establish the most efficient one on the basis of criteria to which different weights of importance can be assigned considering the BIM users' needs.

The third and last level of results brought to the development of a webpage with the aim to collect and communicate the research findings and to work as a decision support tool for different sized companies approaching InfraBIM implementation. The webpage is user-friendly to use because the homepage provides the details on how to proceed with the whole process. The process starts from the analysis of users' business in terms of kind of company, size, etc. to provide basic strategies on InfraBIM implementation. The second step includes the presentation of different examples of BIM workflows developed for specific uses. The third step provides information on the assessment, giving specific details on how the framework for the evaluation was defined. Within the fourth and last section, users can customize the assessment deciding which criteria to prioritize on the basis of their needs as companies. The BIM decision support tool shows the replicability and versatility of both workflows developed and of the methodology proposed not only for the assessment but for the whole research activity process too.

Chapter 9

Conclusions and future developments

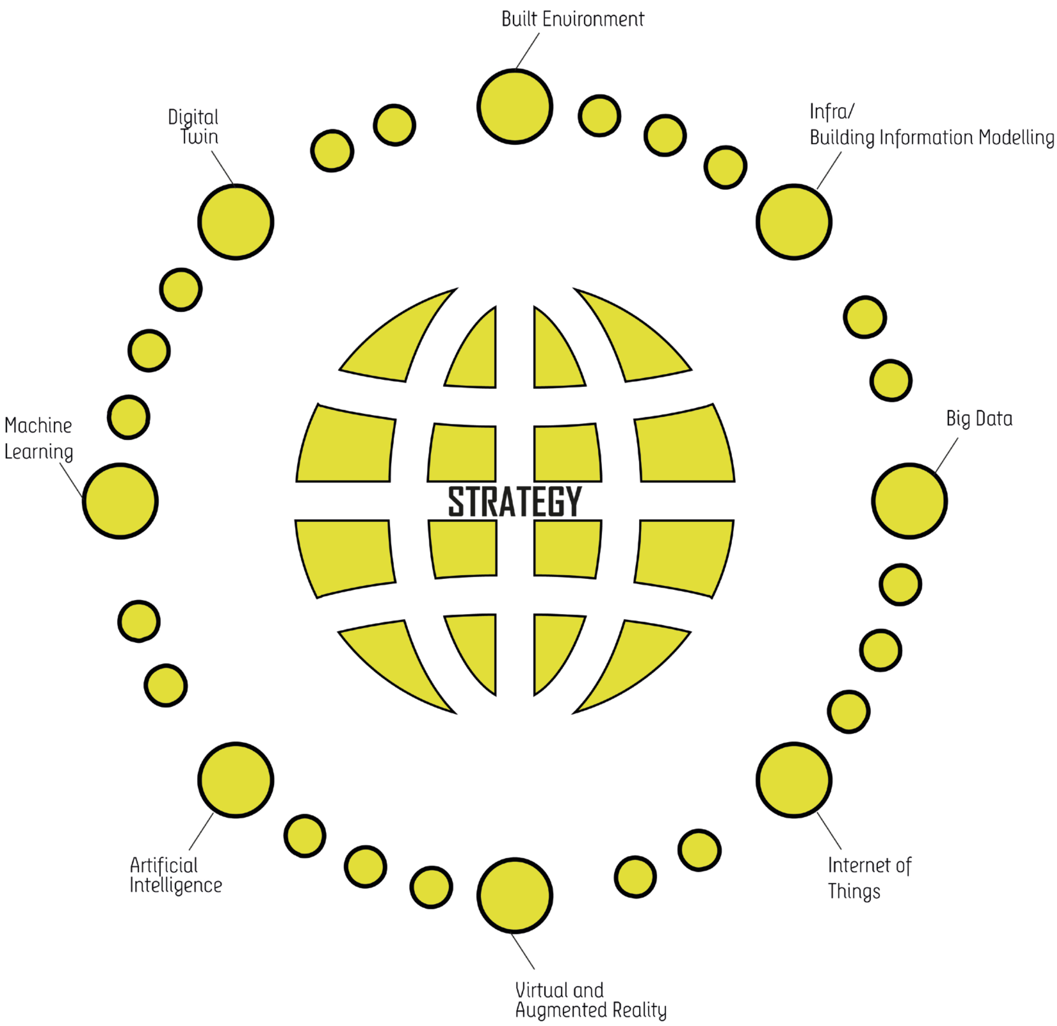


Fig. 89: Strategy as the real driver of digital transformation

Currently, the impact of digital innovation in the AECO sector is still lagging behind other fields, negatively affecting productivity too. Compared to sectors such as the automotive or manufacturing ones, the use of enabling technologies still faces major challenges in the construction industry for several reasons. The lack of resources in terms of cost and people represents one of the main issues towards the implementation of such technologies, limiting possible benefits and advantages deriving from the integration of new methods and tools.

In this framework, the implementation of InfraBIM processes has been currently undertaken by most engineering firms, contractors and contracting authorities also, mainly due to the gradual introduction of mandatory use of electronic tools as required within the Directive 2014/24/EU. The research activity highlighted the importance to combine enabling technologies and innovation management, because the real driver of digital transformation is "strategy, not technology" (Kane, Palmer, Philips, Kiron, & Buckely, 2015) (Fig. 89). This means that technologies do not necessarily provide an added value, but companies must be willing to adapt strategies and capabilities to embrace new ways of perceiving and creating value. However, future developments involve the use of information models (the "virtual" products) in order to establish a connection with the "physical" assets. The aim of such integration is to develop a Digital Twin as an environment for an automated data exchange in real-time, collecting data from smart sensors to perform simulations and predict the system's future state.

Within this context, several research projects already developed Digital Twins with the aim to establish such a connection; each of these activities showed different possible characteristics of the DT environment, but there are still issues in its practical application. This is due to several factors, such as the difficulties within the collaboration among professionals, data standards integration, the substantial amount of data to collect and process etc. A very ambitious project is under development by the European Space Agency (ESA); the scope is to develop a Digital Twin Earth to "visualize, monitor and forecast natural and human activities on the planet" (ESA, 2020). The DT aims to be able to perform simulations on Earth's systems and monitor the health of the planet. Such experiences represent ambitious projects that could serve as a decision support tool for future development of interconnections between what is "Physical" and what is "Virtual".

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10 Appendix A: List of publications

Proceedings: Fonsati, Arianna; Osello, Anna; Damiani, Alessandro (2018) "A BIM-based infrastructural project approach for time and cost estimation". In: Rappresentazione/Materiale/Immateriale. Drawing as (in)tangible representation. 40° Convegno Internazionale dei Docenti delle Discipline della Rappresentazione, Milan, Italy, 13-15 September, 2018. Gangemi Editore, Roma, pp. 1511-1514. ISBN: 978-88-492-3651-4

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Book: Osello, Anna; Fonsati, Arianna; Rapetti, Niccolò; Semeraro, Francesco (2019) "InfraBIM. Il BIM per le infrastrutture", Gangemi Editore spa, Roma. ISBN 9788849237993

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Proceedings: De Luca, Daniela; Fonsati, Arianna; Osello, Anna (2019) "Virtual Reality for training the public towards unexpected emergency situations". In: 2019 IEEE 9th International Conference on Consumer Electronics (ICCE-Berlin), Berlino, 8-11 Settembre 2019, IEEE. ISBN elettronico: 978-1-7281-2775-0. ISBN stampa: 978-1-7281-2745-3

Scientific paper: Fonsati, Arianna; Del Giudice, Matteo; Zanor, Loris (2020) "Livello di formazione BIM: un possibile approccio/ BIM level of education: a possible approach". In DN, vol. 6, pp. 29-40. ISSN 2620-8755

Book Chapter: Fonsati, Arianna (2020) "KPIs to Drive Smart City Assessment". In: Handbook of Research on Developing Smart Cities Based on Digital Twins/Del Giudice, Matteo; Osello, Anna, IGI Global, Hershey PA, pp. 172-195. ISBN: 9781799870913

Proceedings: Ugliotti, Francesca Maria; De Luca, Daniela; Fonsati, Arianna; Del Giudice, Matteo; Osello, Anna (2020) "Students and teachers turn into avatars for online education". In: 15th International Technology, Education and Development Conference (Digital) 8-9 March, 2021. pp. 4556-4565

Book Chapter: Fonsati, Arianna; De Marco, Alberto; Osello, Anna (2021) "OpenBIM methods and tools for schedule and cost management". In: Sustainability and Automation in Smart Constructions/Rodrigues H., Gaspar F., Fernandes P., Mateus A, Springer, pp. 37- 43. ISBN 978-3-030-35533-3

11 Appendix B: Sheets of AHP assessment

AHP_GeoBIM

ALTERNATIVES	DESCRIPTION
1	Rockworks
2	Civil3D-Geotechnical Module-Revit
3	Novapoint-Civil3D-Navisworks
4	Leapfrog-Revit

	INDICATORS					
ALTERNATIVES	Number of formats for import/export [N]	Information modelling share [%]	Customization share [%]	Time for worklow execution [min]	User-friendliness Share [%]	Overal Cost of Workflows [€]
1	6	0.3	0.01	30	0.3	5000.00
2	7	0.6	0.8	120	0.6	3115.00
3	10	0.5	0.4	180	0.2	5615.00
4	5	0.4	0.7	60	0.8	33115.00

maximize	minimize
value - min / max - min	max - value / max - min

Maximization/Minimization of Indicators

ALTERNATIVES	Number of formats for import/export [N]	Information modelling share [%]	Customization share [%]	Time for worklow execution [min]	User-friendliness Share [%]	Overal Cost of Workflows [€]
1	0.20	0.00	0.00	1.00	0.17	0.94
2	0.40	1.00	1.00	0.40	0.67	1.00
3	1.00	0.67	0.49	0.00	0.00	0.92
4	0.00	0.33	0.87	0.80	1.00	0.00
	1.6	2	2.367	2.2	1.833333333	2.854

Pairwise comparison

AHP Method for selecting workflows that satisfy certain criteria

IMPORTANCE OF CRITERIA

The importance of criteria is assigned a value between **1-9** comparing one criterion to another; when the comparison is the opposite put the reciprocal number

For example: by comparing **Interoperability** over **Cost**, **Interoperability** results "Very Much More important" than **Cost**, a value of 9 is assigned in F35.

	Inf. modelling share	Exchange formats	Customization	Time	User-friendliness	Cost
Inf. modelling share	1	3	3	5	7	9
Exchange formats	0.333	1	3	5	7	9
Customization	0.333	0.333	1	3	5	7
Time	0.200	0.200	0.3	1	3	5
User-friendliness	0.143	0.143	0.2	0.333	1	3
Cost	0.111	0.111	0.143	0.2	0.333	1
sum	2.121	4.787	7.676	15	23.333	34

MATRIX IS

ALWAYS SQUARE!

Cell to fill in

WEIGHTS CALCULATION ON THE BASIS OF THE IMPORTANCE OF CRITERIA PREVIOUSLY CALCULATED

							Weights
Exchange formats	0.157	0.209	0.391	0.344	0.300	0.265	0.278
Inf. modelling share	0.472	0.627	0.391	0.344	0.300	0.265	0.400
Customization	0.157	0.070	0.130	0.206	0.214	0.206	0.164
Time	0.094	0.042	0.043	0.069	0.129	0.147	0.087
User-friendliness	0.067	0.030	0.026	0.023	0.043	0.088	0.046
Cost	0.052	0.023	0.019	0.014	0.014	0.029	0.025
checksum	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Sum must be 1

EVALUATION OF CHOICES

In this matrix the values for the indicators of each alternative after Maximization/Minimization are inserted

	Number of formats for import/export [N]	Information modelling share [%]	Customization share [%]	Time for worklow execution [min]	User-friendliness Share [%]	Overal Cost of Workflows [€]
1	0.2	0	0	1	0.166666667	0.937
2	0.4	1	1.000	0.400	0.666666667	1.000
3	1	0.666666667	0.494	0.000	0	0.917
4	0	0.333333333	0.873417722	0.8	1	0.000
sum	1.6	2	2.37	2.2	1.833333333	2.854

This matrix may or may not be square.

COLUMN-NORMALIZED MATRIX:

1	0.125	0.000	0.000	0.455	0.091	0.328
2	0.250	0.500	0.422	0.182	0.364	0.350
3	0.625	0.333	0.209	0.000	0.000	0.321
4	0.000	0.167	0.369	0.364	0.545	0.000
checksum	1.000	1.000	1.000	1.000	1.000	1.000

	Weights
Exchange formats	0.278
Inf. modelling share	0.400
Customization	0.164
Time	0.087
User-friendliness	0.046
Cost	0.025

Multiply the Column-normalized matrix by the Weights column vector to yield the SCORES column vector.

SCORES:

1	0.087
2	0.380
3	0.349
4	0.184
checksum	1.000

Highest score is the recommended alternative: alternative workflow n. 4 for GeoBIM is the most efficient on the basis of the importance given to criteria

Notes:
This example had five criteria, and four choices.
There could have been two choices, or four. Matrix 3 need not be square.
Matrix 1 will always be square.

AHP_Structural analysis

ALTERNATIVES	DESCRIPTION
1	Revit-ETABS (IFC)
2	Revit-SAP2000 (IFC)
3	Revit-ETABS (CSixRevit)
4	Revit-SAP2000 (CSixRevit)
5	Revit-ETABS-Dynamo

	INDICATORS					
ALTERNATIVES	Number of formats for import/export [N]	Information modelling share [%]	Customization share [%]	Time for worklow execution [min]	User-friendliness Share [%]	Overal Cost of Workflows [€]
1	5	0.3	0.3	1.5	0.3	3815
2	7	0.2	0.2	2	0.4	6715
3	5	0.4	0.5	3.53	0.6	3815
4	7	0.5	0.4	1.38	0.7	6715
5	8	0.7	0.9	13.2	0.75	3815

maximize	minimize
value - min / max - min	max - value / max - min

Maximization/Minimization of Indicators

ALTERNATIVES	Number of formats for import/export [N]	Information modelling share [%]	Customization share [%]	Time for worklow execution [min]	User-friendliness Share [%]	Overal Cost of Workflows [€]
1	0.000	0.200	0.143	0.990	0.000	1.000
2	0.667	0.000	0.000	0.948	0.222	0.000
3	0.000	0.400	0.429	0.818	0.667	1.000
4	1.000	0.600	0.286	1.000	0.033	0.000
5	1.000	1.000	1.000	0.000	1.000	1.000
	1.666666667	2.2	1.857	3.755499154	1.922222222	3.000

Pairwise comparison

AHP Method for selecting workflows that satisfy certain criteria

IMPORTANCE OF CRITERIA

The importance of criteria is assigned a value between **1-9** comparing one criterion to another; when the comparison is the opposite put the reciprocal number

For example: by comparing **Interoperability** over **Cost**, **Interoperability** results "Very Much More important" than **Cost**, a value of 9 is assigned in F35.

	Inf. modelling share	Exchange formats	Customization	Time	User-friendliness	Cost
Inf. modelling share	1	3	3	5	7	9
Exchange formats	0.333	1	3	5	7	9
Customization	0.333	0.333	1	3	5	7
Time	0.200	0.200	0.3	1	3	5
User-friendliness	0.143	0.143	0.2	0.333	1	3
Cost	0.111	0.111	0.143	0.2	0.333	1
sum	2.121	4.787	7.676	15	23.333	34

MATRIX IS

ALWAYS SQUARE!

Cell to fill in

WEIGHTS CALCULATION ON THE BASIS OF THE IMPORTANCE OF CRITERIA PREVIOUSLY CALCULATED							Weights
Exchange formats	0.157	0.209	0.391	0.344	0.300	0.265	0.278
Inf. modelling share	0.472	0.627	0.391	0.344	0.300	0.265	0.400
Customization	0.157	0.070	0.130	0.206	0.214	0.206	0.164
Time	0.094	0.042	0.043	0.069	0.129	0.147	0.087
User-friendliness	0.067	0.030	0.026	0.023	0.043	0.088	0.046
Cost	0.052	0.023	0.019	0.014	0.014	0.029	0.025
checksum	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Sum must be 1

EVALUATION OF CHOICES

In this matrix the values for the indicators of each alternative after Maximization/Minimization are inserted

	Number of formats for import/export [N]	Information modelling share [%]	Customization share [%]	Time for worklow execution [min]	User-friendliness Share [%]	Overal Cost of Workflows [€]
1	0	0.2	0.142857143	0.989847716	0	1.000
2	0.666666667	0	0.000	0.948	0.222222222	0.000
3	0	0.4	0.429	0.818	0.666666667	1.000
4	1	0.6	0.285714286	1	0.033333333	0.000
5	1	1	1	0	1	1.000
sum	2.666666667	2.2	1.86	3.755499154	1.922222222	3.000

This matrix may or may not be square.

COLUMN-NORMALIZED MATRIX:

1	0.000	0.091	0.077	0.264	0.000	0.333
2	0.250	0.000	0.000	0.252	0.116	0.000
3	0.000	0.182	0.231	0.218	0.347	0.333
4	0.375	0.273	0.154	0.266	0.017	0.000
5	0.375	0.455	0.538	0.000	0.520	0.333
checksum	1.000	1.000	1.000	1.000	1.000	1.000

	Weights
Exchange formats	0.278
Inf. modelling share	0.400
Customization	0.164
Time	0.087
User-friendliness	0.046
Cost	0.025

Multiply the Column-normalized matrix by the Weights column vector
to yield the SCORES column vector.

SCORES:

1	0.080
2	0.097
3	0.154
4	0.262
5	0.406
checksum	1.000

Highest score is the recommended alternative: alternative workflow n. 5 for Structural analysis is the most efficient on the basis of the importance given to criteria

Notes:
This example had five criteria, and four choices.
There could have been two choices, or four. Matrix 3 need not be square.
Matrix 1 will always be square.

AHP_4/5D

ALTERNATIVES	DESCRIPTION
1	Revit-Navisworks-Excel/Microsoft Project
2	Revit-Synchro Pro-STR CPM Vision-Microsoft Project
3	Revit-Dynamo

	INDICATORS					
ALTERNATIVES	Number of formats for import/export [N]	Information modelling share [%]	Customization share [%]	Time for worklow execution [min]	User-friendliness Share [%]	Overal Cost of Workflows [€]
1	5	0.6	0.2	40	0.9	3115
2	2	0.7	0.4	60	0.3	7547
3	1	0.5	0.8	20	0.6	3115

maximize	minimize
value - min / max - min	max - value / max - min

Maximization/Minimization of Indicators

ALTERNATIVES	Number of formats for import/export [N]	Information modelling share [%]	Customization share [%]	Time for worklow execution [min]	User-friendliness Share [%]	Overal Cost of Workflows [€]
1	1	0.5	0	1	1	1.000
2	0.25	1	0.333	0.000	0	0.000
3	0	0	1.000	1.000	0.5	1.000
	1.25	1.50	1.33	2.00	1.50	2.00

Pairwise comparison

AHP Method for selecting workflows that satisfy certain criteria

IMPORTANCE OF CRITERIA

The importance of criteria is assigned a value between **1-9** comparing one criterion to another; when the comparison is the opposite put the reciprocal number

For example: by comparing **Interoperability** over **Cost**, **Interoperability** results "Very Much More important" than **Cost**, a value of 9 is assigned in F35.

	Inf. modelling share	Exchange formats	Customization	Time	User-friendliness	Cost
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Time	0.200	0.200	0.3	1	3	5
User-friendliness	0.143	0.143	0.2	0.333	1	3
Cost	0.111	0.111	0.143	0.2	0.333	1
sum	2.121	4.787	7.676	15	23.333	34

MATRIX IS

ALWAYS SQUARE!

Cell to fill in

WEIGHTS CALCULATION ON THE BASIS OF THE IMPORTANCE OF CRITERIA PREVIOUSLY CALCULATED

							Weights	
Exchange formats	tt	0.209	0.391	0.344	0.300	0.265	0.302	
Inf. modelling share	0.472	0.627	0.391	0.344	0.300	0.265	0.400	
Customization	0.157	0.070	0.130	0.206	0.214	0.206	0.164	
Time	0.094	0.042	0.043	0.069	0.129	0.147	0.087	
User-friendliness	0.067	0.030	0.026	0.023	0.043	0.088	0.046	
Cost	0.052	0.023	0.019	0.014	0.014	0.029	0.025	
checksum	0.843	1.000	1.000	1.000	1.000	1.000	1.024	Sum must be 1

EVALUATION OF CHOICES

In this matrix the values for the indicators of each alternative after Maximization/Minimization are inserted

	Number of formats for import/export [N]	Information modelling share [%]	Customization share [%]	Time for worklow execution [min]	User-friendliness Share [%]	Overal Cost of Workflows [€]
1	1	0.5	0	1	1	1.000
2	0.25	1	0.333	0.000	0	0.000
3	0	0	1.000	1.000	0.5	1.000
sum	1.25	1.5	1.33	2	1.5	2.000

This matrix may or may not be square.

COLUMN-NORMALIZED MATRIX:

1	0.800	0.333	0.000	0.500	0.667	0.500
2	0.200	0.667	0.250	0.000	0.000	0.000
3	0.000	0.000	0.750	0.500	0.333	0.500
checksum	1.000	1.000	1.000	1.000	1.000	1.000

	Weights
Exchange formats	0.302
Inf. modelling share	0.400
Customization	0.164
Time	0.087
User-friendliness	0.046
Cost	0.025

Multiply the Column-normalized matrix by the Weights column vector
to yield the SCORES column vector.

SCORES:

1	0.462	Highest score is the recommended alternative: alternative workflow n. 1 for 4/5D is the most efficient on the basis of the importance given to criteria
2	0.368	
3	0.195	
checksum	1.024	

Notes:
This example had five criteria, and four choices.
There could have been two choices, or four. Matrix 3 need not be square.
Matrix 1 will always be square.