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Building Information Modelling

BIM adoption for structural engineering design.

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STATEMENT OF INTEGRITY

I hereby declare to have conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of ethics and conduct of Politecnico di Milano.

SOMMARIO.

L'obiettivo di questa Tesi consiste nel valutare gli sviluppi, vantaggi e le applicazioni nell'adozione del "Building Information Modeling" (BIM) in generale, e per la progettazione strutturale degli edifici in cemento armato gettati in opera in particolare.

Il BIM è stato considerato come un nuovo modo di progettare, costruire e gestire un'opera edilizia che genera maggior efficienza, miglior ottimizzazione delle risorse, miglior gestione e manutenzione dell'opera durante tutto il suo ciclo di vita. Il BIM aumenta il grado di digitalizzazione dei processi, aprendo le porte a tecnologie integrate e collaborative per la progettazione, costruzione e gestione delle opere edilizie.

Per capire il BIM ed i suoi vantaggi, è necessario considerare tutte le fasi di un progetto. Un costo iniziale più elevato per la progettazione può portare a costi inferiori per la costruzione e la sua gestione. La creazione di modelli digitali ricchi di dati aiuta a prevedere e coordinare meglio le fasi di costruzione e gestione dell'opera. Uno dei principali limiti individuati nell'adozione del BIM è la mancanza di conoscenze e di professionisti qualificati. Discipline specifiche come la progettazione strutturale e meccanica dipendono dal fatto che l'appaltatore, il proprietario, o l'architetto utilizzino o richiedano l'applicazione del BIM per i loro progetti. La presenza di una policy BIM di supporto o obbligatoria, può quindi segnare definitivamente la sua adozione.

Il "Business Process Re-engineering" (BPR) consente di analizzare i processi "AS-IS" attuali, i passaggi attraverso i quali il BIM può essere implementato, ed i processi "TO-BE" dello stato futuro. L'applicazione del BIM per la progettazione strutturale consente a gestori e proprietari di prevedere meglio e più rapidamente i costi, supporta una corretta programmazione dei lavori di costruzione, contribuisce al rilevamento dei conflitti, facilita gli interventi futuri durante la costruzione, riduce i costi per i lavori di costruzione ed in generale contribuisce ad una visione integrata dell'opera.

Molte realizzazioni sono state realizzate con successo negli ultimi anni grazie alla metodologia BIM. Gli ingegneri strutturisti risultano essere più disposti all'adozione del BIM rispetto ad altre discipline. Si nota che chi fa più uso del BIM, è probabile che apprezzi la sua applicazione anche nei progetti futuri. La sua adozione porta benefici in tutte le fasi di un progetto. Maggior qualità, costi ridotti, progetti dettagliati, migliori stime dei lavori, automatizzazione dei processi, gestioni dei disegni, visualizzazione virtuale 3D del progetto e miglior coordinamento in cantiere, sono solo alcuni dei vantaggi identificati.

Per lo scopo della tesi, sono stati costruiti alcuni processi di lavoro ed il BPR è stato applicato per migliorare l'adozione del BIM. Software che fanno uso del BIM per la progettazione strutturale, *Autodesk Revit-Robot 2021, Autodesk Revit-SOFiSTiK 2021, ProSap Professional v21 e Tekla Structures-Tekla Structural Designer 2021*, sono stati introdotti ed analizzati in processi integrati di lavoro a dei Casi di Studio, e succesivamente valutati in base a dei criteri prescelti. Un nuovo modello, il *BIM SDWAM ("BIM Structural Design's Workflow Assessment Model")*, vi è proposto ed applicato nella valutazione dei processi. Discussioni e conclusioni sonno presentate nell'ultimo capitolo.

Parole chiave: Adozione del BIM, processi di lavoro, progettazione strutturale.

ABSTRACT.

The intention of the Thesis is to exploit the developments, benefits, and applications of "Building Information Modelling" (BIM) adoption in general, and with focus to the structural design discipline for cast in place reinforced concrete buildings.

BIM has been mainly considered as a new way of designing, constructing, and operating a building or infrastructure. It has been identified as generating bigger opportunities for higher efficiency, optimization of resources and in general better management during all the life cycle of a facility. BIM increases the digitization of processes, offering integrated and collaborative technologies for design, construction, and operation.

To understand BIM and its benefits, it is necessary to take into evaluation all the phases of a project. Higher initial cost for design can bring to lower ones for construction and operation. Creating data rich digital models, helps to better predict and coordinate the construction phases and operation of a building. One of the main limitations identified in BIM adoption is the lack of knowledge and qualified skilled professionals. Specific disciplines like structural and mechanical design depend, if the main contractor, owner, general contractor, or architect are making use or require applying BIM for their projects. The presence of a supporting or mandatory BIM policy, can then finally conclude its adoption.

"Business Process Re-engineering" (BPR) allows to analyse actual "*AS-IS*" processes within AEC firms, vision steps through the ones BIM can be implemented, and consolidate "*TO-BE*" processes that can be developed with time. Applying BIM for structural engineering design, allows managers and owners to predict costs better and faster, supports a correct scheduling of constructions works, contributes to clash detections, facilitates future interventions during the building operation, reduces costs for construction works and in general contributes to an integrated vision of the facility.

Many realizations have been identified in the BIM adoption for projects with success in the last decades. Structural Engineers are very positive to the BIM adoption compared to the other disciplines. It is noted that more you make use of BIM, more it is likely you will appreciate its application also in the future projects. Its adoption it is identified to generate benefits in all stages of a project. Higher quality, reduced costs, reliable designs, accurate quantities, automated processes and drawing management, 3D virtual visualization and better site coordination, are just some of the benefits identified.

For the scope of the Thesis, some workflows for structural design are built, and BPR applied to improve them towards BIM adoption. Structural design BIM enabled software, Autodesk *Revit - Robot SA 2021*, *Autodesk Revit – SOFiSTiK 2021*, *ProSap Professional v21* and *Tekla Structural Designer (TSD) - Tekla Structures (TS) 2021*, are introduced, analysed, and applied in integrated workflows to some Case Studies, and subsequently evaluated based on some defined criteria. A new *BIM SDWAM (*"*BIM Structural Design's Workflow Assessment Model"*) is proposed and applied for the evaluation of the presented workflows. Discussions and conclusions are presented in the last Chapter.

Keywords: BIM adoption, workflows, structural design.

TABLE OF CONTENTS.

LIST OF FIGURES.

LIST OF TABLES

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1. INTRODUCTION.

BIM stands for "*Building Information Modelling*". It has been initially introduced a few decades ago to better define the new data-rich models developed, compared to the standard traditional 2D designs. It consists in a collaborative approach for an integrated management of building information, facilitating the interoperability of data through digitalization and automation. It goes through all the life-cycle phases of a project starting from design, construction to facility management (Sacks R. et al., 2018) (Tang et al., 2017)

In 1975 Charles Eastman will introduce the BDS - "Building Description System" as a database capable of describing buildings at a higher level of detail for the design and construction phases. The focus of the BDS is for custom designed or system buildings. This is the beginning, where more attention is given to the enrichment of models with data structures and schemas with interaction between the non-graphical information and the graphical designs. These programs consisted in databases with functionalities of customization and modification, they reduced costs by executing quantity analysis, allowing several level reporting of construction drawing and building descriptions. They could automatically produce order lists and scheduling for the contractors, supporting the automation for the building parts fabrication. (Eastman, 1976) (*see Appendix 1 – Historical BIM*)

One of the main advantages for BIM, is the capability to improve coordination between the different AEC disciplines, reducing errors and responding to the need for predictability of costs, quality, and scheduling. "*Clash detections*" make possible to find incompatibilities between the different discipline models in time and not discover them during the construction works. If these incongruences are found late, they can bring to the need for design's change, construction orders, develop delays and in general increase costs. (Sinopoli, 2010)

Integration of programming skills in the AEC sectorial disciplines have resulted to be a key factor in the BIM development. Eastman as one of the first pioneers was educated in both architecture and programming. BIM proprietary platforms are built from programmers with the support of the specific professionals from the different AEC disciplines, like architects, engineers, constructors, facility managers etc. Parametrics and computational design are a crucial knowledge in the avant-garde competitive scene. The industry has started to realize only recently the big potentials for BIM. Modelling with higher interaction between human and computers, "augmented reality", "cloud computing" and "generative design" supports the growth of BIM applications. (Quirk, 2012)

BIM is basically composed of 3D modelling objects enriched with information databases in interoperable software or formats, with possible access from the different BIM users involved. This also defines the level of BIM implementation within an Organization, as given in the UK BIM Maturity Levels from (Bew and Richards M., 2008) (see Appendix 4 - BIM Maturity Assessment Models). Further considerations on BIM Maturity Assessment Models will follow in the next Chapters of the Thesis and in the Appendices.

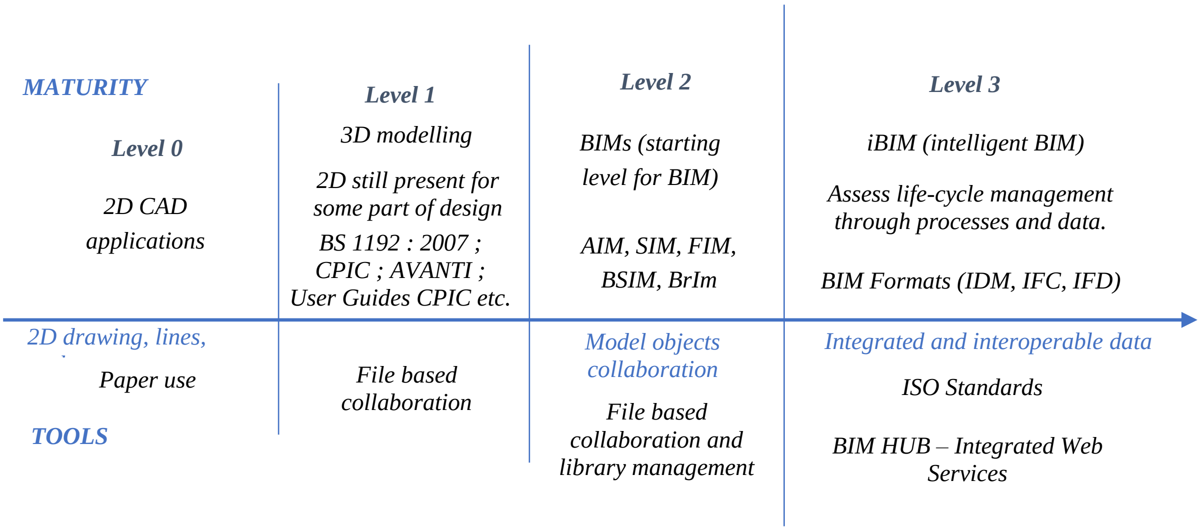

Fig. 1-UK BIM Maturity levels (Bew and Richards M., 2008)

Most of the actual design companies have succeeded the Level 0 - BIM, which means "*no collaboration*". At this level are applied only 2D CAD drawings with output and distribution via paper or electronic prints (Cherkaoui, 2017). Level 1 BIM consists in a mix of 3D CAD and 2D designs enriched with some information. Some common data sharing tools are used, and responsibilities assigned in advance. Level 2 BIM is the next stage, and it is focused in a more collaborative working and interoperable exchange of information. Common data formats such as IFC – "Industry Foundation Class" may be used at this stage. Level 3 BIM is the final goal in BIM adoption and consists in fully "*open data*" information exchange and in structured collaborative environments between the different actors involved from the early stages of planning and design. (NBS, 2014)

The Thesis starts with a general background in BIM developments, discussing benefits, challenges, and risks on its adoption, and then concentrate to the BIM application for structural engineering design of reinforced concrete buildings. Workflows are introduced, detailed, and Business Process Re-engineering (BPR) is applied to improve them towards full BIM adoption. The design stage involves working together different disciplines, making use of the last technological available solutions. Different software are presented and their integration is discussed, for the uses in modelling, analysis, design and detailing of concrete buildings.

Performance indicators may be applied to evaluate the benefits and challenges in BIM. Performance evaluation may be done related to a project, organization, or an individual. Different model maturity assessments have been developed during time to establish the level of BIM adoption. By applying BIM, professionals like structural engineers, may concentrate into solving complicate problems of design, instead of just managing quantity analysis for detailed design, that may be solved through automated procedures. People and lack of knowledge are some of the main challenges identified from the literature.

For the structural design of reinforced concrete buildings have been chosen to be applied the last versions of Autodesk Revit - Robot 2021, Autodesk Revit - SOFiSTiK 2021, ProSap Professional v21, and Tekla Structural Designer (TSD) - Tekla Structures (TS) 2021. Applying different BIM authoring tools is possible to evaluate the potentials, differences, and challenges that each one of them faces in this process. Comparing traditional approaches towards BIM friendly workflows, we can check and evaluate the improvements and challenges faced in this direction.

BIM is still young, and technologies update everyday replying to market needs for better management, integration, and coordination of information. Applying structural BIM authoring tools to some case studies it is possible to directly identify the performance of each software for the different stages of the design process, and check what can be improved for higher accuracy, better interoperability, and automation of design.

The Thesis will be developed in the following Chapters:

Chapter 1. Introduction and general objectives.

The first Chapter consists in an introduction to the general objectives of the Thesis. It opens with an historical introduction to BIM, how it has been evolving during time, BIM developments, maturity levels framework, methodology and expectations of the Study.

Chapter 2. General background and methodology for BIM adoption.

BIM is not simple to be explained in just a few concepts. Its definition is quite vast and should take into consideration different disciplines and actors. Within this Chapter, the focus is to give some instruments to analyse and evaluate its adoption. It starts with general definitions, performance factors evaluations, maturity assessment models and some introduction in business strategies. It continues with a general overview in BIM benefits, challenges, risks, and concludes in a discussion of integrated workflows.

Chapter 3. Background for structural design.

Chapter 3 proceeds in the analysis of BIM adoption with focus to structural design. Since you need to have a bigger picture when dealing with BIM, some workflows are presented for the design, including some activities of the construction processes. BPR is applied to improve the processes from a "*traditional design*", to "*IFC exchange*" and "*integrated modelling*". Different software in integrated workflows of Revit - Robot 2021, Revit - SOFiSTiK 2021, ProSap Professional v21, and Tekla Structural Designer (TSD) - Tekla Structures (TS) 2021, are introduced and discussed to be applied for the analysis and design of some Case Studies. Interoperability within and between the chosen workflows is also investigated.

Chapter 4. Case studies.

This is the experimental chapter, where the workflows are applied specifically to the Case Studies, by checking, analysing, and discussing the involved processes. Uses are evaluated towards some criteria of modelling capacities, quality, analytical model configurations, structural analysis, design and detailing, automation, interoperability, drawing documentation capabilities and accuracy, quantity estimations, reporting, IFC information exchange quality, exported model reliability and accuracy. Results are analysed and compared in the different scenarios.

Chapter 5. Discussion and Conclusion.

Results from each Chapter, mainly the fourth one, are summarized and discussed with Conclusions.

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2. THEORETICAL BACKGROUND FOR BIM ADOPTION.

The NBS - National Institute of Building Sciences defines BIM as "*a process for creating and managing information for a construction project across its life-cycle".* It is "*a digital description of every aspect of the built asset".* It has information built in collaboration at all stages of a project. Applying BIM, enhances collaborative processes and optimizes actions with greater value for the whole life cycle of a project (NBS, 2016). The USA Government Services considers BIM "a *multi-faceted computer software data model",* used to simulate the construction and operation of a facility (GSA, 2007) (see Appendix 2 – Definitions and recent developments)

BIM is a new "*govern*" methodology that changes the way we manage the entire construction production processes. It has been developing in the most industrialized countries, as a "*game changer*" for the AEC industry. It consists in a *collaborative platform*, allowing *higher efficiency at all stages* of a project. BIM results in an integrated model with graphical design and non-graphical information, shared between the different stakeholders. BIM adoption in the AEC Industry, impacts the quality of facilities. It gives the possibility to the "*Top Management*", the necessary databases and resources to make efficient strategic decisions, for the operation and maintenance phases of a facility. (Caputi and Ferrari, 2014)

2.1. BIM adoption.

Literature shows that BIM can be implemented with success in the design practice from professionals that have the right expertise. BIM creates easier **workflows and modelling**, saving **time and money**. The requirement of skilled people is a must to assure an *effective BIM process*. It has been identified that *applying BIM,* produces higher income for projects. Economies of scale results in better prices for BIM costs. (Czmoch and Pękala, 2014)

BIM adoption evaluation can be done at a **"Project"** or **"Organization"** level, based on workflows and technologies applied within an organization (Dakhil et al., 2015). BIM capacity assessment evaluation are also important towards the "**Individual**" competencies, being the base for the organizational functioning. [1]

Implementing BIM methodology within a firm is a radical and innovative change. Specialty Contractors have a reduced role in its adoption through the life cycle of a facility. They are focused to maximize their outputs, based on the requirements from the *(GC) – General Contractors* or *Architects*. A clear *organizational strategy* is necessary to adopt *BIM* with *positive incomes* for a Company (E. Poirier et al., 2015). The innovative process consists in the following steps: 1. *Creation of an idea 2. Opportunity 3. Diffusion and 4. Adoption*.

Innovation can be "*Technological*" involving *products or processes*, related to "*Services*", supporting *competencies and products*, or "*Organizational*" involving *management improvements*. (Rogers, 1983)

[1] The **(ICI) – Individual Competency Index,** proposed from (Succar et al., 2013), defines in a simple way the individual performance following five levels: *level 0 – no skill, level 1 – basic, level 2 – intermediate, level 3 – advanced* and *level 4 – expert*. It takes consideration of the core and "*procedural knowledge*" within a field necessary to produce determinate deliverables. "*BIM Maturity*" and "*BIM Capability Stages*" are further concepts introduced that can be applied to define the maturity at an Organization level.

Another construction innovation model comes from (Winch, 1998) consisting in four steps, starting from 1.*Adoption* 2.*Implementation*, 3. *Learning process* and 4. *Problem-solving*. These processes can be analyzed through firm's "**Organizational**" levels or can be "**Project's** related. In addition, (Winch, 1998) has included the "**Industry**" environment or the "**Market**" evaluation, as will be later analyzed from (Kassem and Succar, 2017).

Different research has evaluated the BIM adoption benefits at a "**Project**" level [1]. A study from (Bryde et al., 2013) follows the analysis for 35 realized projects (see Table 1). It was reported a *reduction of costs* and a *better control* of the project *through the whole life cycle*. "*Time saving*" was also a relevant result from this evaluation process. The comparison was done based on a *cost/benefit analysis* of the projects. Challenges are identified in *BIM education and training*. Marketing operations that *state benefits*, which are supported from *detailed analysis*, can be more convincing for Owners and professionals to make use of BIM, with expected returns that *justify the initial investment*.

The *BIM implementation* from the different stakeholders should be processed *under a common understanding with focus to benefits*. The factors that lead to BIM adoption should be analyzed at all levels of an *Organization* or a *Project*. To be effective, *a staged process for adoption is necessary with defined targets for each one of the steps*. Some of the main factors for the BIM adoption are: "*Top Management*" decision framework, *policies and requirements*, *technological resources*, *skilled staff*, *decisive* and *technical mindset*. The BIM adoption consists in radical changes for all *organization's workflows*, *buildings*, or *infrastructure projects*. (Doumbouya et al., 2016)

Project name	City	Country	Design	Construction	Budget	Size	Type	Reference from literature
Shanghai Tower	Shanghai	China	2007–2008	2008–2014	1,716 M €	380,000 m^2	Office Skyscraper	McGraw-Hill (2010b)
Aylesbury Crown Court	Aylesbury	UK	–2011	2011–	43 M €	5,200 m^2	Government	McGraw-Hill (2010a)
ESEAN Children's Hospital	Nantes	France	2004–2007	2007–2009	13 M €	7,000 m^2	Healthcare	McGraw-Hill (2010a)
CMG Medical Office Building	Mountain View, CA	USA	–2007	2005–2007	76 M €	23,000 m^2	Healthcare	Khanzode et al. (2008)
La Bongarde	Paris	France	2003–2010	Not started	uk	86,000 m^2	Retail	McGraw-Hill (2010a)
Palomar Medical Centre West	Escondido, CA	USA	2004–	–2012	377 M €	69,000 m^2	Healthcare	McGraw-Hill (2010b)
Research 2	Aurora, CO	USA	2002–2006	2006–2007	157 M €	50,000 m^2	Laboratories	McGraw-Hill (2009)
Springfield Literacy Centre	Springfield, PA	USA	2006–2007	2007–2008	12 M €	4,600 m^2	Education	McGraw-Hill (2008)
St Helens and Knowsley PFI	Merseyside	UK	–2006	2006–2010	434 M €	120,000 m^2	Healthcare	BSI (2010)
Endeavour House	Stansted	UK					Office	BSI (2010)
Palace Exchange	Enfield	UK			37 M €	18,000 m^2	Retail	BSI (2010)
General Motors plant, Flint	Flint, MI	USA		2006		44,200 m^2	Industrial	BSI (2010)
Eagle Ridge		Canada	2006	2006			Residential	Kaner et al. (2008)
Dickinson School of Law	Old Main	USA		2007–2009	47 M €	10,500 m^2	Education	Leicht and Messner (2008)
Blackfoot Crossing	Calgary	Canada		before 2007			Museum	Kaner et al. (2008)
Modi'in		Israel		before 2007			Retail	Kaner et al. (2008)
Walt Disney Concert Hall	Los Angeles, CA	USA	1987–1991	1992–1996 200–2003	214 M €		Concert Hall	(Haymaker and Fischer, 2001)
Audubon Centre	Audubon, OH	USA	2004–2008	2008–2009		1,700 m^2	Civic Centre	McGraw-Hill (2010b)
School of Cinematic Art	Los Angeles, CA	USA	2005–2006	2006–2009	129 M €	12,700 m^2	Education	McGraw-Hill (2010b)
Expeditionary Hospital		Middle East	2006	2006–2007		8,920 m^2	Healthcare	Manning & Messner (2008)
Maximilianeum Expansion	Munich	Germany	2009–2010	2010–2012	14 M €	4,500 m^2	Residential	McGraw-Hill (2010a)
Precast Shelter		Israel		before 2007			Shelter	Kaner et al. (2008)
Heathrow Express recovery		UK	1995–				Railway	BSI (2010)
Terminal 5, Heathrow	London	UK	1992–1999	2002–2008	5,208 M €	371,000 m^2	Airport Terminal	BSI (2010)
UCSF Cardiovascular	San Francisco, CA	USA	2005–2007	2008–2010	198 M €	22,000 m^2	Laboratory	McGraw-Hill (2008)
Texas A&M Health Science Centre	Bryan, TX	USA	–2008	2008–2010	81 M €	24,000 m^2	Education	McGraw-Hill (2009)
St Joseph Mission Hospital	Orange, CA	USA		2008–2009			Healthcare	McGraw-Hill (2009)
Department of Energy	Amarillo, TC	USA			78 M €	4,200 m^2	Industrial	McGraw-Hill (2009)
SF Public Utilities Commission	San Francisco, CA	USA	2001–	–2012		2,600 m^2	Government	McGraw-Hill (2010b)
ShoWare Centre	Kent, WA	USA		–2009	43 M €	14,000 m^2	Sports Arena	McGraw-Hill (2010b)
US Food and Drug Admin HQ	Silver Spring, MD	USA	1996–	2010–2013		113,000 m^2	Lab + Office	McGraw-Hill (2010b)
Festival Place	Basingstoke	UK		–2002	136 M €		Retail	BSI (2010)
Sutter Health Medical Centre	Castro Valley, CA	USA	2007–2009	2009–2013	250 M €		Healthcare	McGraw-Hill (2009)
University Campus Suffolk	Ipswich	UK	2006–2007	2007–2008	25 M €	10,500 m^2	Education	McGraw-Hill (2010a)
Cascadia Centre	Bothell, WA	USA		2011–2012		5,000 m^2	Education	McGraw-Hill (2010b)

Table 1-Projects analyzed for BIM adoption (Bryde et al., 2013)

[1] BIM adoption has been evaluated at an "*organisational level"* for *mid-sized structural engineering firms* specialized in precast concrete (Kaner et al., 2008). *Leadership* and *persistence* were identified as a must in this process. The BIM adoption resulted with changes in *workflows* and *personnel capabilities* for the firm. Different steps were necessary to implement BIM at an "*organizational level*", resulting *with shorter times for drawing production* and *higher quality*. Companies adopting BIM must develop their "*organizational knowledge"*, "*standardization*" and "*documentation procedures*" that allow accurate, automate shop drawings, and fast reporting.

Several data and Vendor's information showed that a lot of software offer BIM solutions with higher costs. These costs may be relevant at the beginning, but the future outcomes of the project justify the initial investment, with higher *(ROI) – Return on Investments* [1].

"*People*" are a main challenge in *BIM adoption.* Preliminary "*agreements and cooperation"* are necessary for BIM to succeed. An "*integrated design approach"* and an "*effective engagement process"* through the different design phases can guarantee the full expected BIM potentials to be achieved. (Bryde et al., 2013)

The effective collaboration associated with efficient use of BIM technologies, brings to higher quality for the *BIM products*. *Knowledge* and *innovation* of the actors involved are important in this direction. *Decision making* is enhanced and facilitated from the support of data rich models. BIM brings a lot of benefits to the construction projects with higher quality and efficiency. Even though, it has not reached yet an adequate level of adoption in the AEC Industry. (Doumbouya et al., 2016)

BIM can be applied in the following cases (Azhar, 2011):

- *3D modelling* enriched with graphical and non-graphical information, virtual visualization and render simulation.
- Facilitation for *fabrication* and *shop drawings*.
- Use of the model for *analysis and verification* for the different disciplines, structural analysis and detailing, energy modelling, sustainability evaluations, fire safety, etc.
- *Cost's estimation*: BIM methodology allows to have automated quantity analysis and costs estimations for every update of the model.
- *Time scheduling* of the construction works for coordination of materials ordering, fabrications (cast in place or in situ, assembling etc.) and delivery scheduling for all the building elements.
- *Clash detections* (conflicts, incompatibilities), verifying elements not intersecting, doubling, or distance criteria between relevant components.
- *Sustainability analysis* for green certification like LEED, carbon footprint evaluation etc.
- *(FM) – "Facility Management"* for future maintenance, renovations and in general facilitation within the (BMS) – "*Building Management Systems*"
- *Dismantling procedures* and recycling of the building elements for future uses.
- *"Forensic analysis"*, like evacuation plans, failure and so on.

(For some real-world applications see Appendix 3 - Real)

[1] (ROI) – Return on Investments represents a "*performance measure*", used to calculate the "*efficiency*" or "*profitability*" for an investment. (ROI) evaluates its saving or returns compared to the initial costs. The calculation consists in a ratio of the benefits (income or savings) of the investments divided by its costs. The result may be given in percentage (%). (ROI) is quite simple to apply but has some limitations, like the fact that is not taking into consideration the timeframe of an investment. (Fernando, 2021)
In such cases may be more appropriate to apply different criteria for evaluation, like (NPV) – Net Present Value, or (IRR) – Internal Rate of Return, which take into consideration interests as well. (NPV) evaluates actualized cash flows discounting the investment costs, while the (IRR) defines the (%) interest for which (NPV) gets equal to zero. They both gives an idea of how much an investment is desirable, taking account timeline. (M. Caputi, 2021)

2.2. Performance indicators.

(Succar, 2009) is one of the first, to well define a structured 3D framework evaluation in BIM adoption, based on "*BIM fields*" and "*BIM stages*". Technology, processes, and policies represent the "*fields*", instead "*object-based modelling"*, "*model-based collaboration"* and "*networked integration"* are the "*stages*". A third dimension is the "*BIM lenses*", giving the layers through which "*fields*" and "*stages*" are evaluated.

(Erik Poirier et al., 2015) have analyzed in 2015, the BIM adoption changes faced from some small and medium specialty companies, considering an "*embedded context for innovation*". A gap was identified between the *BIM implementation* and the *current innovation in BIM* with the transition process to be a radical change for companies. A specialty contractor will always maximize its efforts to respond to requirements of the Appointing Company, with low possibilities to influence the application of BIM through the whole life cycle of a facility. Instead, they identified that is more probable that *Owners* and *General Contractors*, can have a decisive leverage for it. Also, a clear overall structured organization with focus to *BIM implementation*, is necessary to *obtain good results*, independently of the external context. The authors will study this relation and its development through 4 key lenses: *industry's context, institutional aspects of companies, organizational schema, and project development*. Benchmarking and performance assessment in BIM adoption is followed at an integrated level for both project and organizational context. Indicators are used to establish the level of BIM maturity for modelling and capacity assessment.

(Talamo and Bonanomi, 2020) identified *technologies*, *processes*, and *organizational issues* as three element factors, necessary to analyze digitalization, through *challenges and achievements for architectural and engineering firms*. It was concluded that a balanced approach could bring to higher level of adoption and better results. Application of new technologies should be balanced with organizational changes. It is necessary to make use of collaborative and integrated processes between architectural and engineering firms in addition to the modelling ones. *The role of people with higher knowledge in digital technologies* inside a company should be defined in a *structured organization with clear responsibilities*.

In the evaluation for the BIM impacts in construction projects, (Suermann, 2009) identified six key performance indicators (KPIs), as metrics in the project performance assessment. These included: *quality check, scheduling timeline under control, quantity estimations, safety, unit costs, unit productivity for man hour and overall costs.* Through different surveys resulted that *quality, unit costs and productivity* were the main KPIs impacting the BIM adoption performance in the projects.

2.3. BIM Maturity Assessment Models.

Maturity represents "*the quality, repeatability and degree of excellence in delivering BIM models".* It defines the moment for which you have a "*fully developed state*". Achieving maturity is a sequential process, that passes through evolutionary stages. Maturity models are necessary to manage the organizational change processes and to implement improvement strategies. The BIM maturity assessment models toward projects implementation are defined as (PAMs) and at an organization level as (OAMs) (Succar, 2010) (Dakhil et al., 2015)

"*Succar's BIMMI*", "*TNO's BIM QuickScan*", "*Vico's BIM Score*" and "*IU's BIM Proficiency Matrix*" are BIM Assessment Maturity models that can be applied for Designers. The "*BIMe Competency*" is an individual focused, instead "*ICMM*", "*VDC ScoreCard*", "*BIMe Competency*", "*UK Wage Model*" and "*Arup Model*" are *Project*'s focused. (Dakhil, 2017)

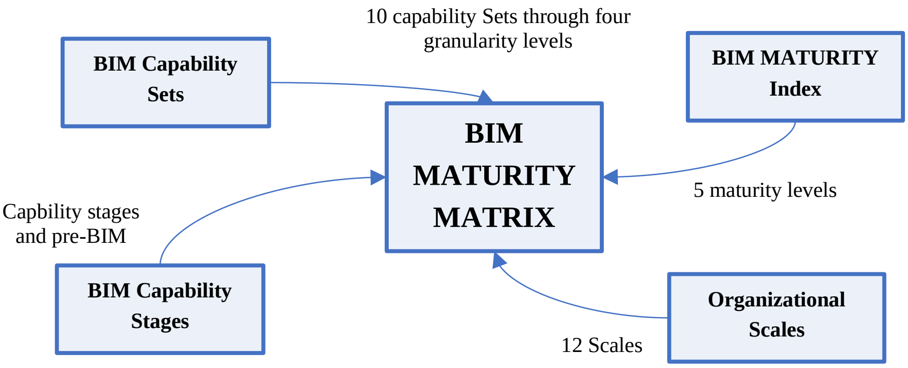

Fig. 2-General Schema of the BIMMI Maturity Assessment (Dakhil et al., 2015) (Succar, 2010)

(see Appendix 4 - BIM Maturity Assessment Models.)

2.4. Business Strategy.

Adopting new workflows for design and technology, requires also to check the Business Model. It consists in working strategies to achieve better goals optimizing the financial outputs (M. Caputi, 2021). The positive financial revenue is a main factor in BIM adoption. If you have negative incomes in adopting a new methodology, it is highly improbable that you are making use of it.

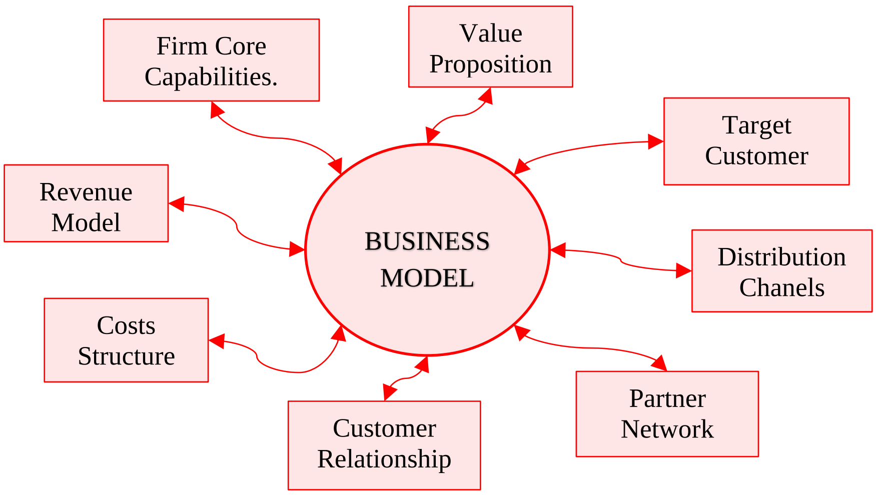

Fig. 3-Business Model (M. Caputi, 2021)

Harvard Professor M. E. Porter, defined in 1980, three different types for business strategies: "*differentiation*", "*overall cost leadership*" and "*focus*" (Porter, 1980). The first one is a strategy for which firms work in the market by offering to the clients a different or better product. They don't deal with price, but provide services, for which you can pay more. The "*overall cost leadership*" deals mainly with cost issues, by applying strategies for economies of scale and similar, offering lower prices. The "*focus*" strategy consists in targeting a specific small portion of the market and provides products or services which are easier to offer with less competition.

Obviously, BIM doesn't fall on the "*overall cost leadership*", since you may have higher costs in the design stage, and a design company is going to ask more for a BIM approach instead of a traditional one. The higher economical advantage for BIM, resides in the reduction of the *construction & operation* costs. (Smith and Tardiff, 2009)

The situation changes at various scales of the facility. If you deal with small villa, or low residential buildings, it is different compared to big facilities, residentials, offices, public buildings, or mixed ones. The profitability gets higher in economies of scale and it is in proportion with the size of a facility. Higher fixed costs (better software & hardware, staff training, established BIM processes), affect lower applications on small scale buildings. BIM influences the efforts/costs distribution along the different phases of a facility, as given in Fig. 4.

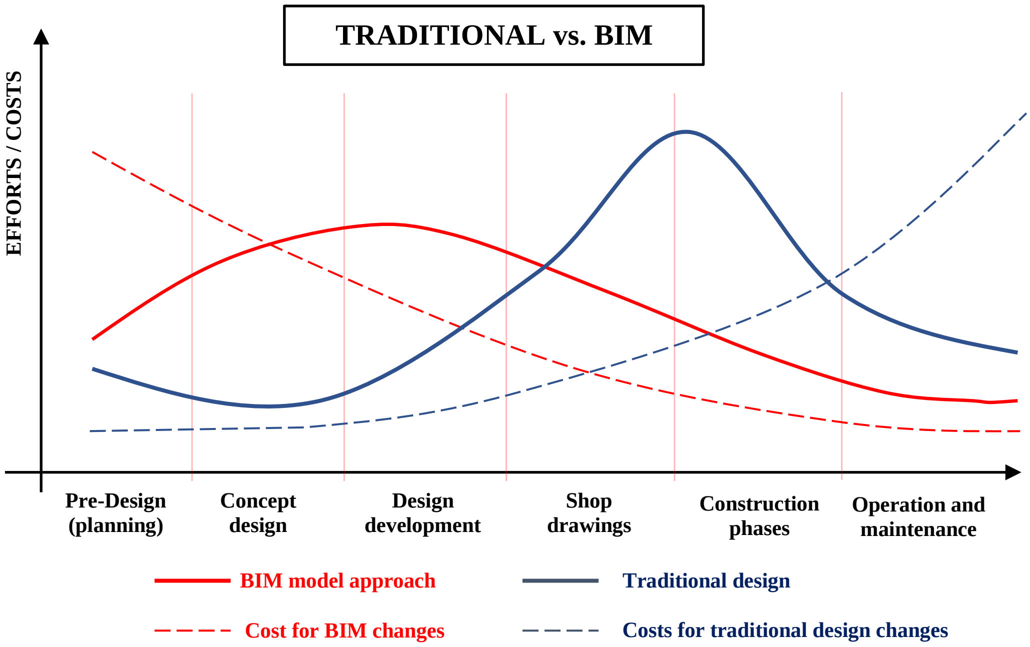

Fig. 4-Traditional Design vs BIM modelling (Smith and Tardiff, 2009)

Following Porter's Business Strategies, we can say that BIM leads to a *market differentiation*, offering *a better product* based on the series of benefits defined in the literature. It is a *general inclusive approach* and produces *higher income*, where all people and different disciplines are working together. BIM enables *market differentiation* and creates *lower costs* for bigger projects.

Business strategy approaches are categorized in: "*internally driven*", following strategies based on what has been done in the past from the firm, "*customer oriented*" that try to understand client's expectations and "*market oriented*", focused on what the market needs and reasoned decisions to be adopted, to define what the firm should do to be competitive, by adding value to their products or services. (Beckwith, 2015). BIM can be considered as "*market oriented*".

Business strategies succeed when they generate growth, are competitive and produce financial income. A *5-step approach* starts with *building a vision, defining top objectives, plan the attack, check the model versus reality, and finally create a strategic framework.* (M. Caputi, 2021)

2.5. BIM trends.

Different market reports in advanced economies on BIM's use in the construction industry, have revealed that (McGraw-Hill et al., 2008):

- *Architects are the one making more use of BIM*, with half of them identified from the Survey, that have applied it to more than 60% of their projects. Contractors are the one less using BIM, with 45% applying to just a quarter of their projects.

- More than *80% of BIM users have expressed that BIM enhanced productivity in their projects* and companies, improving *project outcomes* and reducing *Site problems*.

- *BIM users that already* have been applying BIM in their projects, state that *they intend to use it more in the future ones.*

- The major BIM applications have been identified for *construction work documents, concept designs, clash detections, visualization renderings and costs estimation*s. Even though it was identified that industries still rely a lot on traditional 2D methodologies and documentations.

	Architects	Structural Engineers	MEP Engineers	GC/CMs	Structural Trades	MEP Trades
Tools that allow visual and creative insight to produce better design alternatives in less time	83%	78%	45%	70%	70%	76%
Intelligent models that lead to more consistent and coordinated contract deliverables	77%	72%	52%	67%	67%	73%
BIM-based processes that produce better coordinated shop deliverables in less time	77%	72%	48%	73%	70%	67%
Single source of truth of project data, accessible anytime, anywhere in the office, shop or field	73%	66%	55%	53%	73%	70%
Integration of analysis and code-based design with 3D models*	63%	66%	48%	47%	53%	61%
Ability to visually simulate project delivery timelines for estimation and coordination	52%	63%	39%	53%	57%	61%

Table 2-BIM trends prediction from different AEC discipline (DODGE, 2016)

In general, the AEC industry's expectations for BIM adoption, are high for: *better quality projects*, with *more design alternatives* in *less time, coordinated shop drawings and contract deliverables and models accessible everywhere within an integrated approach*. The discipline that is less enthusiastic for BIM, is the *MEP Engineering*. Structural engineers generally evaluate above average the BIM adoption and have high evaluation for the *costs simulation and the construction works scheduling*. (DODGE, 2016) (see Table 2)

Architects (A), General Contractors (GC) or Construction Manager (CM) can influence the BIM uses for the other specialties. If architects have been using BIM *for half of their projects, it is highly probable they will require it also for the other disciplines*.

2.6. BIM challenges.

Different research has suggested that the lack of *project experience* and *skilled personnel* are main challenges for the BIM development. There is a *shortage of professionals with BIM expertise*. This translates in the need for more *education and training*. It can make a novice designer that knows very well basic modelling commands, an incredible BIM designer, while a very experienced professional to struggle with software interfaces. It creates a generational break that becomes stronger as new technologies develop and existing ones continuously update. (Quirk, 2012)

So, we may say that in general **"People" are the first challenge in BIM adoption**. When you are used in a way of doing things, the application of a new technology always faces resistance**. The lack of training and programs to educate and certify BIM experts is a well-known problem identified from literature** (Olawumi et al., 2018).

Different educational programs have been developed in the last years, but they are not always accepted as an industry standard. BuildingSMART for example, has been developing some international certification for BIM (Sacks R. et al., 2018). The EMJMD BIM A+ European Master's in Building Information Modelling, is another successful initiative from some well renowned European Universities (https://bimaplus.org).

The lack of knowledge and skills is seen differently also between the discipline's professionals. MEP engineers deal with more difficulties, instead structural engineers result to be less challenged and more prepared about it. (see Fig. 5)

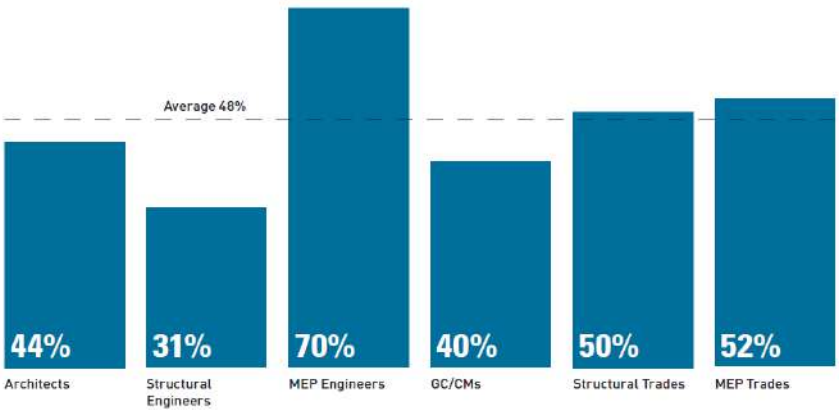

Fig. 5- Survey for the approval rate for evaluating as a main challenge in BIM adoption the "BIM skills and expertise" (DODGE, 2016)

Training cost. Professionals involved in BIM should have the necessary education and expertise. Staff requires training and weeks of preparation if you want to fully implement BIM for big scale projects.

There are investments that companies need to face for its development, and the training for BIM's specialists is the first one. (Czmoch and Pękala, 2014)

Skepticism may still be present. Some may say that BIM is just some technological "*smoke and mirrors*" and that it will go before integrating within the AEC Industry. Others think that BIM is like "*the panacea*" for everything that happens within the industry. It is quite probable that like everything, the truth lays in the middle. BIM has been developing in an impressive way in all different disciplines, faster than even data justifying its application (Suermann, 2009). The "*industry's resistance to adapt to new practices*" and the "*longer time in doing that*", have been identified as barriers in BIM adoption (Olawumi et al., 2018).

BIM adoption should work on several directions, from one side applied from the public and private users and on the other following policies and practices for the industry. It is not enough just to implement BIM technology; **the success of BIM adoption depends also on how it is implemented.** BIM management of people, processes and policies are crucial in this development, as defined from the (PPP) Framework (People, Processes and Policies) (Trivedi, 2017) The number of actors involved and the heterogeneity of participants can be a challenge for coordination, causing work delays.

Policies are a key aspect. Different countries like Singapore, Finland, Korea, USA, UK, and Australia have been driving BIM adoption from the beginning of 2004. Creating online platforms to deliver IFC neutral formats for public buildings in Singapore, making BIM adoption mandatory for public projects bigger than 1 million € from 2007 in Finland and for major governmental projects in USA. The AIA – "*American Institute of Architects*" has been supporting from the beginning contractual BIM oriented approaches and the BIM Forum LOD's.

The British Government from 2011 has made his country a world leader and innovator in the construction digitization industry. "*Fully collaborative 3D BIM*" is required for all central governmental public projects in UK from 2016. Netherlands, Finland, Sweden, France, Germany, Spain, Korea, Japan, Australia, and China have been working and proposing policies for BIM adoption in their respective countries for public funded projects, infrastructure investments, housing and in general for building owners. (Lee and Borrmann, 2020).

Italy has recently updated the previous Ministerial Decree DM nr. 560/2017 involving BIM, with the new updated Ministerial Decree DM nr. 312 02/08/2021, following legislation objectives and the national and EU level framework. It introduces premium quality criteria, ISO EN UNI 19650 requirements, new definitions like "information model", advice the use of "augmented reality" and the application of an information management plan. It is better structured with a more rigorous logic, referring also to national, international legislation and good practices.

Higher initial costs are a barrier in BIM implementation, requiring more powerful hardware and new interoperable software. They result still expensive (autodesk.com, bexelmanager.com, oracle.com) and are generally evaluated for each BIM user and working place. This complicates the application to small and medium scale projects. (see Fig. 6)

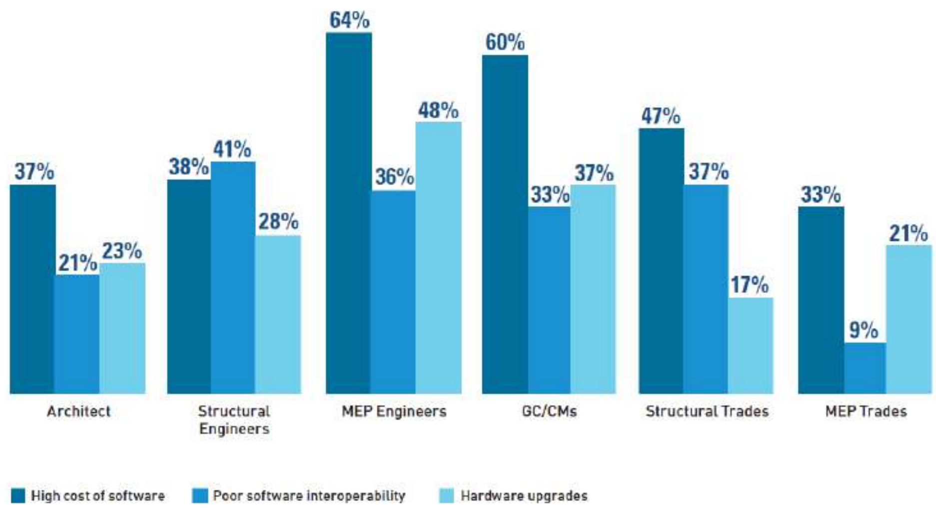

Fig. 6-Technology challenges in BIM adoption from AEC disciplines (DODGE, 2016)

Accuracy. The BIM model should be the virtual twin of the future physical one. A high accuracy is required from the model. Standards should be in place and respected from the beginning in order that anyone is following the process at the same way. Since the modelling is hierarchical and sequential, small mistakes at the beginning can generate bigger ones later. All members should be willing to abandon their personal schemas and follow a collaborative one. (Czmoch and Pękala, 2014)

BIM's terminology. BIM has its own terminology, and it must be mastered at the beginning of a training to avoid misunderstandings.

Full BIM model. Project's documentation or any part of the project can be generated only when the full BIM model is completed. You cannot create separate design documentation if you don't have the conclusive BIM model.

Extra BIM costs cannot be afforded only from the design team. For BIM to succeed and benefit from its value, it is important that all actors involved become aware of the economic advantages for the construction and operation phases during its implementation. The Owner, Constructor or Facility Managers should understand that higher reduced costs for the construction and operation phases follow bigger efforts and costs during the design stages.

Standardization. To achieve better BIM deliverables, you need to increase standardization. It is still under completion a unified International Standard for BIM implementation, regulating all processes and responsibilities of actors involved. The first parts of the (ISO, 2018) have been concluded and are under elaboration the next ones. Each country depending on the market, developments and practices, approves, and issues its own policies and standards.

Copyright laws. If an Owner is paying for a project, he may feel the right that he owns the full model and design, but on the other Side, all the information given from the design members need to be protected. The ownership of Data must be clarified at the beginning of the process, based on Contractual Agreements between the Parties. Vendor's property information may include copyright information. (Azhar, 2011)

Interoperability in processes and technologies, is a common issue that usually is considered as a synonymous for BIM itself. It is one of the main problems coming out from the fact that tools and software, are produced from different Vendors. They may apply different data structure, so making difficult the interoperability to be guaranteed. The "IFC" format is one of the main achievements in this direction and openBIM standards as well. Every effort to achieve interoperability runs at the same time with the need for specialization, so with fragmentation. The "perfect" interoperability seems to be something that cannot be never achieved (Turk, 2020). The "incompatibility between the different software and tools", has been largely identified to be of higher importance (Olawumi et al., 2018).

The (NIST) National Institute of Standards and Technology in USA, has foreseen in 2004, interoperability problems and management of data to have a high cost for the construction industry. They are estimated at 3-4% of the total cost of the projects, and if considered only for the USA economy it is around 15.8 billion $ every year. (Suermann, 2009)

Trust between the different actors. Organizations have different objectives, requiring more trust for collaboration. BIM is a core approach to guarantee this shift from a paper-based communication to the Integrated Database System. In integration with the *(IPD) – Integrated Project Delivery*, it can support better communication between the different actors involved. *BIM can reengineer the processes of works*, by *coordinating all stakeholders* to be linked within a*n integrated system*. (Bryde et al., 2013)

Code	Barriers
B1	Varied market readiness across organizations and geographic locations
B2	Industry's resistance to change from traditional working practices
B3	Lack of client demand and top management commitment
B4	Lack of support and involvement of the government
B5	Low level of involvement of BIM users in green projects
B6	Societal reluctance to change from traditional values or culture
B7	The lack of awareness and collaboration among project stakeholders
B8	Inadequacy of requisite experience, knowledge, and skills from the workforce
B9	Longer time in adapting to new technologies (steep learning curve)
B10	Lack of understanding of the processes and workflows required for BIM and sustainability
B11	Low level of research in the industry and academia
B12	Inadequate in-depth expertise and know-how to operate sustainability-related analysis software programs
B13	Shortage of cross-field specialists in BIM and sustainability
B14	High cost of BIM software, license, and associated applications
B15	High initial investment in staff training costs
B16	Recurring need for additional and associated resources and high economic expenses
B17	Lack of initiative and hesitance on future investments
B18	Fragmented nature of the construction industry
B19	Organizational challenges, policy, and project strategy
B20	Difficulty in assessing environmental parameters of building properties
B21	Difficulty in accessing sustainability-related data (such as safety, health, and pollution index, etc.)
B22	The risk of losing intellectual property and rights
B23	Difficulty in allocating and sharing BIM-related risks
B24	Lack of legal framework and contract uncertainties
B25	Increased risk and liability
B26	Lack of suitable procurement policy and contractual agreements
B27	Non-uniformity of sustainability evaluation criteria and measures
B28	Lack of comprehensive framework and implementation plan for sustainability
B29	Absence or non-uniformity of industry standards for sustainability
B30	Inaccuracy and uncertainty in sustainability assessments for projects
B31	Incompatibility issues with different software packages
B32	Absence of industry standards for BIM
B33	Insufficient level of support from the BIM software developers
B34	Inadequacy of BIM data schemas to semantically represent sustainability-based knowledge
B35	Lack of supporting sustainability analysis tools
B36	Non-implementation of open source principles for software development
B37	Domination of the market by commercial assessment tools
B38	User-unfriendliness of BIM analysis software programs

Table 3-Barriers identified in the integration for BIM and sustainability practices from an international expert's survey (Olawumi et al., 2018)

Markets condition across different geographic locations; *top management decision making; longer time for learning new methodologies*; *procurement contracts* and *assessment tools available in the market* are some other challenges identified from literature (Olawumi et al., 2018). (see Table 3)

Dimension	Factor		Description
Technical risk	F1	Inadequate project experience	•Because of inadequate experience with projects that implement BIM technology, the unclear business value and unknown risk results could lower the willingness to apply BIM.
	F2	Lack of software compatibility	•Most project participants are accustomed to working with particular tools (software and hardware); consequently, data transfer is often limited because of incompatibility, which affects the transmission of consistent information to other participants. The untransferred data must be recovered and additional efforts must be made to recover it or add the information for other particular tools.
	F3	Model management difficulties	•As the model is updated continually to create new versions, version control problems will likely occur •Accurate data entry strictly required •Compiling a single file that shows a virtual 3-D model can easily cause company knowledge to be leaked; hence, information security must be readjusted. •Software unable to handle large amounts of data
	F4	Inefficient data interoperability	•During BIM-IFC file exchange or when reading BIM models on distinct software files, data loss will occur after file conversion
Management Risk	F5	Management process change difficulties	•Managers still follow traditional 2D design-management models to manage 3D design workflow, could make it difficult for department or division to clarify responsibilities and thus result in incomplete assignments. •Reluctance to openly share information •Shift of liability among project participants
	F6	Inadequate top management commitment	•Insufficient commitment of top management would lead to poor performance
	F7	Workflow transition difficulties	•Lack the ability to integrate traditional 2D workflow such as design and review process with new 3D design tools, would lead to ineffective collaboration between people with distinct roles •Shift of liability among project participants
Environmental Risk	F8	Lack of available skilled personnel	•BIM knowledge and ability of existing staff not fully established •Lack of technical personnel familiar with BIM
	F9	Increase in short-term workload	•Compiling a BIM library early on in the process increases the initial workload •A considerable amount of time required to become familiar with software operation •Existing staff require training to learn new techniques
Financial Risk	F10	Rise in short-term costs	•Initial BIM implementation could increase expenses related to BIM model review, personnel training, hardware and software acquisition, and other processes
	F11	Additional expenditures	•Additional funds are required for legal disputes, software updates, and other expense
Legal Risk	F12	Lack of BIM standards	•No clear product delivery and acceptance criteria and no clear criteria for model building
	F13	Unclear legal liability	•Standard contract, insurance policy, intellectual property ownership, dispute-settlement mechanisms, and other laws and lines of responsibility still in the discussion stage

Table 4-BIM Risks identified from (Chien et al., 2014)

Analysing challenges and risks you can identify what can be done to *predict, reduce or avoid future problems* in BIM adoption. More *government policies, educational programs and knowledge portals* are necessary to support the *BIM implementations and mitigate risks*. (Chien et al., 2014) (see Table 4)

Efforts are required from Public and Private Organizations, Governmental Institutions and Policy Makers, Professional Organizations, Educational and Research Institutions, and as well Market Regulators. You need to analyze the long term, work on the waste elimination, communication and consensus, standardization, faster processes, project integrity, support educational programs and good practices, automatize workflows, and improve interoperability. Higher digitalization is an inevitable destination. More people involved will reduce costs, increase trust, lower barriers, and improve outcomes.

2.7. Investing in BIM.

The Italian OICE – "Organizzazioni di Ingegneria e di Consulenza" based on a national survey 2021 (OICE, 2021), has published that 86% of Italian engineering companies have done investments in adopting BIM. The data is around 83.9% for small and medium companies with less than 50 employees, and 94.3% for the big ones with 50 and more. Investments are principally in formation and education 87.4%, following technology with software in 76.4% and hardware 48%.

The utility/efficacity of the BIM investments has been evaluated in general positively from 62.9% of the interviewed. The appreciation is higher for big companies (31.3% high, 62.5% satisfied), compared to small and medium companies (16.3% high, 63% satisfied).

The presence of certified BIM professional is also evaluated positively, with the necessity for a role of "*BIM manager*" in following the technical functions, required from 64.9% of the companies.

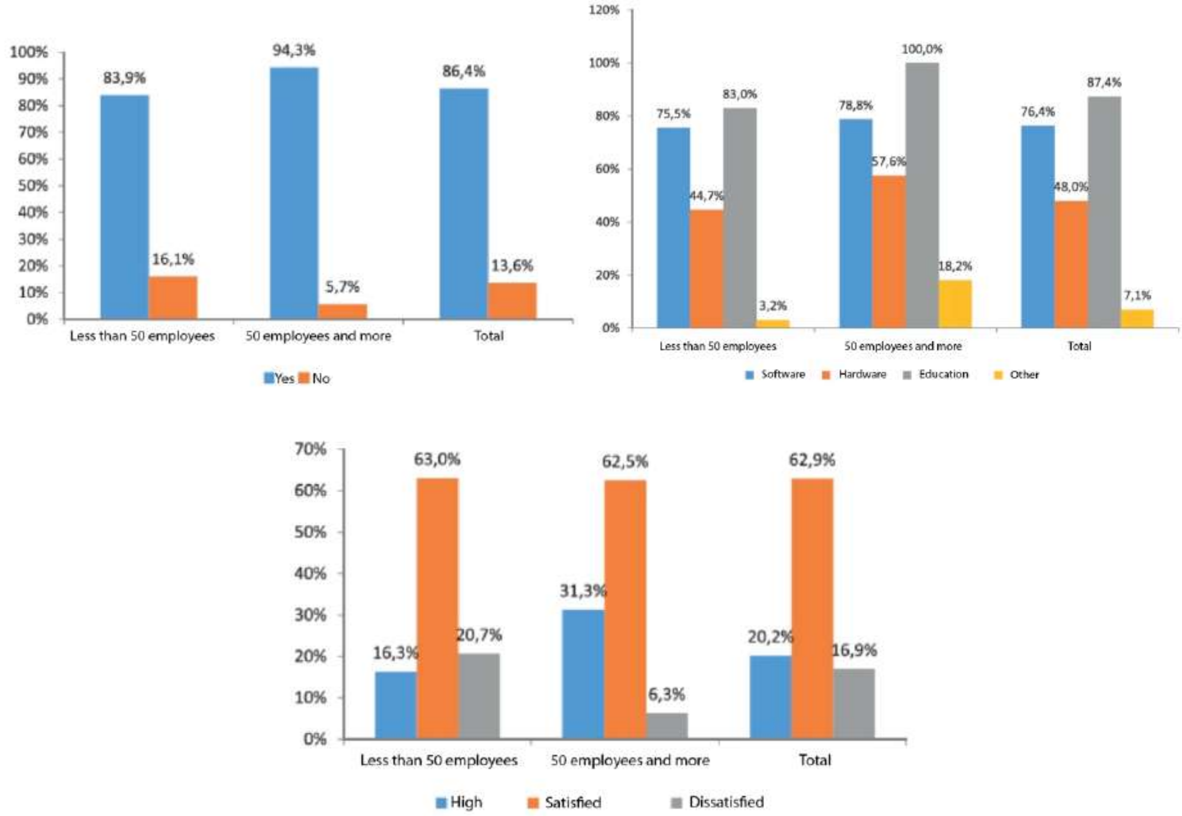

Fig. 7-BIM's investments, areas of investments and satisfaction based on the OICE's Survey (OICE, 2021)

The Survey is generally evaluating positively the BIM adoption for the structural engineering companies with expected advantages overcoming the initial investment costs.

2.8. BIM benefits.

BIM benefits are numerous, starting from *better coordination, better design, and clash detections*. Adopting BIM can *reduce rework for design* and can *avoid incompatibilities during construction*. BIM increases *production, efficiency, efficacy, value, design quality, sustainability and deals most of constructability issues from the beginning* of the process. BIM *improves communication* between the different actors involved. It results *faster with automated processes and less environmental impacts.*

Standardization is an important issue in achieving good results in BIM. *Project execution, Exchange Information Requirement documents (EIR) and BIM Execution Plans (BEP)* are some of the standardized documents required for BIM. (ISO, 2018)

It can be applied to all phases of an asset including planning, procurement processes, architectural design, structural, MEP, construction, and facility management. BIM has the potential to *enhance collaboration* between the different actors involved, creating the right environment to increase collaboration of stakeholders, who before were seeing themselves as adversaries. This supports the process towards IPD project delivery, integrating "*people, systems and business structures*" in the AEC industry. (Azhar, 2011)

Having accurate quantity estimation in advance, allows to save on *materials, shipping, labor work, have better predictions and reduce errors*. Also, it supports to build *faster, saving money, with earlier use of the facility and so increasing the ROI*. Higher collaboration from "*one single source of truth*" permits to make improvements and corrections of the model based on everyone's contribution. Constructors can build based on the last updated *BIM model* directly on Site, without losing time for clashes. Safety is increased with in advance prediction for potential risks. More detailed and accurate modelling and calculations are available, generating higher quality of the facility. A full data enriched model makes possible to generate reliable 3D views with aesthetic aspects enhancement. (Bryde et al., 2013) (DODGE, 2016) (HMC, 2020)

A study Survey, for Professionals and Contractors (Architects, (GC) General Contractors and (CM) Construction Manager), from (DODGE, 2016) resulted that:

- 70-100 (%) of the interviewed claimed that BIM *improved coordination for materials and works on site,*
- 65-75 (%) stated *higher quality and performance of the building,*
- 45-65 (%) supported that BIM can improve *better project's scheduling, budget control and cost's reduction,* and
- around 27 (%) saying that it contributes to *higher safety* of the building or infrastructure.

The collaboration between the different professionals, reduction of costs and materials waste, accurate results withing cloud-based technologies, earlier engagement in materials ordering and in general risks mitigation, were identified as "*Top Values*" in BIM adoption from the Study. BIM users that have been applying it for most of their projects have higher evaluation of its benefits, compared to the ones that have been applying it for less time. It is a quite an interesting result that more you apply BIM, higher is its appreciation. Structural engineer professionals resulted with an above average evaluation, compared to the other design professionals, with similar agreement also from Contractors and Traders (see Fig. 8).

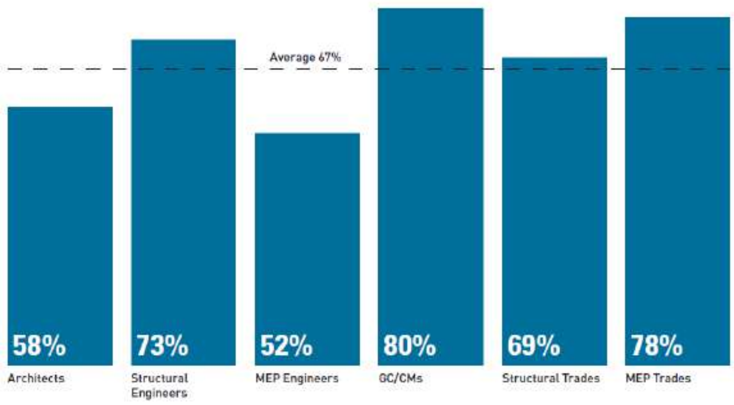

Fig. 8-Agreement to higher value for BIM adoption between the different disciplines and professionals. (DODGE, 2016)

Based on the Centre for Integrated Facility for Engineering at Stanford University (CIFE, 2007), following analysis of 32 projects, resulted that BIM guarantees:

- Reduction to more than 40% of unforeseen changes.
- Accuracy of costs estimation within 3% of the values.

- 10 % of costs savings and higher quality due to clash detections.
- Gain in more than 7% of time considering all processes of design and construction.

A good way to evaluate the BIM benefits is by calculating the (ROI). You can see how much you save and the return income when applying BIM, compared to a situation where you are not making use of it. BIM adoption involves costs that shall be considered in the final balance evaluation. Several research have resulted with high (ROI) values, when taking into consideration all the processes involving the project.

(Azhar, 2011) analyzed several projects with BIM adoption, realized from 2005 to 2007, considering the design and construction stages. For the (ROI) evaluation, were counted the BIM costs for implementation and the direct savings. High values resulted in costs savings starting from ROI 140%.

Year	Cost ($M)	Project	BIM scope	BIM cost ($)	Direct BIM savings ($)	Net BIM savings ($)	BIM ROI (%)
2005	30	Ashley Overlook	P/PC/CD	5,000	(135,000)	(130,000)	2600
2006	54	Progressive Data Center	F/CD/FM	120,000	(395,000)	(232,000)	140
2006	47	Raleigh Marriott	P/PC/VA	4,288	(500,000)	(495,712)	11560
2006	16	GSU Library	P/PC/CD	10,000	(74,120)	(64,120)	640
2006	88	Mansion on Peachtree	P/CD	1,440	(15,000)	(6,850)	940
2007	47	Aquarium Hilton	F/D/PC/CD	90,000	(800,000)	(710,000)	780
2007	58	1515 Wynkoop	P/D/VA	3,800	(200,000)	(196,200)	5160
2007	82	HP Data Center	F/D/CD	20,000	(67,500)	(47,500)	240
2007	14	Savannah State	F/D/PC/VA/CD	5,000	(2,000,000)	(1,995,000)	39900
2007	32	NAU Sciences Lab	P/CD	1,000	(330,000)	(329,000)	32900
Total all types				260,528	4,516,620	4,256,092	1633%
Totals without planning/VA phase				247,440	1,816,620	1,569,180	634%

Table 5-BIM investment analysis for different projects from (Azhar, 2011)

(Bryde et al., 2013) evaluated other 35 BIM project's adoption (project's size from 15 million € to 1.700 million €), based on some success criteria involving: *taking under control costs and their reduction, time's savings, communication and coordination enhancement, project's quality, risk reduction, scope, organization's improvement, and software involved*.

	Positive benefit			Negative benefit		
Success criterion	Total instances	Total number of projects	% of total projects	Total instances	Total number of projects	% of total projects
Cost reduction or control	29	21	60.00%	3	2	5.71%
Time reduction or control	17	12	34.29%	4	3	8.57%
Communication improvement	15	13	37.14%	0	0	0.00%
Coordination improvement	14	12	34.29%	7	3	8.57%
Quality increase or control	13	12	34.29%	0	0	0.00%
Negative risk reduction	8	6	17.14%	2	1	2.86%
Scope clarification	3	3	8.57%	0	0	0.00%
Organization improvement	2	2	5.71%	2	2	5.71%
Software issues	0	0	0.00%	9	7	20.00%

Table 6- Positive and negative benefits in BIM adoption (Bryde et al., 2013)

The projects were evaluated positively (+1), if benefits were identified for that criteria, and (-1) if there was a limitation, barrier, or negative benefit for the project. This allowed to obtain **a score for each one of the projects**. It resulted with **coordination, scope, time, quality, and communication, evaluated positively**, while organization with no difference and **software issues** in negative values. Some of the projects, with higher total positive evaluation, were the "*Shanghai Tower*", "*Aylesbury Crown Court*", "*ESEAN Children's Hospital*" and the "*CMG Medical Office Building*". Location of the most appreciated projects were in China, USA, UK, and France. Bigger size projects resulted with more positive benefits, compared to the smaller ones.

Costs, Time, communication, coordination, and increase of quality were identified as the most benefiting in BIM adoption. *Cost's savings* were reported in more than half of the Cases. *Cost's reductions* were evaluated to be 9% lower compared to the initial ones. Some negative effects included time-consuming processes for the initial creation of the models and the rework for the conversion from CAD drawings to BIM models. The effects of BIM for *communication and coordination* were positive. *Interoperability* was identified as a challenge in coordination, with difficulties in the management for big files, also following hardware limitations. (Bryde et al., 2013)

Another survey research from (Suermann, 2009), has resulted with similar results, like the ones stated above, with BIM adoption improving most of cost issues, delivering in time and project's quality.

Further descriptions on the BIM benefits have been reported in the *Appendix 5 - BIM adoption* .

2.9. Integrated workflows.

Workflows instruct how BIM processes should be implemented within an organization or a project. They are defined from the *Oxford Dictionaries* as the "*sequence of industrial, administrative or other processes, necessary to achieve a product or deliverables from the beginning to their completion".* BIM Dictionary describes the "*BIM Workflows*" as "*successive activities"* necessary to perform and deliver milestones. They are aimed to fulfill "*strategic/operational objectives"* and may be part of larger BIM processes. (BIMe, 2019a)

In the concept of "*integrated workflows*" we mean more interoperability between activities, involving software and tools. You may schematize the workflows in continuous steps, connected to each other.

Integrated workflows are crucial to deliver BIM products. Most of benefits have been identified in *modelling, shop drawings and fabrication, construction, and handover processes.*

All disciplines make use of integrated workflows to achieve BIM objectives. Architects start preparing referenced concept models, structural engineers perform code checking and optimize structural modelling, while MEP Engineers model installations based on the architectural and structural requirements. Models may be shared with other BIM modelers, to follow detailing and generate shop drawings. Fabricators or traders make lists for materials ordering and installations.

The model, the construction drawings and documentations are coordinated between all disciplines and later applied for the construction works. The model may be updated at any time if modifications are required in the different phases of the project.

The integrated workflows allow for the people involved, to achieve a *better communication, reduce the errors onsite, produce and deliver better and coordinated shop drawings, provide accurate estimations, improve scheduling, and in general improve quality* (DODGE, 2016). (see Table 7*)*

Expectations say that BIM workflows in a globalized world, will also increase the support for teams to work within different locations, by reducing costs and raise production, in small efforts.

	Structural Engineers	MEP Engineers	GC/CMs	Structural Trades	MEP Trades
#1 Most Impactful Benefit	Enables better communication*	Enables better communication*	Enables better communication*	Enables better communication*	Reduces errors in field installation
#2 Most Impactful Benefit	Produces better coordinated designs in less time	Minimizes accurate estimates from the specialty trades	Improves schedule performance**	Produces better coordinated shop drawings in less time	Improves schedule performance**
#3 Most Impactful Benefit	Delivers better quality**	More accurate estimates from the speciality trades	Reduces duplication of tasks	Improves schedule performance**	Enables better communica-tion*
#4 Most Impactful Benefit	Improves schedule performance**	Delivers better quality**	Produces better coordinated shop drawings in less time	Reduces errors in field installation	Produces better coordinated designs in less time

Table 7-Benefits identified from Structural and MEP Disciplines, in the use of BIM Integrated Workflows (DODGE, 2016)

The integration of activities in connected workflows, simplifies the modeler and designer’s work. They help to reduce the differences and manual re-working required to go from one step of the project to the other, by automating its connectivity and improving the interoperability. This allows to produce models faster with less errors. It is not a coincidence that the maturity assessment models start from a minimal evaluation for separated processes and increase it towards integrated workflows.

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3. BIM ADOPTION FOR STRUCTURAL DESIGN.

Vendors supports the modelling with BIM enabled software by creating and developing ad hoc programs for structural design and information modelling, enhancing the collaboration in the industry *from fragmented design* towards *integrated project delivery*. Clashes between the different models can be detected by specific software like *Navisworks, Bexel Manager, Tekla Structures* etc. (Quirk, 2012)

Different platforms allow structural analysis and design operation within BIM environments. Revit can make use of some cloud computing or can work together with Autodesk Robot, a complex structural software for modelling, analysis, and design (www.autodesk.com). SOFiSTiK brings structural engineering into Revit with the high interoperable integrated tools, like the FEA analysis + design and the Reinforcement Generation (www.sofistik.com). ProSap Professional is another software for structural engineers, that can import and export IFC formats to guarantee model exchange interoperability (https://www.prosap.it). Trimble offers *Tekla Structural Designer (TSD)* and *Tekla Structures (TS)*, that coordinating together, can do analysis, design, and detailing, guaranteeing an interactive interoperability in the workflows. (https://www.tekla.com)

Research shows that BIM applications in structural engineering design has seen a considerable growth starting from 2014. The research area that has seen more exploration is the "*information management*". Efforts have been identified in the modelling for "*structural components*", the "*automation for assembly"* and the "*planning and optimization*". The research in BIM for civil engineering is in its initial steps. Only limited literature has been found for the state of the art for BIM applications in structural engineering (Vilutiene et al., 2019)

Source	Review period in years	Number of analyzed articles	Source of articles (databases)	Focus	Key findings
Abdirad [13]	2007–2014	97 (selected out of 322)	ASCE, Elsevier, Taylor & Francis, Emerald, and ITcon	BIM implementation assessment	Developments of BIM implementations; metric-based BIM assessment; gaps and limitations
Bradley et al. [10]	2000–2015	259	Scopus, Engineering Village, ScienceDirect, WoS	BIM for infrastructure	4 research gaps in infrastructure and BIM; an information management framework
Bruno et al. [48]	2007–2017	120, 86 of them with international impact, and 1 project	—	Historic BIM	Gaps in historic BIM; methodology for diagnosis of historic buildings using BIM
Cheng et al. [26]	2002–2014	171 case studies and 62 articles	—	BIM for civil infrastructure	Current practices of BIM adoption in different civil infrastructure facilities; research gaps and recommendations; evaluation framework
Davies et al. [51]	2007–2016	36 articles and BIM guides	—	Roles and responsibilities of BIM specialists	Definition of roles and responsibilities of BIM practitioners
Edirisinghe et al. [52]	1996–2016	46 (selected out of 207)	—	BIM in FM	Conceptualization of a BIM-based FM framework; determining the path of future research
Guo et al. [21]	2000–2015	78	WoS and ASCE Library databases	The use of visualization technology	Usage of visualization technologies in safety management
Kylili and Fokaides [63]	2005–2016	Actual European policies and legislation	European policies and legislation	Existing European policies and legislation for the built environment and the construction materials	Future trends in construction

Table 8-Major review studies in civil engineering (part A) (Vilutiene et al., 2019)

Laakso and Nyman [54]	1997–2007	The first 11 years of research on standard 938	—	Research and BIM standardization	Classification of data
Li et al. [14]	2004–2015		WoS	BIM knowledge map	60 key research areas 10 key research clusters
Lopez et al. [64]	—	BIM software websites, articles, brochures, and videos	—	The readiness and development of 4D BIM	A BIM knowledge map; a review of different issues concerning the usability of 4D BIM; matrices for decision-making according to investment in BIM software
Olawumi et al. [55]	—	445	—	BIM research categories	BIM research categories in the project sectors; a visualization of the structure of the BIM literature
Pärn and Edwards [56]	1970–2015	—	—	Laser scanning, 3D modeling devices, modes of delivery, and applications within AECO	Hierarchy of laser scan devices; analysis of 3D terrestrial laser scan technology applications
Pärn et al. [57]	2004–2015	—	—	BIM for asset management within the AECO sector	Challenges facing the FM sector

Table 9-Major review studies in civil engineering (part B) (Vilutiene et al., 2019)

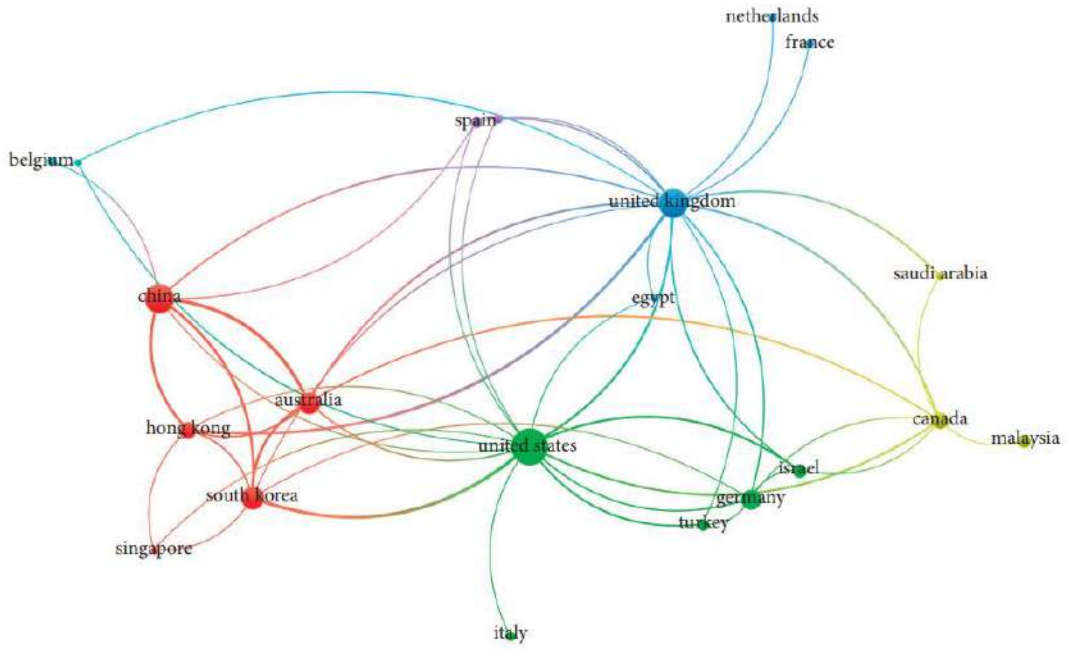


Fig. 9-Most active countries in BIM for structural engineering (Vilutiene et al., 2019)

It was identified that BIM has been generally concerned in solving practical issues of coordination and management. Its capacity in dealing with complex problems in specialized areas for structural engineering remains still unexplored. (Hosseini et al., 2018)

Most European countries have overlooked the research for BIM based adoption for structural engineering. Professionals in the field are still not quite sure in making use of BIM in their everyday work and do not understand the full potential of the BIM methodology.

Author	Number of articles	% of articles	Number of citations
C. M. Eastman	**11**	**13.75**	**704**
R. Sacks	**10**	**12.50**	**476**
X. Wang	**10**	**12.50**	**396**
M. Golparvar-Fard	6	7.50	278
A. Borrmann	5	6.25	46
I. Brilakis	5	6.25	172
S. Staub-French	5	6.25	31
B. Akinci	**4**	**5.00**	**318**
K. K. Han	4	5.00	155
L. Hou	4	5.00	93
J.-K. Lee	**4**	**5.00**	**299**
Y.-C. Lee	4	5.00	42
M. Nahangi	4	5.00	105
W. Solihin	4	5.00	33
Total	80	100	

Table 10-Top author publications in BIM adoption for structural engineering design (Vilutiene et al., 2019)

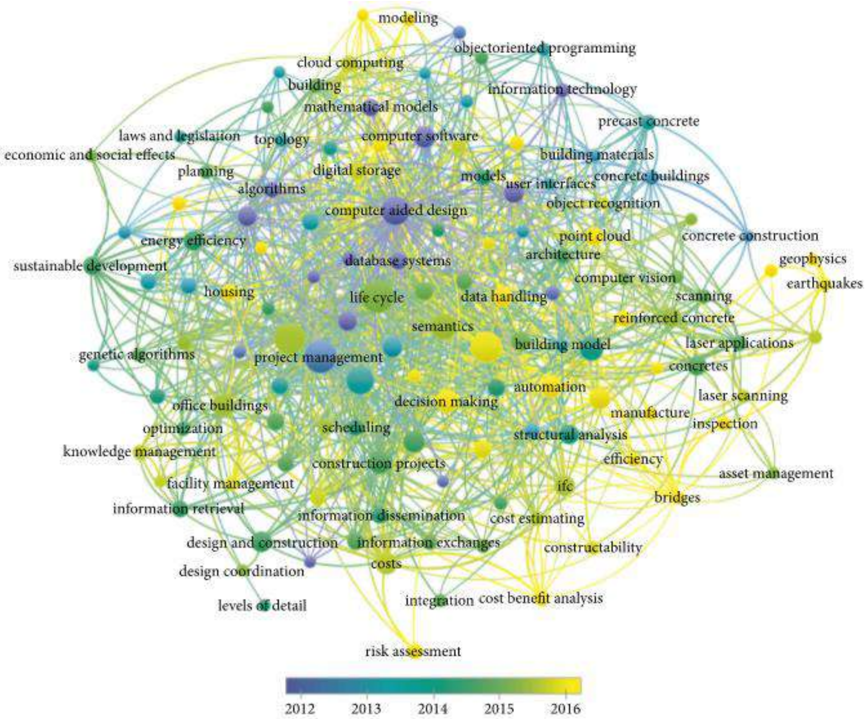


Fig. 10-Research fields in BIM for structural engineering (Vilutiene et al., 2019)

Different research shows that there is still a gap in BIM applications for the specific structural design discipline. BIM has high potentials to facilitate and to improve it. An interesting concept in the structural modelling and analysis within BIM methodology is the definition of the S-BIM (Structural Building Information Modelling), which includes information, related to structural engineering, like the geometry, materials used, boundaries, loads and the analytical model, which distinguish the structural model from the other ones. (Lee et al., 2012)

3.1. BIM for structural design.

Structural design is one of the disciplines involving BIM. The structural model once validated from the engineer, should be integrated with the other disciplines in **one unique federated information model**, to be used for the later stages of the project.

Different design options may be required, depending on the architectural design and costs limitations. BIM allows to facilitate this process by modelling parametric structural elements which include at the same time the physical and the analytical information, in interoperable formats. This can **automate** the processes for design for an information model. In a reduced time, the *structural engineer can evaluate internal forces, stresses and deflections and make the necessary checks*, respective to the Structural Code Requirements, and follow quantity and costs estimations in advance. The structural model produced can be used for all the future operations for coordination, construction, and management.

Applying BIM for structural engineering design, we expect: *a better quality, higher efficiency and more flexibility, enhanced collaboration, rework reduction, higher productivity, better deliverables, errors reduction, time saving, more automation for design, including quantity take off & costs estimation and reduced environmental impacts*. (ALLPlan, 2020)

These results from the use of openBIM software and BIM friendly workflows. They allow to improve the automation of processes and increase the interoperability between the software. Some of these processes for BIM adoption will be investigated during the Thesis.

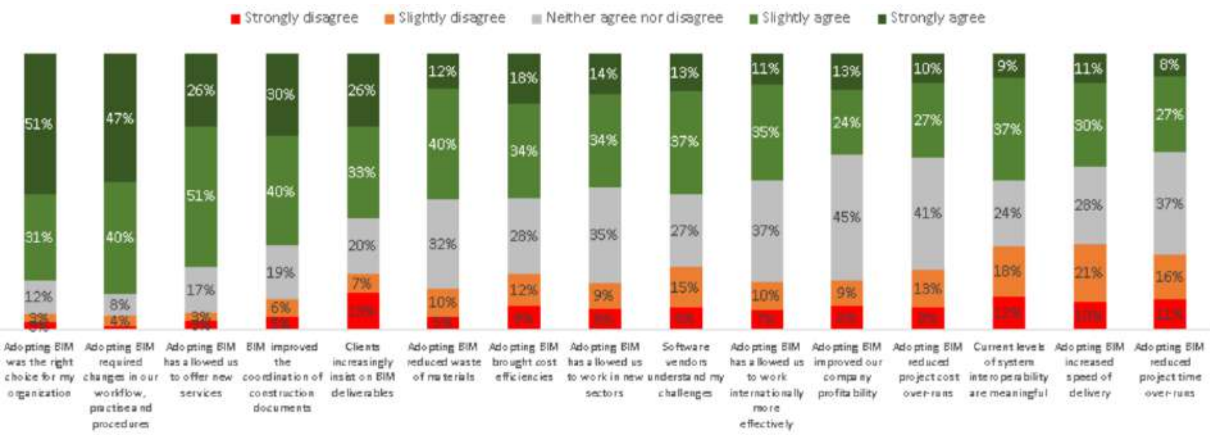


Fig. 11-Approval rate from professionals following BIM adoption for structural engineering, based on an "*ICE Survey*" (ALLPlan, 2020)

3.2. Workflows and software.

It is quite understandable that the structural discipline cannot be seen separate from the other ones and this will be noted during the developments of the workflows for the design processes.

Software and workflows are a crucial part in the design. Different vendors continuously update their products providing new options that support and enhance BIM applications.

Some case studies have been identified *in the literature for the evaluation in BIM adoption*, like:

- (Sampaio and Azevedo, 2018) checking and comparing traditional design approaches towards collaborative Revit and SAP2000 integrated in Revit & Robot.
- (Hamidavi et al., 2020) tries to push to BIM level 3 with optimization integration within Dynamo and Robot.

For the scope of the Thesis, we have chosen three possible scenarios, the first is the "traditional" scenario. The second is the "IFC exchange", making use of interoperable operations, and the third is the "integrated" modelling, where all professionals work on the same environment. As one may soon observe, each of the scenario may be linked with the different BIM level framework (UK BIM Framework, Succar's BIM Framework etc.)

Depending on the type of workflow, different software may be applied. The main issue for "*Traditional Design*", is that processes are not interoperable with each other. The structural model is coordinated separately from the other disciplines, compatibility and clashes are checked manually and not with BIM coordination tools. You may be at a "*traditional*" approach, in case you are not applying a correct workflow, you are exchanging information through paper, you are doing a lot of handy operations, and not making use of automation.

For the second workflow "*IFC exchange*", an openBIM software is required. ProSap Professional allows to have interoperable format exchange for the modelling, and as well does Autodesk Revit/Robot and Tekla Structural Designer (TSD)/Tekla Structures (TS). It is necessary that architectural, MEP and structural modelling should comply with "*IFC*" import/export operations. In this process the software interoperability should be as high as possible to reduce information loss and errors. Structural model can start as referenced to the architectural one and clashes checked between the different models in federated models. Revit/Robot and TSD/TS allow to achieve full 3D models. Problems will be detected and noted in the process.

The third workflow defines a general process for an integrated modelling. In this workflow all actors are expected to work together, collaborate and exchange information within a Common Data Environment (CDE). *Autodesk Revit 2021* can do modelling for the architectural, structural and MEP disciplines and share information within the *BIM 360 CDE*. *TSD & TS* can work in integrated project workflows within the *Trimble Connect CDE*. Other Providers like *Oracle Aconex*, offer a great environment, accepting different native formats, IFC format integration, model checking and advanced coordination and management of the project's information.

3.3. Workflows.

BPR (Business Process Reengineering) is applied to improve the workflow's definition starting from "*Traditional Design*" towards "*Integrated Modelling*". To better define the actors involved and their responsibilities, detailed workflows will be built for each case with the "*Teamflow*" cloud application (https://app.teamflow.com/)

3.3.1. Workflow's detailing.

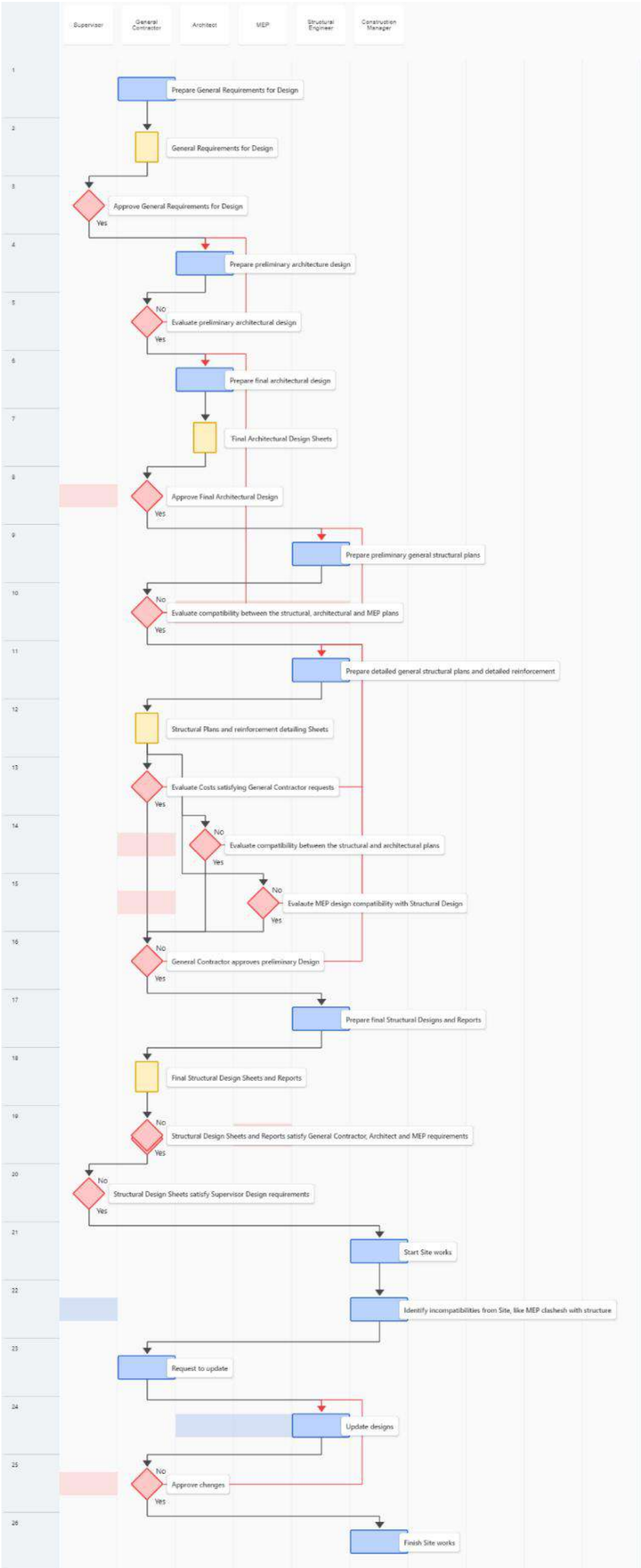


Fig. 12-"Traditional design" workflow (prepared with Teamflow)

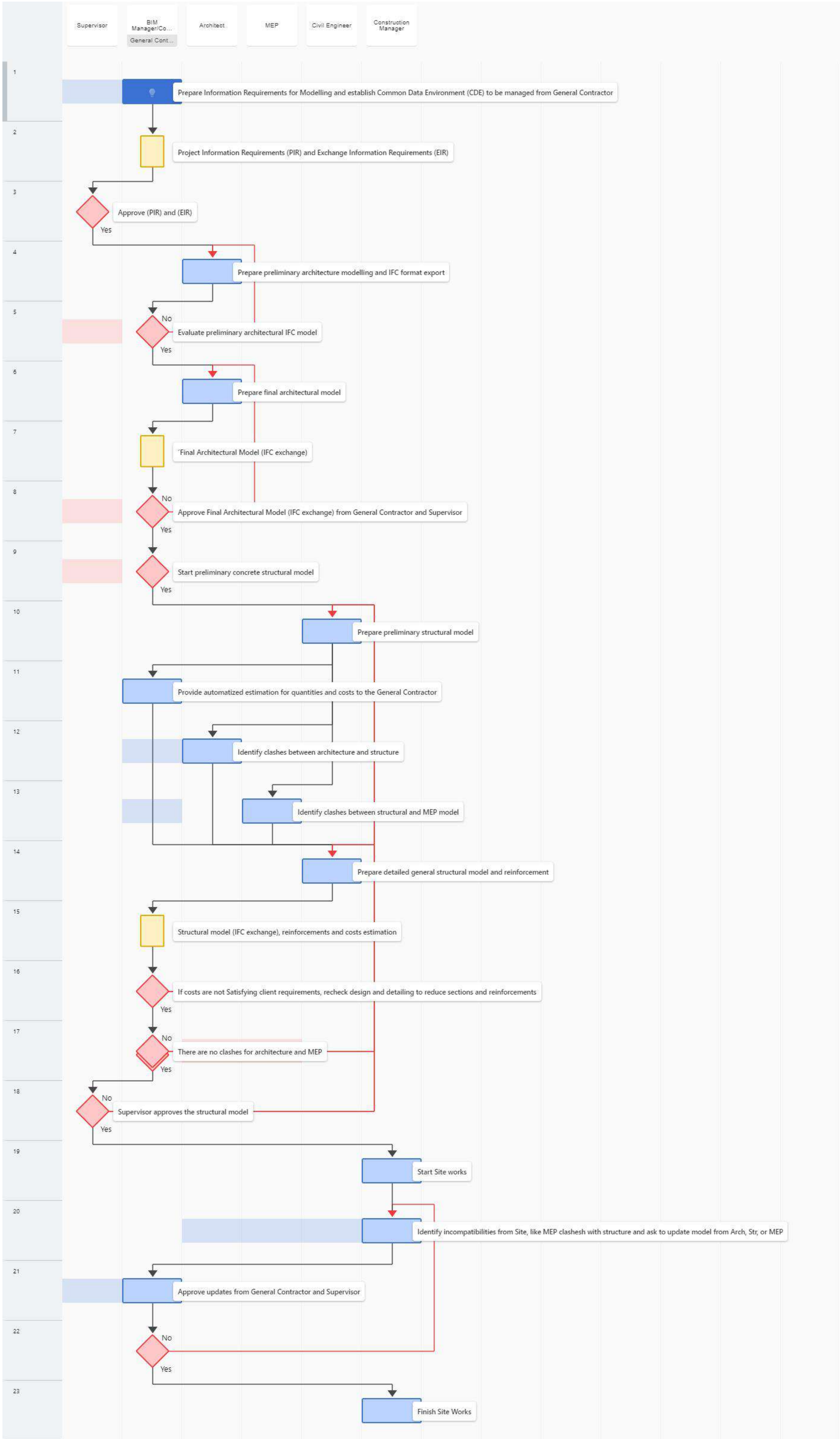


Fig. 13-"IFC exchange" workflow (prepared with Teamflow)

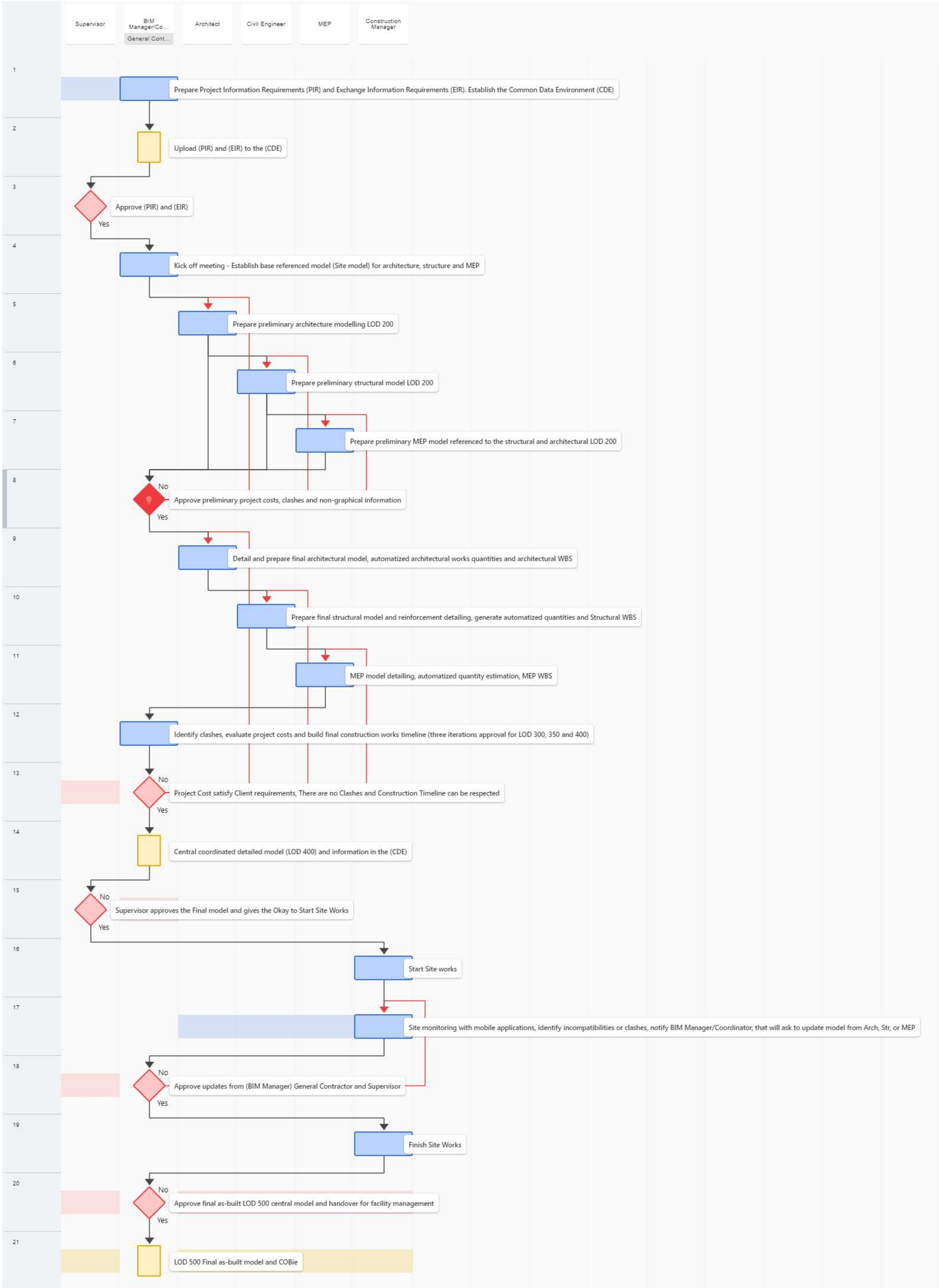


Fig. 14-"Integrated modelling" workflow (prepared with Teamflow)

3.3.2. Workflow's description.

What is generally noticed in the three workflows is how from one case to another, it is evolving from a "*Pre-BIM*" situation to an "*integrated*" modelling. An equivalence can be done with the BIM levels defined in the UK Framework (Bew and Richards M., 2008), (ISO19650-0, 2019), or as well in the "BIM Stages" proposed from (Succar, 2010) (see Appendix 4 - BIM Maturity Assessment Models.).

1. "Traditional design" workflow.

It still includes the current process of working between the different professionals in some countries. BPR can be applied to improve the processes and design. It may be generally considered as BIM level 0 towards level 1 related to the UK BIM Framework.

It is the traditional methodology for design, which consists generally in missing interoperability between the different disciplines, making large use of .dwg and .pdf formats for delivering, and some 3D modelling mostly for architectural client visualization and rendering. Coordination between the different disciplines is done by simply overlapping the designs, without using interoperable exchange formats.

2. "Improved IFC exchange".

In this workflow, there is more attention to collaboration, making use of interoperable formats. Model checking is automatized, and some new responsibilities are defined like the BIM Manager/Coordinator.

This workflow is an evolution towards BIM-enabled processes. The relevant change is the use of interoperable exchange format with the use of the (IFC) and the introduction of a (CDE). If, in the first case the workflow involves a "*Structural Design*", in the second one, we start producing and sharing a "*Structural Information Model*". There is a higher compatibility, clashes are identified making use of BIM Coordination tools, better collaboration, and higher costs savings.

3. "Integrated modelling" within CDE.

This workflow has the intent to exceed the "*Level 2 BIM*", as defined from (ISO19650-0, 2019). It leads the collaboration between the different disciplines at an *integrated level*. It is quite clear that it is difficult to separate the part of the processes that are related to the architectural, structural or MEP. The working activities for design are *inter-related to each other* with a continuous improvement for the model's detailing.

In this workflow, the detailing process, consists mainly in iterations: the first one is for the preliminary model with definition *LOD 200*, and the second group involves three iterations for *LOD 300, 350 and 400*. This is done to guarantee a sequential increase of detailing without having re-works for the Teams. Each step requires an approval from the *BIM Manager/Coordinator and Supervisor*:

- Phase 0 - Preliminary architectural, structural and MEP model at LOD 200.
- Phase 1 - Preliminary architectural, structural and MEP model at LOD 300.
- Phase 2 - Detailed architectural, structural and MEP model at LOD 350.
- Phase 3 - Detailed architectural, structural and MEP model at LOD 400.

3.4. Structural Analysis, Design and Detailing processes within BIM methodology.

There are different software available in the market that can make use of the BIM methodology, and can be applied for the modelling, analysis, design, and detailing processes. In this Thesis we will consider *Autodesk Revit-Robot 2021*, *Revit-SOFiSTiK 2021*, *ProSap Professional v21 and TSD-TS 2021*.

A simple workflow defining the steps and processes of the structural analysis, design and detailing is described as follows. It starts with the *physical modelling* (with references to other disciplines), continues with the *analytical model definition* (depending on the software used), the *structural analysis* (within the same software or linked with mapping of elements, loads, boundaries etc.), the *Code Checking* and concludes in the *Detailing process*.

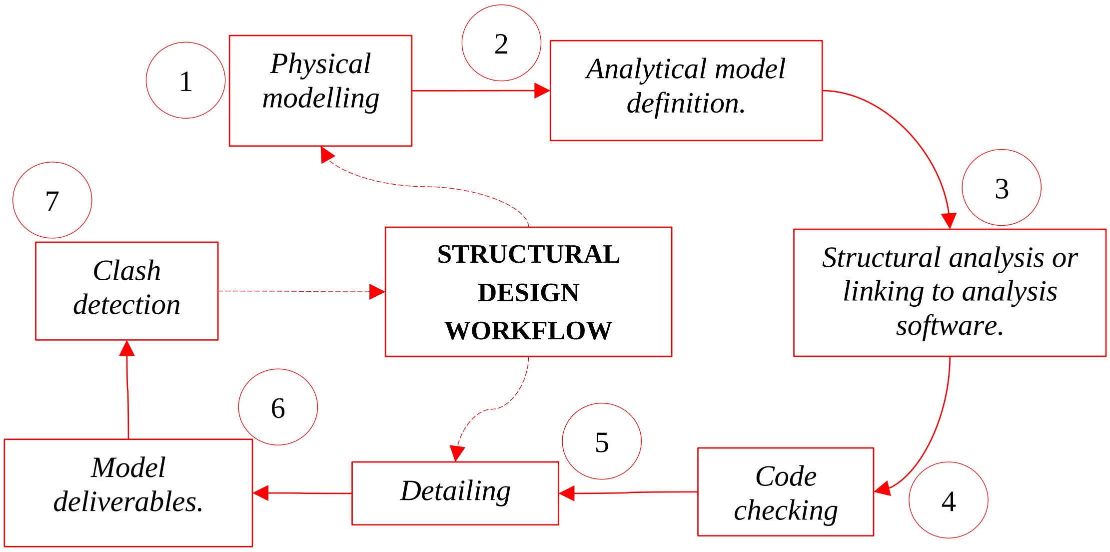


Fig. 15- Simple BIM workflow for structural engineering design and information modelling. (SOFiSTiK, 2019)

Fig. 16-Tools for Revit (AppStore, 2021)

Revit is a globally well-known openBIM software, which can guarantee a coordinated design, fabrication, and construction for the buildings. Revit acts like a general manager making use of Robot

Structural Analysis and tools like Structural analysis Toolkit for Revit, SOFiSTiK analysis + Design, SOFiSTiK Reinforcement Detailing, or as well Visual Programming with Dynamo.

Structural Analysis Toolkit is incorporated in Revit, it works in the cloud and can do some simple static analysis. Results manager and Explorer allows to check in general the results that have been generated from the add-in tools in Revit or the linked one (like Robot). For more advanced calculation, design and detailing you need to go with more professional software like Robot or SOFiSTiK. A general workflow for Revit – Robot (including other AutoDesk software and CDE) is described as follows.

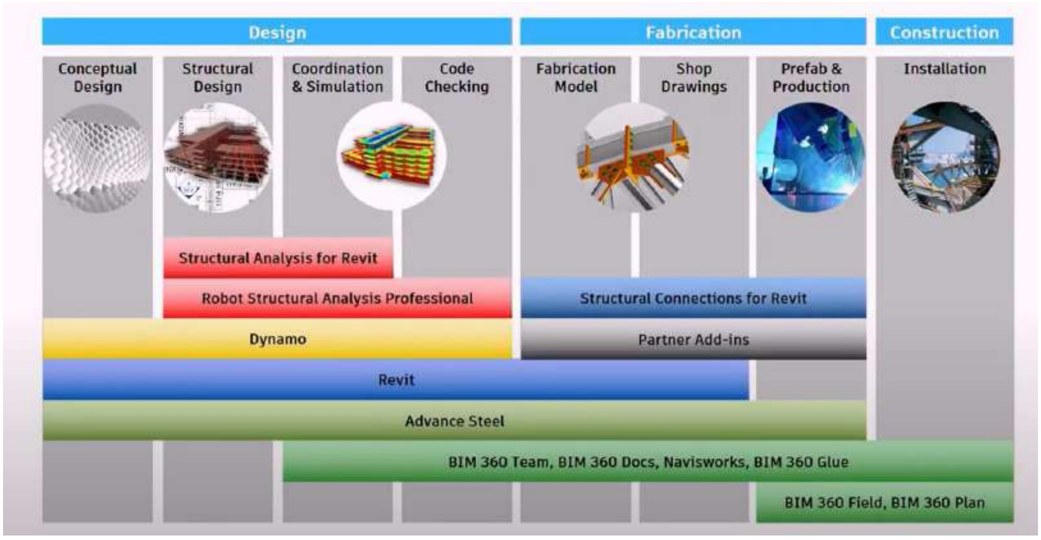


Fig. 17-Workflow for structural design, fabrication & design in Revit-Robot (CAD, 2018)

The object's modelling in Revit comes with an incorporated analytical FE model, which can be modified separately as needed to guarantee the connectivity and the kinematics of the structural schema. Revit-Robot applies some analytical links that can be modified with releases in specific directions to consider the additional forces or moments due to the non-regularity of the structure. The send/receive model operation within Revit-Robot and as well the application of SOFiSTiK workflow processes, follows the Revit analytical model definition.

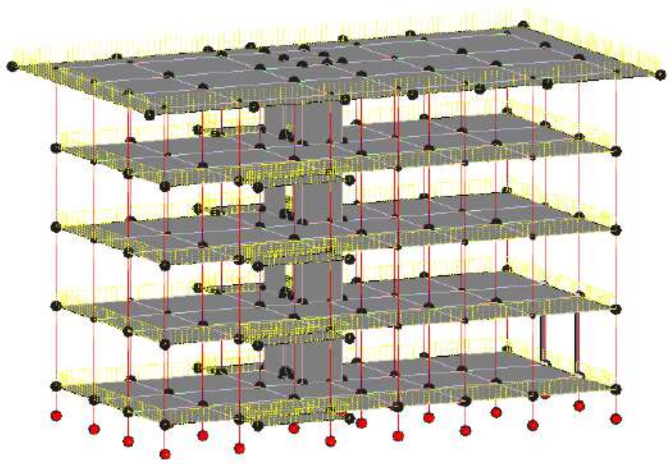


Fig. 18-Analytical model in Revit

ProSap Professional is an *Italian structural analysis* and *design software*, produced from *2SI.it* "*Software e Servizi per l'Ingegneria*". It allows to make *advanced FEM analysis* within different European Code checking (mainly Eurocode and Italian Codes) and to have bidirectional flows of information in *IFC formats*. Also, it facilitates the detailing of structures (*concrete, steel, and wood*), by generating detailed designs based on the results of stresses, deformations, and Code checking. These can be parametrically adjusted according to the designer needs.

The software provides some helpful commands to facilitate the process of import and export for IFC data. The recognition of the IFC building elements to native objects, is done automatically from the software. Incorporated add-in options offer an automation for the correction of the imported analytical model. The BIM object definition can be enriched with properties mainly for one dimensional and bidimensional elements, allowing to create some user customized sections. The detailing process can be automated with 2D drawings. The software deals mainly with concrete, steel, and wood structures.

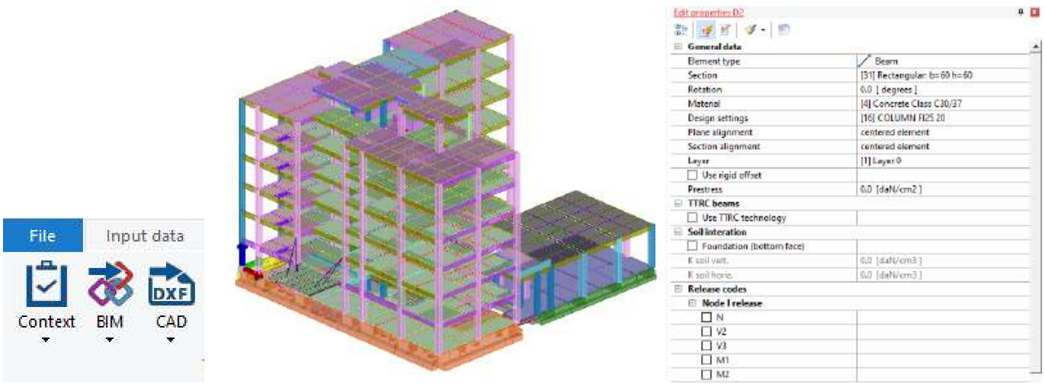


Fig. 19- Graphical and non-graphical information exchange in ProSap Professional.

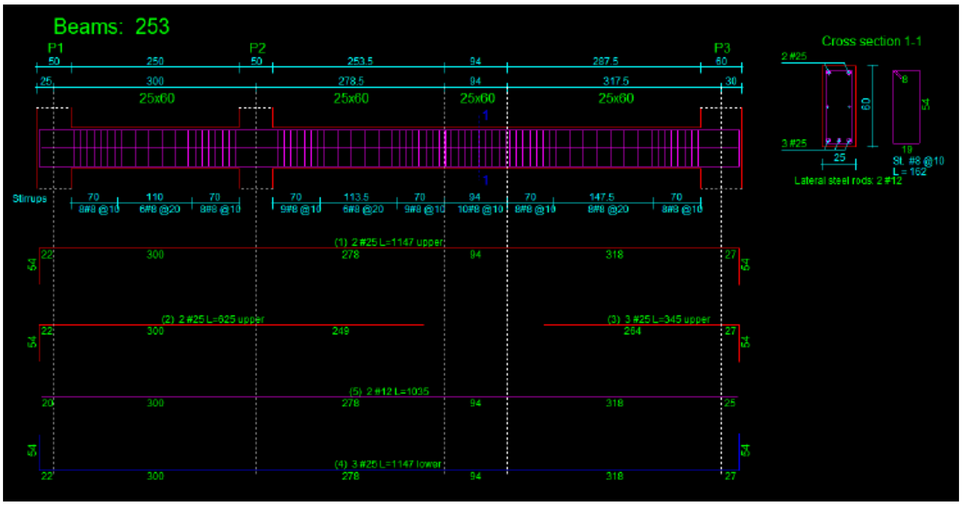


Fig. 20- Concrete beam reinforcement in ProSap Professional.

The last workflow / software that will be analyzed is *Tekla Structural Designer (TSD) / Tekla Structures (TS)*. TS is a BIM modelling software with good interoperability, produced from TRIMBLE. For the analysis and design, it can work in integration with TSD from the same software house. TS allows good information exchange for the analysis and design phases with other vendors like SOFiSTiK, SCIA Engineer etc. Integrated tools for native object import/export operations with TS are available also for Revit. TSD is a calculation software defining mainly the BIM objects dimensions and prediction for quantities, instead TS allows to accurately detail the elements with precise estimations. It can be applied also in the construction and management phases.

3.4.1. BIM structural design within Revit – Robot.

AutoDesk is a global inclusive software provider for the AEC industry, having Revit as a main design software. Its BIM 360 CDE, allows the different users to work contemporary and collaboratively in the same central model. Revit offers the possibility to do some simple calculations with add-in structural analysis toolkits (as described above) and allows to proceed the advanced analysis and detailing in *Robot Structural Analysis (RSA)*.

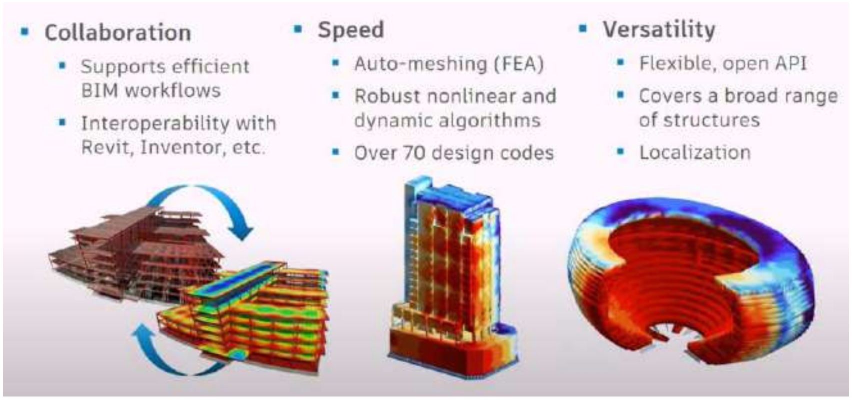


Fig. 21-ROBOT Structural Analysis (RSA) (CAD, 2018)

Robot Structural Analysis RSA is a *FEM analysis software*. It is widely used, covering different Codes. It can be applied for different materials, like *concrete, steel, and timber*, with *2D and 3D elements*, comprising *shells and grillages* or *composite beams*. It allows advanced analytics with damping, nonlinear modelling, and calculations for thermal loads. It accepts nonlinear constraints, material plasticity, nonlinear hinges, 2^{nd} (non-linear) and 3^{rd} order effects (P-delta). It can run modal, spectral, harmonic, linear and non-linear history, elastic-plastic, and pushover analysis (CAD, 2018)

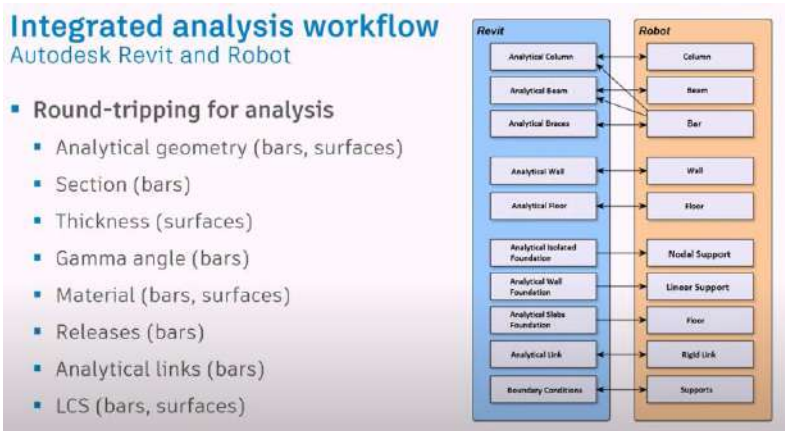


Fig. 22-Structural elements mapping between Autodesk Revit and Robot (CAD, 2018)

Revit and Robot allow to have *bidirectional flows of information*. You start the design in Revit and then continue the analysis and detailing in Robot. The model and results, including detailing (like concrete's reinforcement), can be sent back, and updated into Revit. The analysis results can be explored also in Revit with the Results Manager and Explorer and detailing modified for specific needs. In general, to keep consistency and accuracy of the changes, it is advised to do detailing and modification only in one of the software. The object's modelling may be a bit different between Revit and Robot, so in the send/receive process is applied the mapping of elements (see Fig. 22).

The process follows iteration based on the achieved results. The elements, analysis results and detailing can be sent back to Revit obtaining the integrated model.

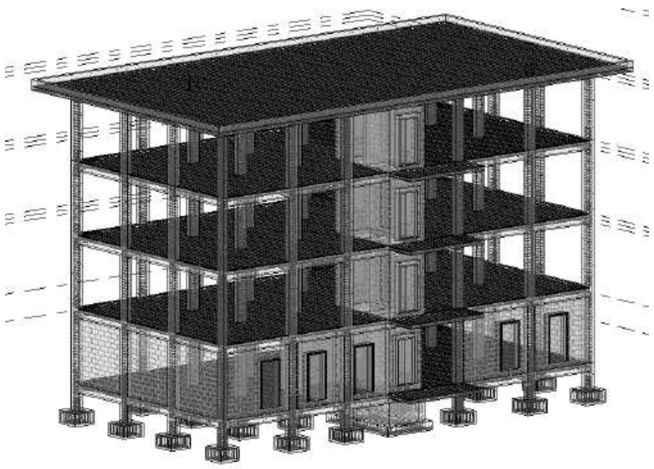


Fig. 23-Revit model with reinforcement from Robot SA.

3.4.2. BIM structural analysis and design in Revit – SOFiSTiK.

Another software with very good use for analysis and design in Revit is the SOFiSTiK FEA and design. The program provides very good integration with Revit, working as an add-in tool in the software. The SOFiSTiK reinforcement generation allows to automatically achieve the detailing of concrete slabs, columns, and beams.

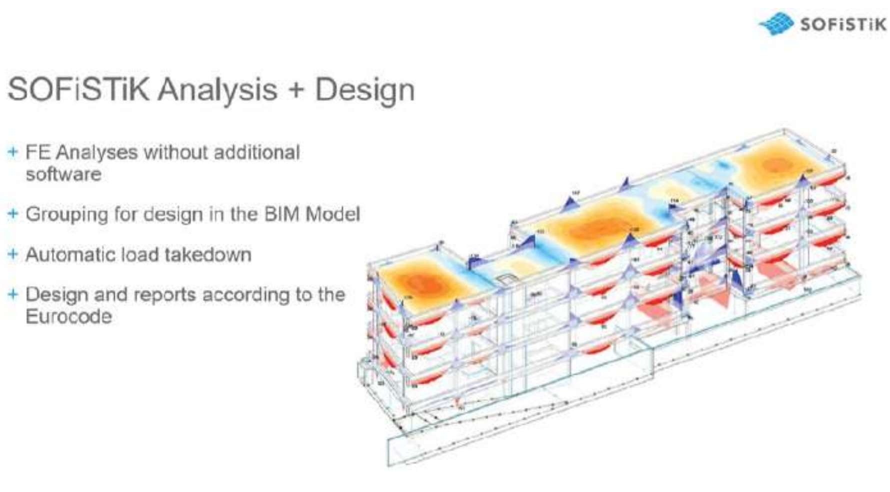


Fig. 24-SOFiSTiK for analysis, design, and concrete's reinforcement in Revit. (SOFiSTiK, 2019)

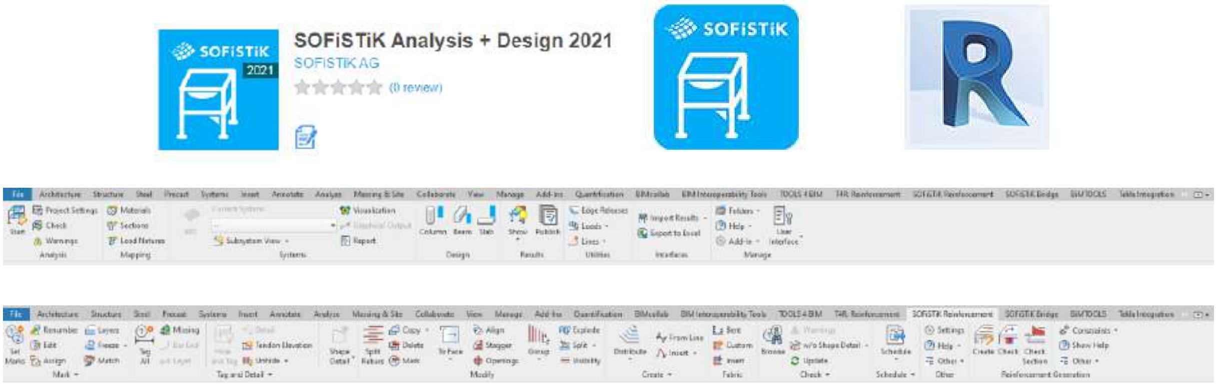


Fig. 25-SOFiSTiK for analysis, design, and concrete's reinforcement in Revit. (SOFiSTiK, 2019)

The workflows within Revit – SOFiSTiK workflow consists in the following steps described in Fig. 26.

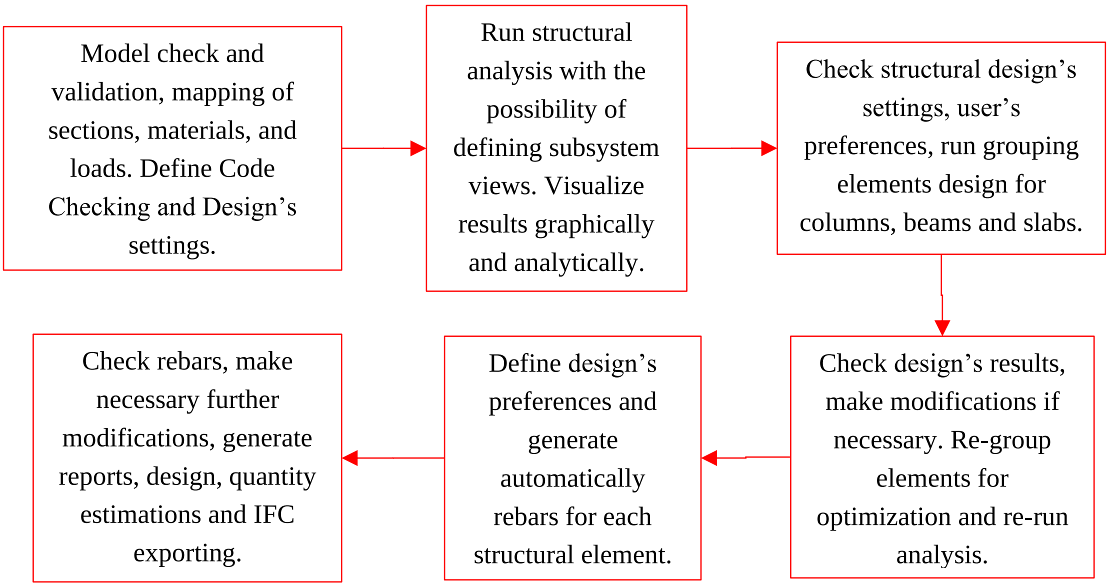


Fig. 26-Simple workflow for the analysis, design & detailing with Revit - SOFiSTiK.

3.4.3. ProSap Professional v21 structural analysis, design, and detailing.

ProSap Professional (produced from 2SI.srl Italia), allows to do structural modelling, analysis, design and detailing within one software. Two workflows for the software are described as follows.

Fig. 27-ProSap Professional 2021 command board.

- **Traditional approach.**

The structural modelling can start from an architectural *.dwg* format file, which can be referenced as a *.dxf*. Initially should be defined all structural parameters, sections, grids and in general the structural model to be analyzed with the FEA.

Next steps follow with the load setting like dead loads, live loads, wind, and seismic ones. Loads combinations may be done automatically or inserted manually. Geotechnical parameters can be modelled in advance in the geometrical and mechanical model, and spring coefficients applied automatically to the foundation elements. Then it follows the model checking, analysis, design, and the detailing of the elements.

- **IFC exchange.**

The software allows bidirectional flows for *IFC exchange*. You can import the preliminary structural model as an IFC and continue in ProSap the analysis and design. ProSap automatically recognizes the BIM objects as native elements. The IFC import/export operation is respected initially for the physical model. For the correction of the analytical model, the software includes some built-in command tools that can be applied after the import process.

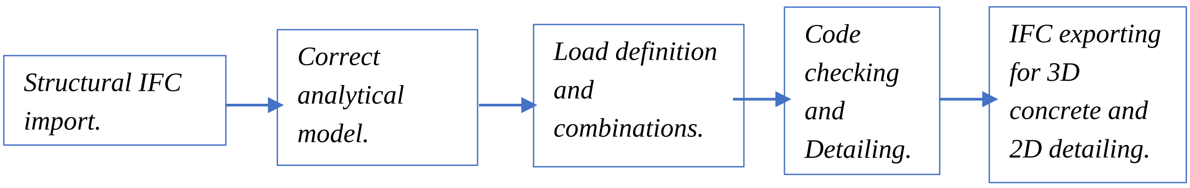


Fig. 28-IFC exchange import/export and 2D detailing in ProSap Professional.

ProSap allows high automation of the processes starting from modelling and analysis, continuing with detailing, drawing and documentation generation. An IFC model can be exported for the concrete elements without rebars reinforcement and 2D drawings may be automatically generated based on Code Checking and designer’s settings.

3.4.4. Tekla Structural Designer (TSD) and Tekla Structures (TS).

Tekla Structures (TS) allows to directly convert imported IFC elements to native objects. TS has a very good interoperability with a wide range of software, and it easily recognizes the analytical geometry for the physical structural elements, included in the IFC format files. In comparison, Revit cannot do such operations in automatic without the support of other software and tools.

Fig. 29-Tekla Product (O’Brien et al., 2021)

You can start the modelling in TSD or TS and then import/export with “*BIM Integration commands*” in *.cxl* formats. The information can be easily exchanged between the software. The operation can include the partial or full model, and for every update it can read the changes that have been done to the project.

TSD/TS offers advanced modelling and analysis, includes worldwide Code Checking and can provide complex detailing for concrete, steel, wood, or glass materials.

Tekla Structural Designer (TSD):

TSD allows automated generation and application of loads. You can build very fast data rich models. Analytical model is automatically generated from the physical one without need to apply further modifications. Building's design and structural performance is evaluated with transparent results. Reinforcement for concrete can be generated for structural elements with early optimum designs. More alternatives can be evaluated with small efforts. Calculation Reports are linked to the model and can be directly updated. Material's take off, drawing and documentation management with steel quantities, are available just in one click.

Data can be exported in various formats, raising the interoperability of the software. It works and integrates well the physical information model with TS or Autodesk Revit. All updates and changes can be identified and highlighted in the import process. (Tekla, 2021)

Tekla Structures (TS):

TS is an advanced structural BIM software, for design and management of 3D models enriched with construction information. It can be applied through all the phases of a life cycle of a facility starting from planning to management. Tekla can achieve as built LOD 500, importable and exportable with other software, can deal with digital tools, IFC formats and send information directly to fabrication machineries.

Fig. 30-Analysis and Design openBIM software with TSD/TS. (Tekla Structures, 2021)

Tekla is an openBIM program interfacing and connecting with different software for the phases of design, construction, and management. You can work with other providers and fabrication machinery and still be in Tekla. Tekla Open API allows collaborative workflows with very good information exchange. Some software that Tekla can coordinate very well information for the analysis and design starts from TSD, Dlubal, STAAD.Pro, Midas, Cype, Robobat, SCIA, SAP2000, StruSoft etc.

It connects well also to fabrication machinery, like for the rebars processing systems, using BVBS formats, PXML, Unitechnik or proprietary formats of aSa, LP-System, Arma+ etc.

Fig. 31-Rebars fabrication formats openBIM with Tekla (Tekla Structures, 2021)

3.5. Interoperable operations between the software.

The different models can be checked for the information exchange quality, to understand the interoperability between the software. A structural model done in one of the software can be exported and imported in the other ones. Coherence, reliability, and accuracy of information are evaluated in the process.

The analytical model should be correctly exported and imported from one software to another. You can start modelling in one software and do the analysis and design in the other one. This happens in the Revit/Robot workflow. Another case is to divide the processes between the analysis and design and the detailing (like in the TSD/TS workflow). The TS Integrator Tool offers good information exchange between Revit and Tekla with possibility of mapping to native objects. SOFiSTiK works integrated in Revit as an add-in tool and makes use of the Revit native objects following some simple automatic relations between the structural sections.

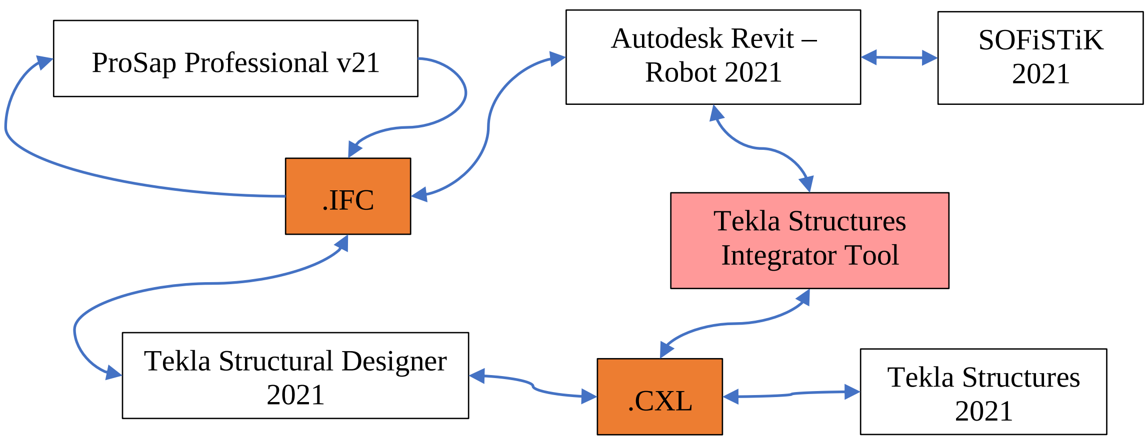


Fig. 32-Model's information exchange between the software.

3.6. 2D shop drawings and 3D concrete reinforcement objects.

A main change that comes with BIM is the digitalization and automation of workflows with 3D modelling and interoperable operations between the different phases of creation, production, and maintenance. Reinforcements in concrete structures have been mainly modelled and managed in 2D shop drawings. With BIM approaches, it is possible to generate 3D reinforcement objects with all rebars indexed in a CDE database. In such way, coordination is easier, estimation and fabrications are done automatically, and data management follows 3D objects and not 2D drawings. (buildingSMART, 2020)

The data management process compared to the traditional one, generates changes in the workflow, since installations should be based on digital tools for automation with no paper reporting.

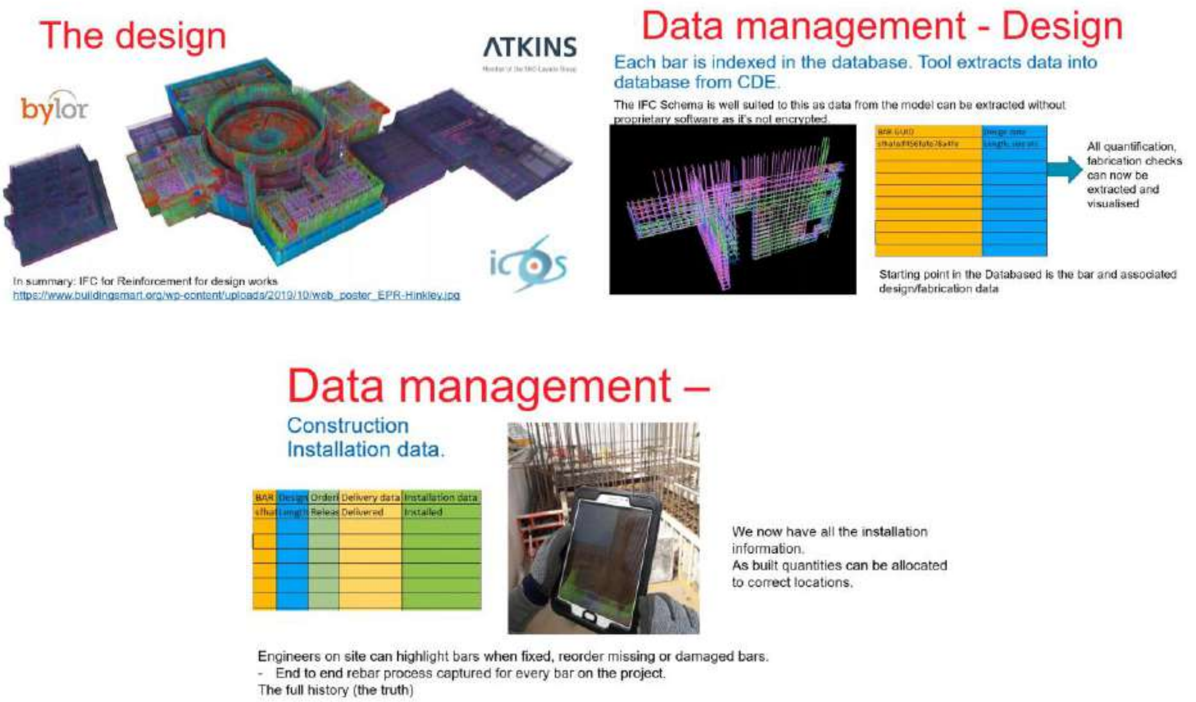


Fig. 33-Data management for concrete reinforcement - HINKLEY POINT C (UK) (buildingSMART, 2020)

Fig. 34-Automation in rebars production (buildingSMART, 2020)

Following the automated data management processes, fabrication workflows can follow the rebars production directly from the IFC geometry and data model, not going through 2D tables, which may create loss of information and errors. Applying reinforcement management software and manufacturing machine suppliers you can send directly the rebars from the IFC model to the fabrication.

It is required for rebars to be modelled separately and uniquely with one ID and to have scheduled all rebars. A 3D IFC model allows to have full model view, easily accessed, and checked.

3.6.1. BVBS format for rebars production.

Rebars design and fabrication follow shape codes based on standardized tables. With 3D reinforcement modelling, new standards are connecting to the BIM modelling, like the BVBS format, which allows to automatically fabricate rebars, with automated cutting and bending directly from the IFC model. (Maciel and Fabiano R, 2016)

These fabrication machine code relations to BIM are still in development, optimizing the mapping processes, improving the data exchange, and removing the need for manual interventions. Visual programming tools like Dynamo can be applied to extract efficiently the data to the BVBS format for automated fabrication. (Liu et al., 2021)

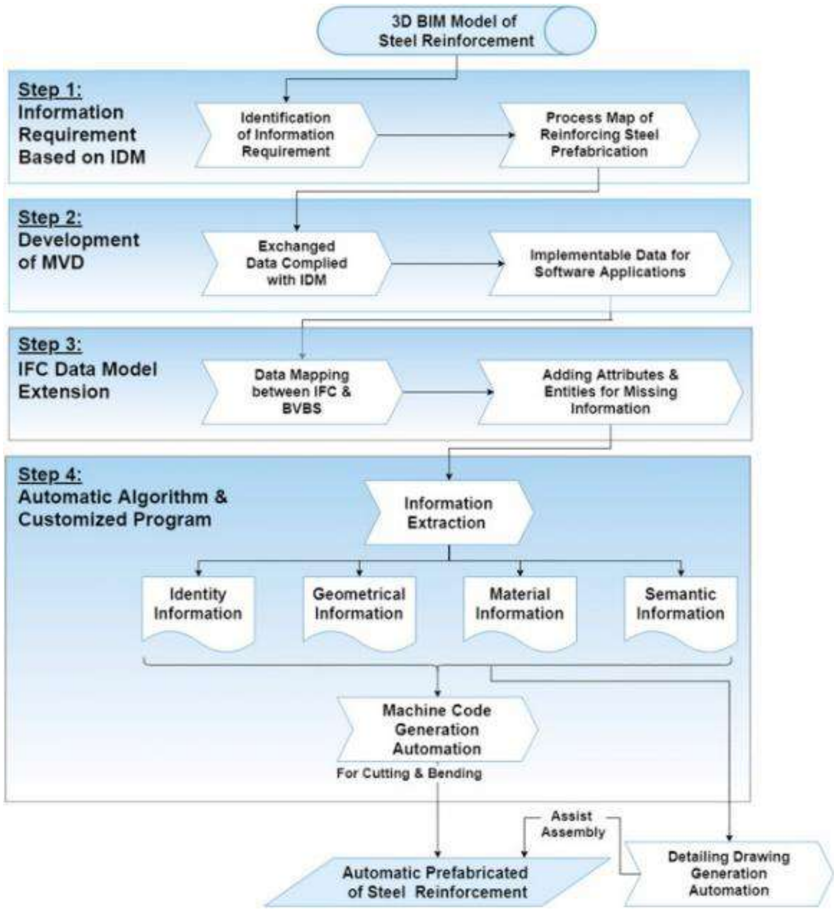


Fig. 35- BIM-BVBS automation for reinforcement prefabrication. (Liu et al., 2021)

4. CASE STUDY - APPLYING BIM.

This Chapter will be mainly focused on the developments, analysis, and discussion of some Case Study Scenarios, involving BIM adoption for structural design.

- **Four floors residential building - named as "Conventional".**

The analysis will start from a conventional academic model, which has been developed during the BIM A+ program 2020/2021. It consists in a four floors residential use building. For this case, will be analysed how BIM enabled software like Revit, Robot, SOFiSTiK, Tekla Structures (TS), Tekla Designer (TSD) and ProSap, can deal with the design and information modelling processes. Results will be discussed case by case.

- **Six floors building (4800 m^2) governmental use "Government Object A & B".**

Case study nr.2, will involve the uses of the IFC information modelling formats and comparison with traditional design applications. "*Government Object A*", is a real project and has been already realized following the "*Traditional Design*" workflow. Following experiences from this project, it is built the improved "*IFC exchange*" workflow and applied for the "*Government Object B".* Since both buildings are similar, comparisons can be done for the differences between the workflow's applications.

- **Six floors building (4800 m^2) governmental use – "Government Object C".**

In the third case study there is a higher complexity of the project but with similar area. The design will proceed towards the application of the "*integrated modelling*" workflows. Results from the previous studies and best practices will be applied in the process.

The workflows applied in each Case Study will be discussed and evaluated based on some criteria:

1. Software's facilitation to deal with the structural modelling, analysis, design and detailing.
2. Information Modelling capacities of the software and workflows.
3. Interoperability problems between the different software and workflows.
4. Import/export operations for the structural model, loads, analysis & design's results.
5. Facilitation in the production of the BIM deliverables.
6. Required improvements for automation of processes, better interoperability, clashes etc.
7. Facilitation for coordination between the different disciplines, clashes etc.
8. Quantity estimations, Drawing documentation and Reporting.

Critical aspects, that will require more careful attention are:

- Accuracy of the analytical model, respectively to the physical modelling.
- Correct definition of the properties, parameters and in general design's Code Checking settings and user's preferences.
- Boundary conditions of the structural model and soil-building interaction with definition of elastic coefficients for Winkler soil modelling.
- Correct mapping of element's sections, materials, and loads in the import/export operations.
- Coherence, reliability, accuracy, and in general quality of the drawings, reporting, quantity estimations, 3D reinforcement detailing and IFC information exchange.

4.1. Case Study nr.1 - Four floors residential building.

4.1.1. Description.

The model of this building is based on the main Assignment for BIM A+5. It was built in the BIM 360 CDE with the use of Autodesk Revit 2021 software. It is developed in an area of around 950 m^2, planned for destination of residential use.

Fig. 36-Case Study nr.1 – Model's view from Revit 2021.

4.1.2. Structural Design with Revit-Robot.

The model is initially checked for the correct definition of the physical structural elements, and for the continuity and integrity of the analytical geometries. The foundation required to make some decisions, in choosing between isolated footings, continuous beams, or slab foundations.

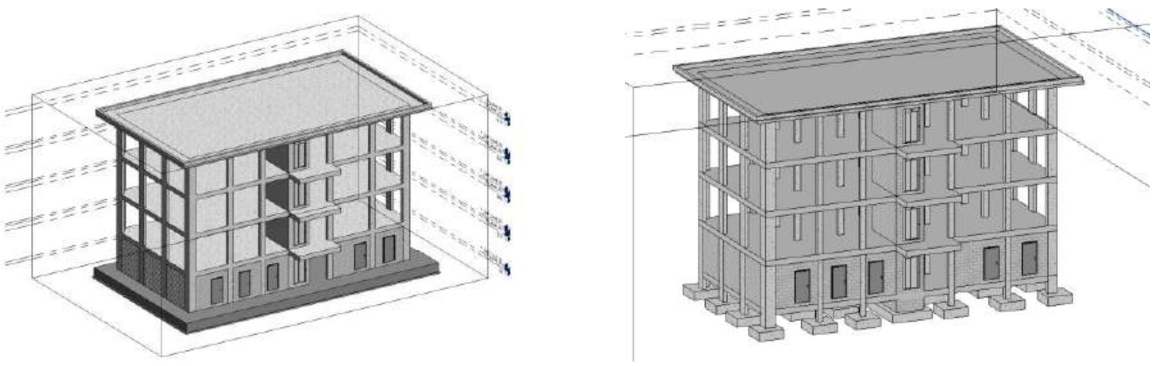


Fig. 37-Initial model and corrected one with isolated footings and structural continuous foundation's wall strips.

It was observed that REVIT does not include in the default foundation families, the T reversed beams. It gives the optionality to model as foundation families, footings, slabs, or wall's strips.

Once concluded the check with the physical modelling, it continued with the analytical geometries, requiring the modification and correction of the analytical connections between some of the structural elements. The analytical geometries can be modified in a separated view and at the same time checked parallelly that no differences are created for the physical structural elements.

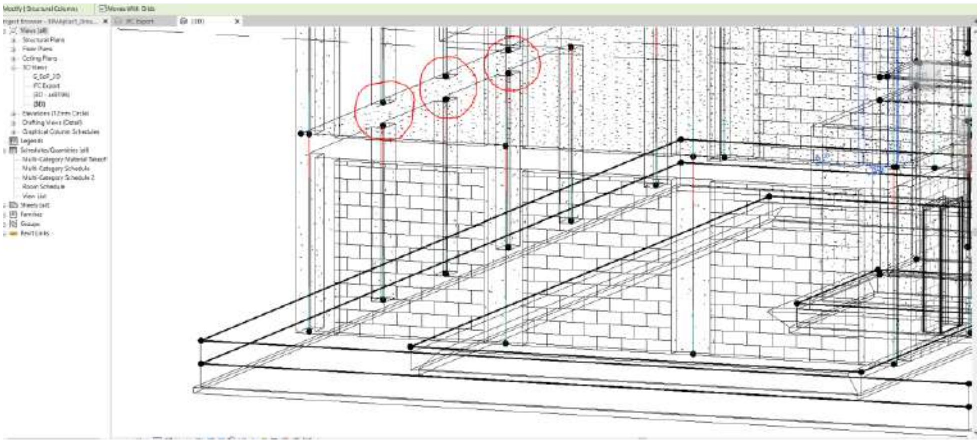


Fig. 38-Analytic model correction.

4.1.2.1. Isolated footings and continuous foundation strips under the wall.

For Case Study nr.1, it was decided to apply for the foundation, isolated footings for columns and strips for the walls. The model was sent to Robot 2021 for structural analysis and design. Some live loads could be applied in advance for every floor in Revit (2.00 kN/m^2).

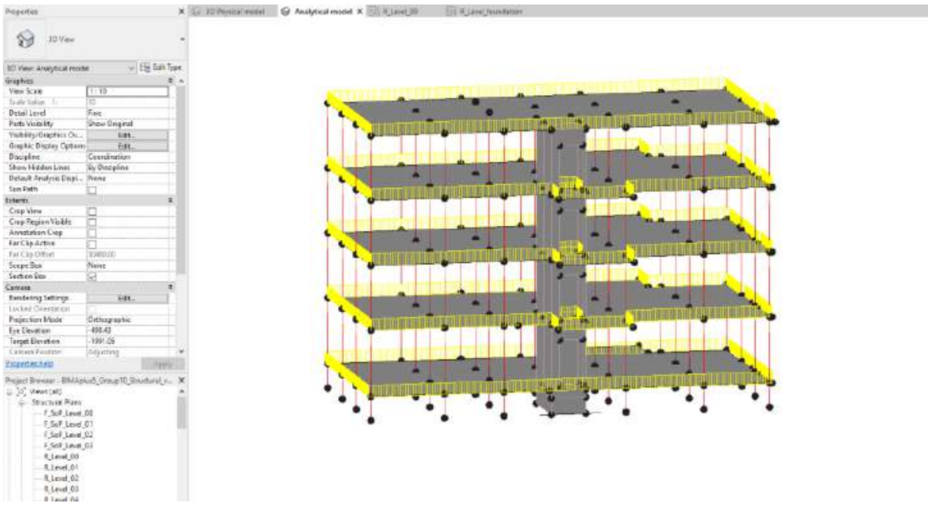


Fig. 39-Analytical model view - Live loads applied in Revit.

Boundary conditions can be assigned in Revit or in Robot. For preliminary analysis you can run analysis with fixed boundary conditions and later apply K-coefficients to achieve more realistic results [1].

[1] When modelling the footings in Revit, the program is automatically applying some fixed boundary conditions. More specialized and advanced analysis can be run in Robot by evaluating and applying K-elastic soil-structure interaction coefficients.

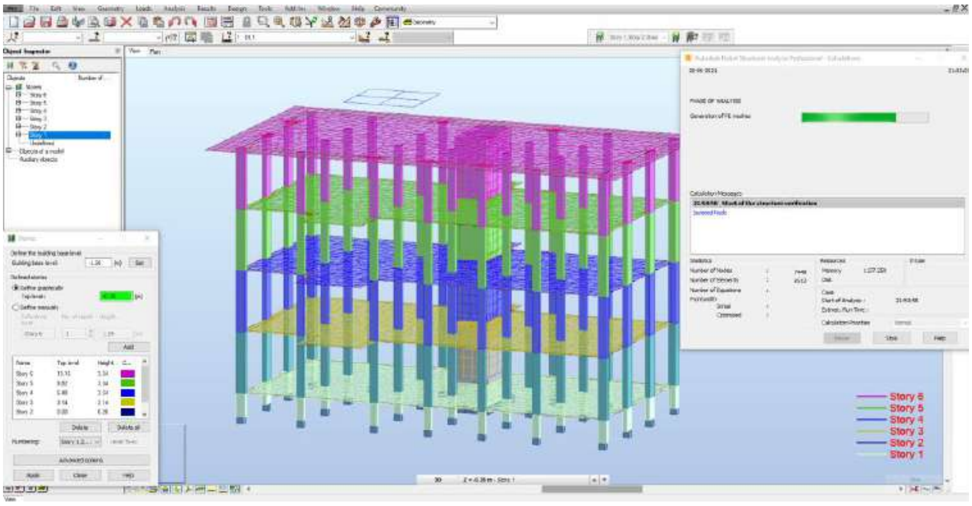


Fig. 40-Robot's imported model view with assigned objects to every story (floor) for fixed boundary conditions.

Robot requires to assign objects to every story (floor), to run the calculation analysis. Model verification is done automatically from the software, with errors displayed in the respective analysis windows.

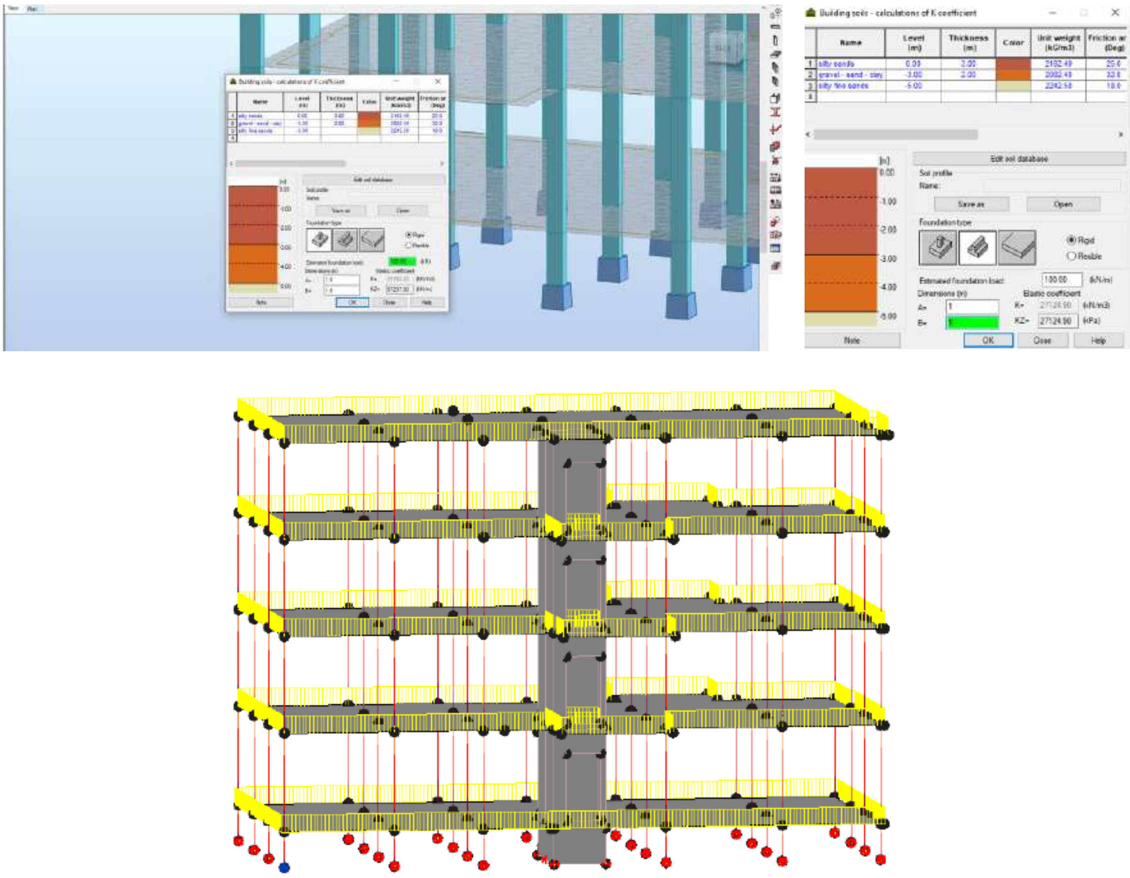


Fig. 41-Spring boundary conditions assigned in Revit or in Robot.

The building-soil K coefficients can be automatically calculated and assigned to the structural elements according to the geological layers in Robot (see Fig. 41).

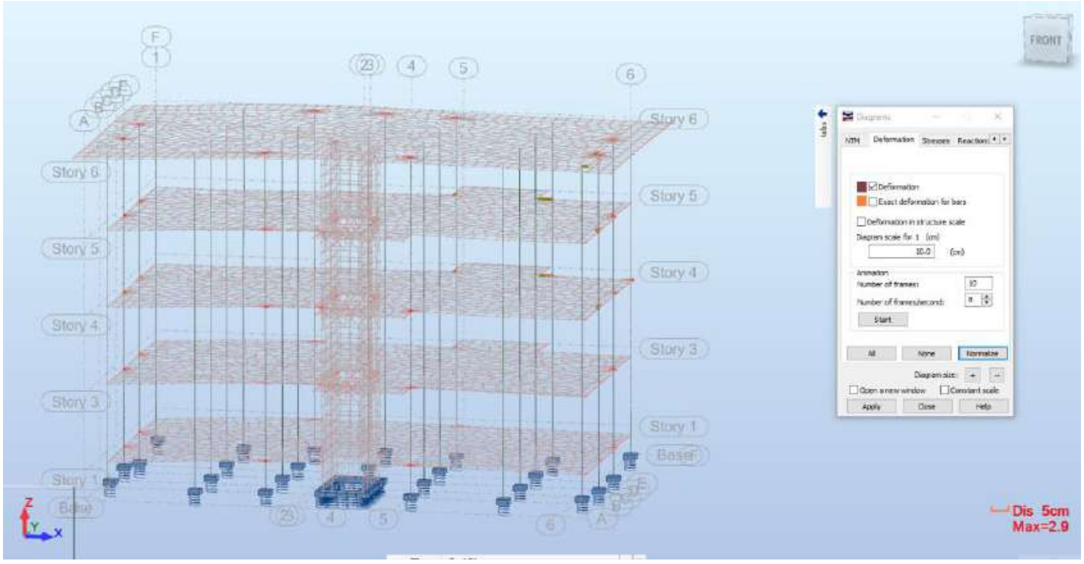


Fig. 42-Result’s analysis with deformation view.

After running the FEA calculation, you can proceed with the “*required reinforcements*” and “*provided reinforcements*”, views and commands. These are applied to follow the design and code checking based on the designer’s reinforcement schema, for the different structural elements, of floor’s slabs, columns, beams, and walls. Once reinforcement is generated, the model with design’s results and reinforcements can be sent back to Revit. Robot offers advanced configurations and functionalities for the analysis, design, and detailing processes.

4.1.2.2. Concrete slabs design and reinforcements.

Concrete slabs reinforcement in Robot SA follows a similar logic to the other structural elements. You should check in advance that the physical & analytical model has no mistakes and that the loads are correctly applied. Loads combinations can be defined manually or based in the Code chosen for the design. Robot provides worldwide Code checking including Eurocode that is being applied in this Thesis. A workflow is detailed for the reinforced concrete slabs design in Revit – Robot SA, as presented in Fig. 43.

In this process it is noted that:

- Designer’s preferences can be customized to automate the process, but they need to be applied individually for each one of the analysed slabs.
- Robot requires high computational resources. It is crashing sometimes, when going from one slab to another with the next slab command. You need to go back to “*slabs reinforcements*” and then again to “*provide reinforcement*”, to change from one slab to the other one.
- The software is not very flexible in keeping memory of the previous reinforcements of the slabs, if making modifications to the main structure.
- Robot provides some default reinforcement patterns for the rebars, which can be customized and updated following the designer’s needs. The reinforcements are generated and can be checked in 3D in “*concrete’s slabs reinforcement*”.

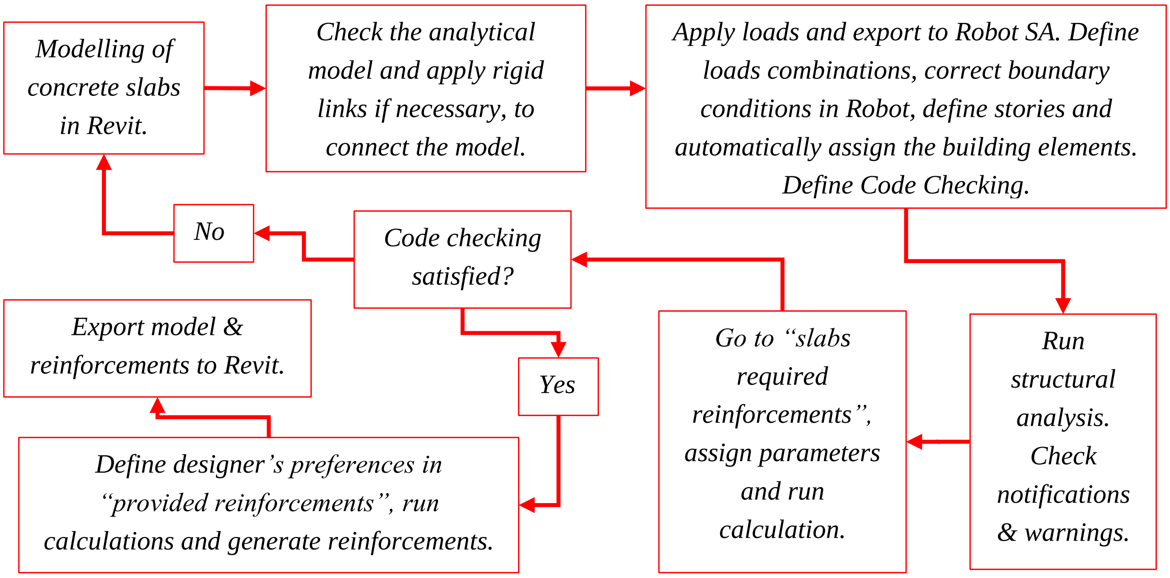


Fig. 43-Concrete slabs design, analysis, code checking and reinforcement’s detailing.

Fig. 44-Code checking, slabs calculation for bending moment, deflections, and required reinforcements.

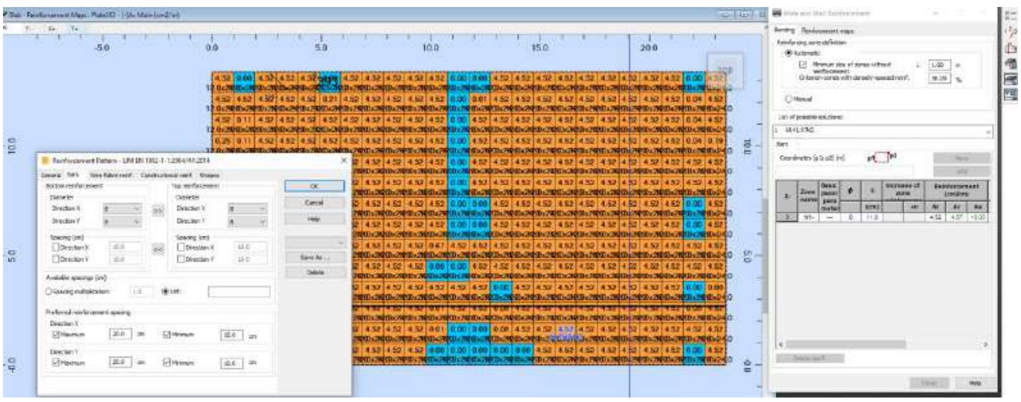


Fig. 45- Designer’s preferences and provided reinforcements.

4.1.2.3. Beam's reinforcement.

Robot offers an advanced environment for the beam's design and detailing. You can set up parameters for Code Checking, and designer's preference schemas for the reinforcement. Detailing is automatically generated and can be sent back with design results to Revit.

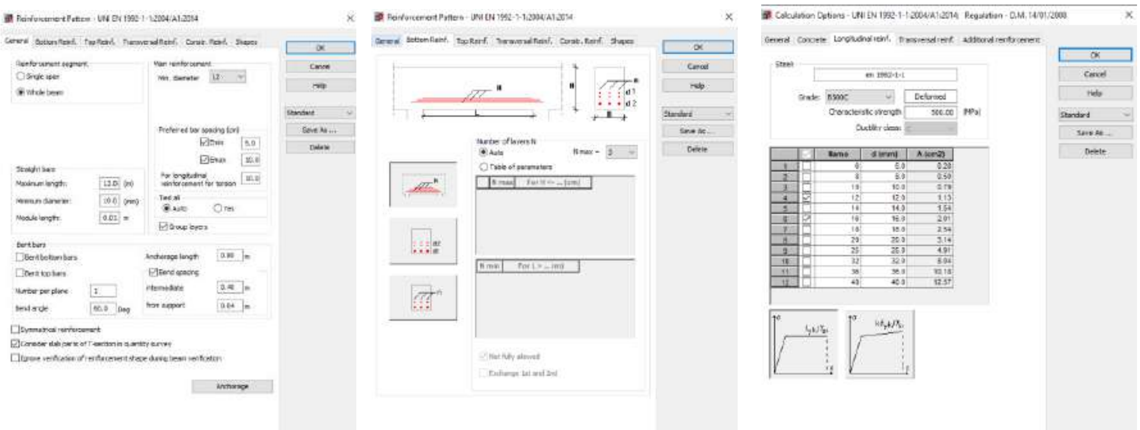


Fig. 46-Advanced Code Checking parameters and designer's preferences for the reinforcement of concrete beams in Robot.

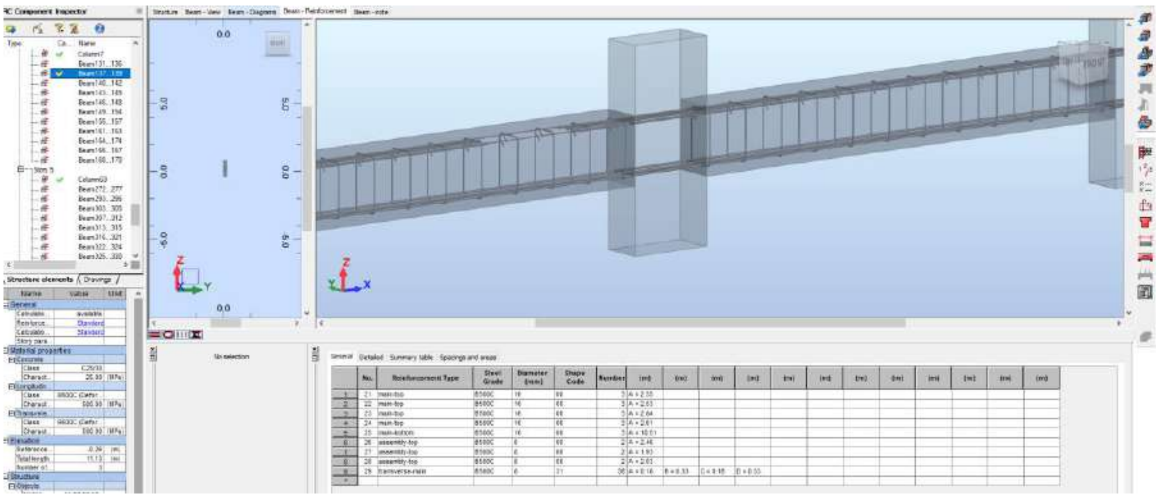


Fig. 47-3D visualization of the concrete beams including the rebars scheduling.

4.1.2.4. Column's reinforcement.

The column's reinforcement detailing, proceeds with "*provide reinforcements*" commands. Interactive windows allow to decide the detailing based on the Code Checking parameters and the designer's preferences. Robot allows to set different calculation options and reinforcements schema. You can save these configurations with specific naming. Their application may require some automation, since it may be required to apply the saved configurations every time you run the design calculation. [1]

[1] This was observed generally for all concrete elements design.

Once the design is successfully verified and reinforcements are generated, the model with results and reinforcements can be sent back to Revit. If the process has been carefully respected, the information is successfully exported and can be viewed and further modified in Revit.

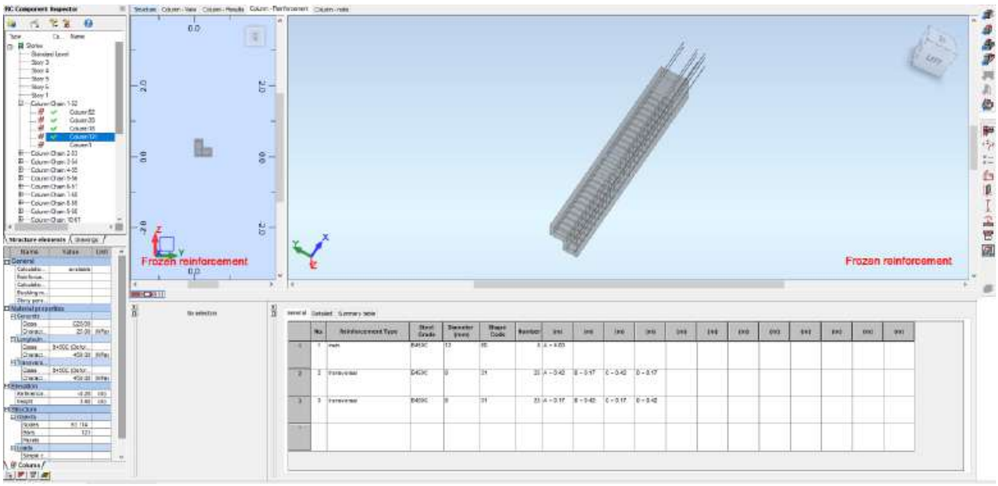


Fig. 48- 3D visualization of the column's reinforcements including the rebars scheduling.

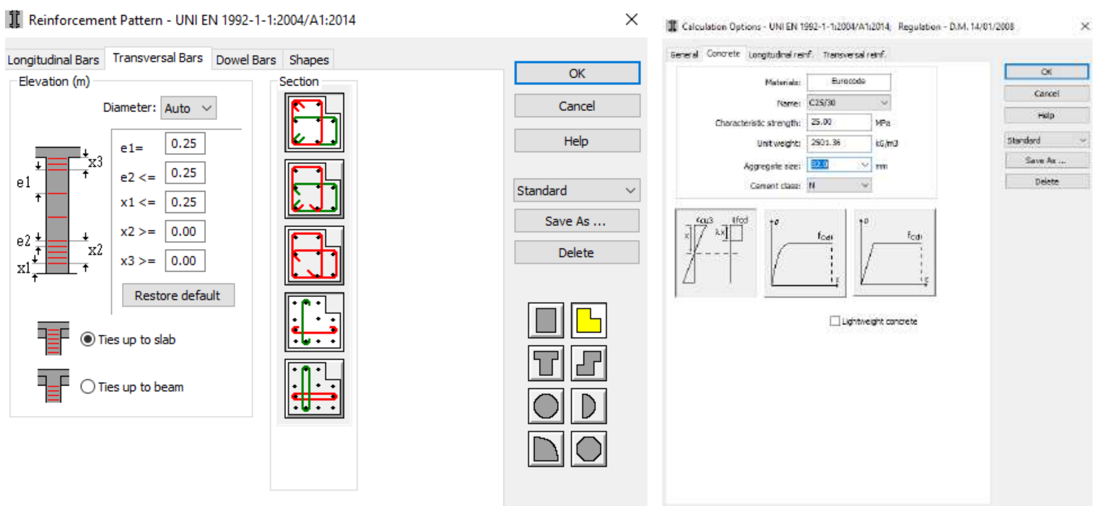


Fig. 49- Column's reinforcements schema and designer's settings.

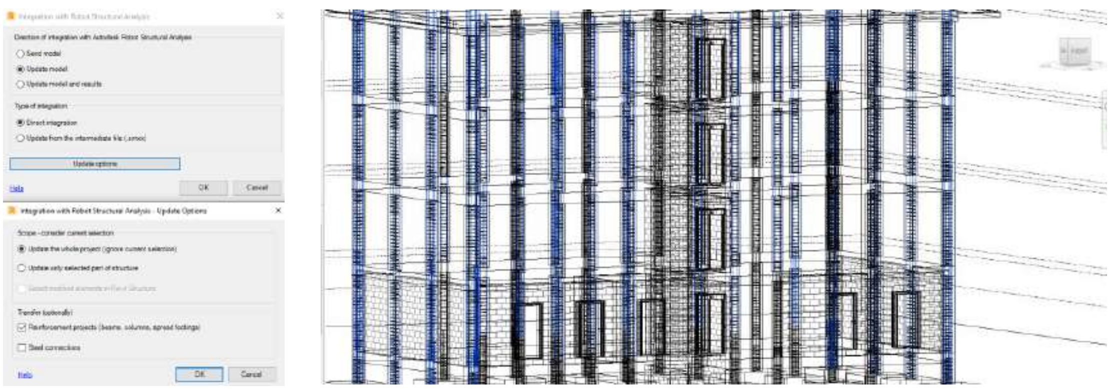


Fig. 50-Revit's model update with design's results and rebars reinforcements.

4.1.2.5. Footing’s design and reinforcement.

The footing’s design continues like the column’s reinforcement. The designs and detailing calculation are done with the “*provide reinforcement*” commands view in Robot.

It was observed that the information exchange for reinforcements in the Revit-Robot workflow, is a *time-consuming* process. To save time for the detailing, reinforcements transfer and update to Revit may be done only once the design for elements is concluded, and all reinforcements are generated.

Robot does not calculate reinforcements for punching shear in footings. It calculates and verifies only for pure concrete. This problem has been identified also in the previous versions.

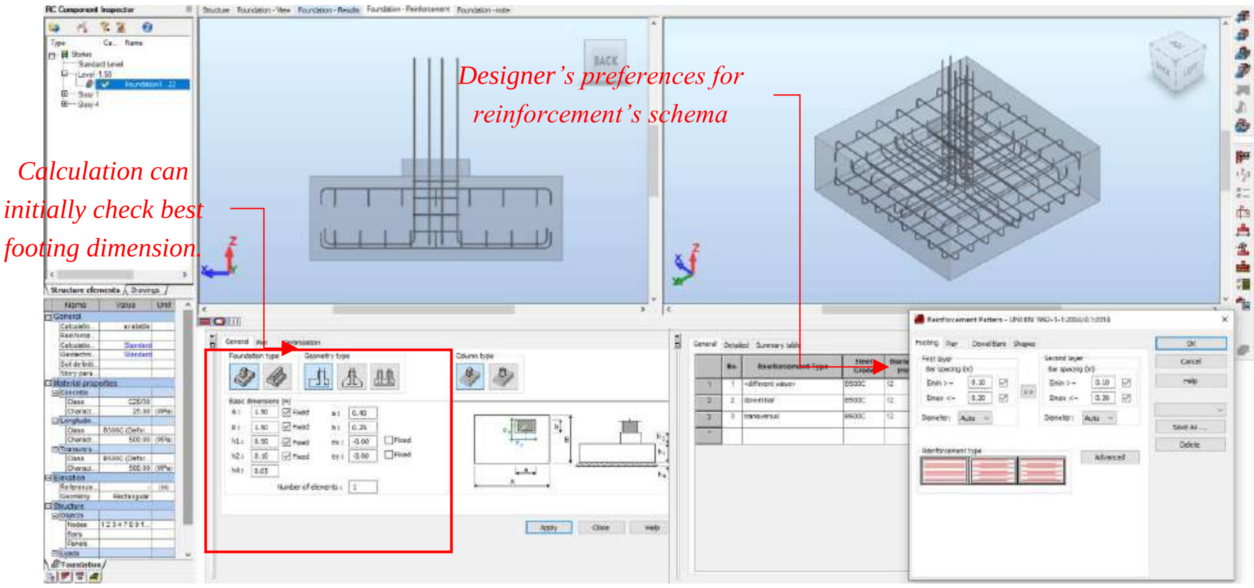


Fig. 51-Footing’s reinforcement calculations and designer’s preference schemas.

The applied workflow for the footing’s analysis, design and detailing is described as follows (Fig. 52):

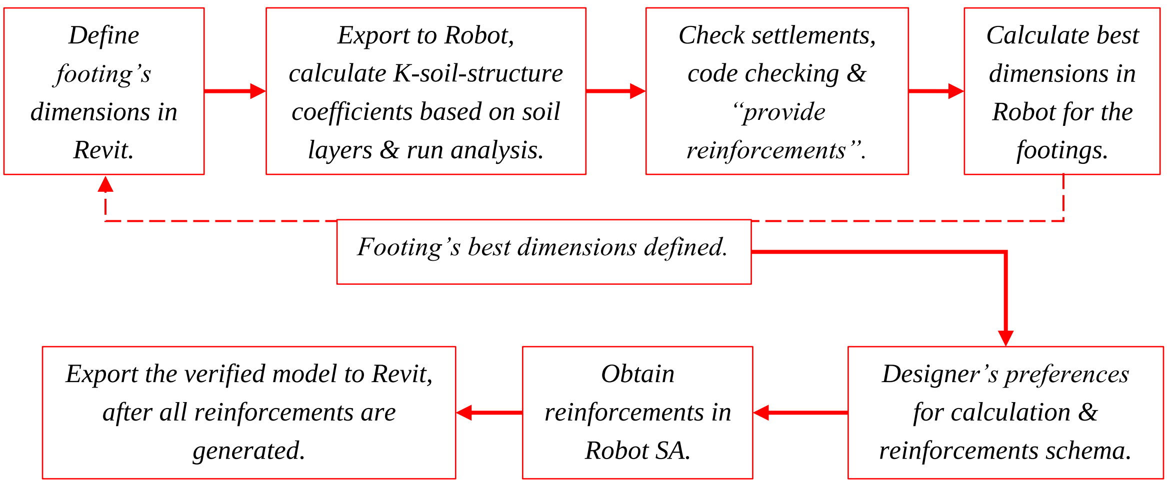


Fig. 52-Footing’s analysis, design, and detailing.

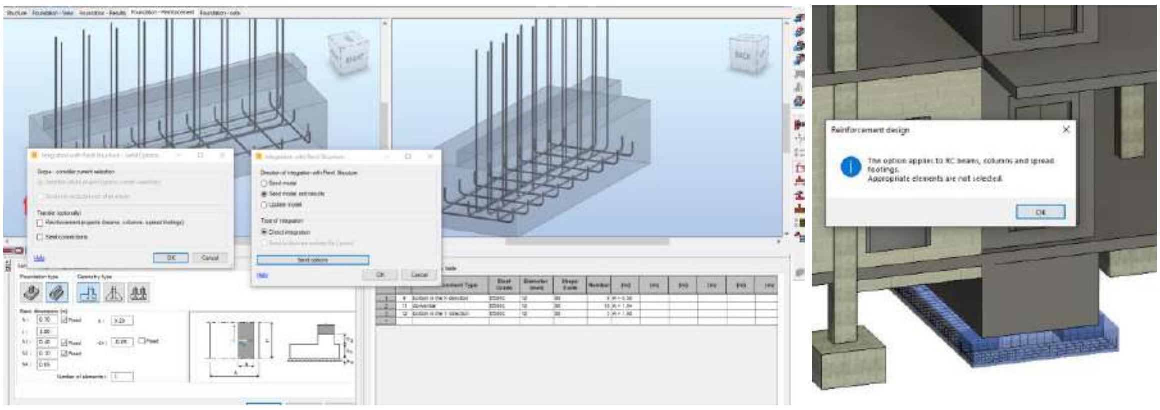


Fig. 53-Walls foundation's strips reinforcements in Robot SA (left) and manual reinforcement detailing required in Revit (right).

Wall's foundations strip reinforcements were identified to not be properly imported from Robot SA. For this purpose, it was necessary to manually model them after the design in Robot.

4.1.3. SOFiSTiK application in integration with Revit.

The second workflow that is applied for the structural design, includes Autodesk Revit 2021, SOFiSTiK FEA analysis & design and SOFiSTiK reinforcement 2021.

In this workflow Revit is responsible for the modelling and loads, instead SOFiSTiK for the model checking, analysis, design, and detailing. Loads should be applied in advance in Revit. SOFiSTiK applies a mapping for loads and sections that are preliminary defined in Revit. Once designer's preferences are established, and model checking is verified you can run the analysis in SOFiSTiK. This can be done also by dividing the model in subsystems based on the different levels.

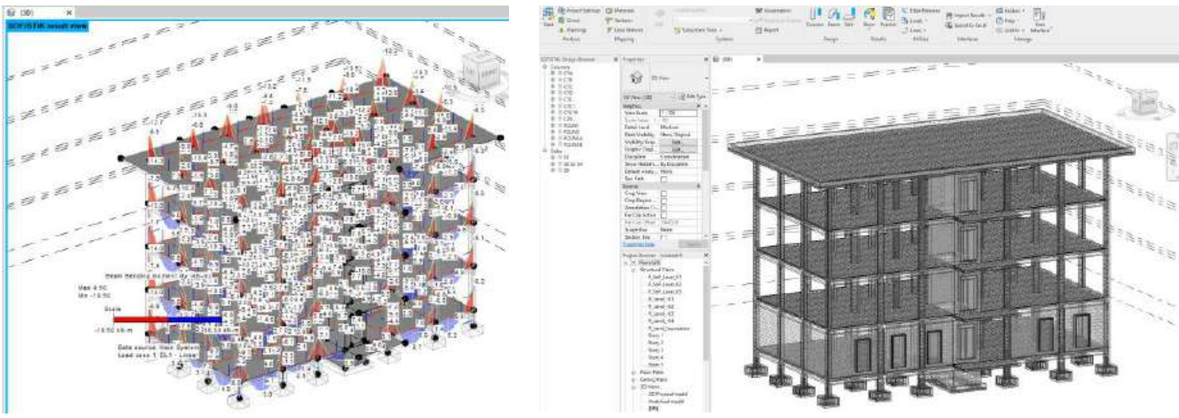


Fig. 54-Structural analysis results, design, and reinforcement detailing.

After obtaining analysis results, it is possible to proceed with the design. Structural elements can be grouped in the design process to optimize the reinforcements. Following evaluations of quantity estimations in Revit, you can do manual regrouping of the elements. The design defines interactively the required reinforcement for the elements. The reinforcement generation command automatically generates in 3D the reinforcement rebars in the model's views. Manual modelling of rebars can also be done for specific structural elements.

4.1.3.1. Further consideration and comparison with Revit-Robot.

Once the design check is verified in SOFiSTiK and reinforcements are generated in Revit you can:

- Follow quantity and costs estimations in Revit, subsequently do modifications to the structural model, and provide other design alternatives.
- Coordinate the model with the architectural discipline since both are created and referenced in Revit. Export the model as an IFC and follow clash detections in other BIM coordination software and tools.
- Follow other uses in the next stages of the project, manage and update the model within the BIM 360 CDE.

In the first two workflows the main software is Revit. The further uses of the model for these cases are similar. For the modelling, analysis & design were identified the following differences:

- Robot offers more advanced analysis & design optionality for all the phases of the structural design but presents some difficulties in the information exchange with Revit for the rebars reinforcements.
- SOFiSTiK integrated in Revit is simple and fast to run, but it is presented with limited parameter settings. For more advanced analysis you should run the SOFiSTiK Desktop Software.
- Running integrated in Revit, SOFiSTiK has a higher interoperability with Revit. This brings to faster processes for analysis, design, and detailing. Robot instead provides more advanced analysis and design but does not guarantee full interoperability with Revit.
- In the beams and columns analysis and design, each software provides interactive design and detailing with user's preference schemas.
- SOFiSTiK checks and makes use directly of the analytical model configuration from Revit. Robot instead, allows to do further considerations, like more advanced analytical link configurations and K elastic soil-structure coefficients calculations and automatic assignment as a property to the foundation elements. The elastic boundary conditions values in Revit-SOFiSTiK should be evaluated externally and assigned manually.
- Some limitations are presented in the foundation elements. SOFiSTiK tool integrated in Revit follows design for columns, beams, and slabs with limitation to foundations. Also, Robot presents some difficulties in the import/export operations of reinforcements with Revit. Manual modelling may be required for specific elements like the wall's foundation strips.

4.1.4. Structural Design with ProSap Professional.

ProSap Professional v21 has no direct interoperability with Autodesk Revit 2021, but it allows IFC import/update/export operations. The model for analysis in this workflow, is not built in ProSap but will be imported from an IFC exported from Revit. So, the interoperability for the IFC exchange between the software can also be investigated.

The IFC importing window in ProSap defines the mapping process for the structural elements. You can import the IFC objects as D2 and D3 meshing elements, representing respectively the one-dimensional and two-dimensional columns, beams, walls, and slabs.

The model imported to ProSap is accurate for the physical modelling but requires some correction for the analytical geometry. ProSap includes a "*Help for BIM*" integrated command tool that can be applied to make the analytical model adaptations. With this functionality, the software searches for nodes that are positioned within a radius range, and subsequently starting from elevation values, columns nodes, beams and slabs, corrects the analytical model's nodes positioning.

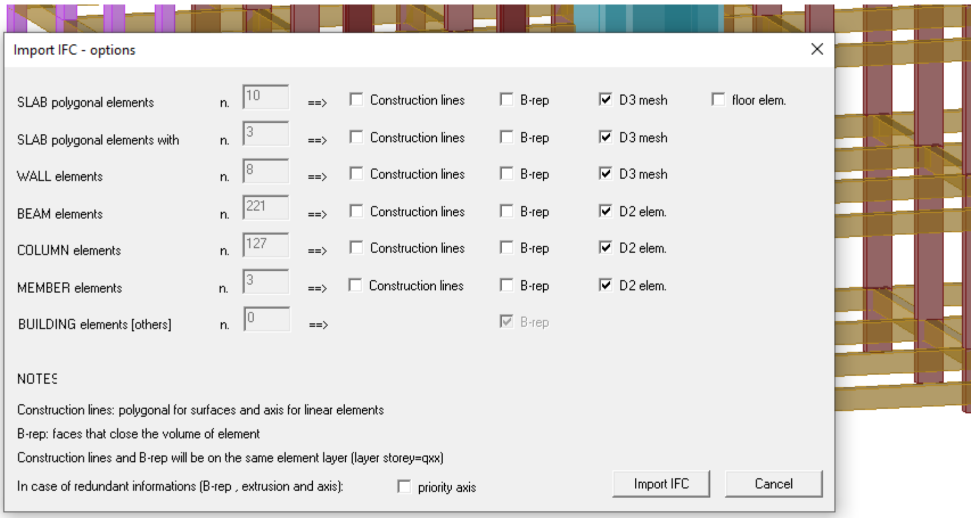


Fig. 55-IFC importing in ProSap Professional.

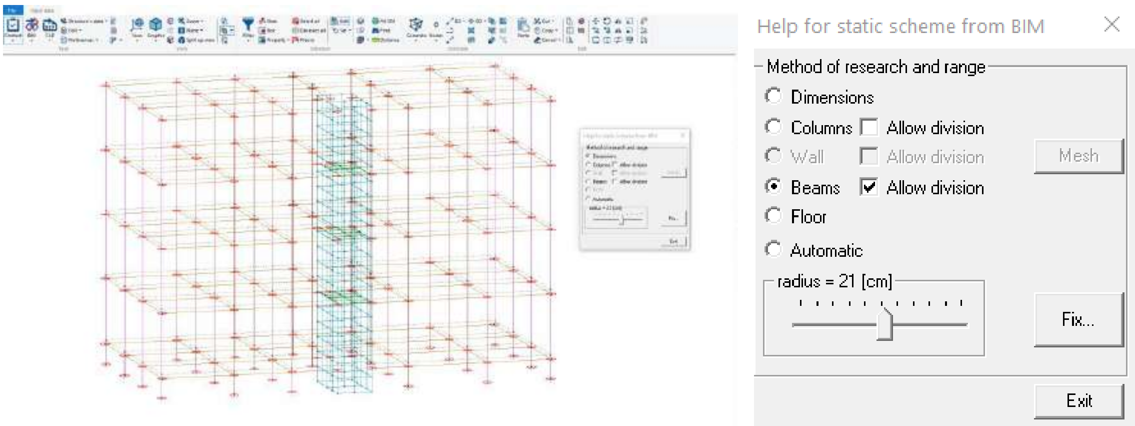


Fig. 56-IFC analytical model correction in ProSap.

Once the analytical model is correctly checked and verified, walls and floor's slabs may be generated from the actual nodes' configurations. This process is fast and once the full model is obtained it can be finally checked for any incongruency.

K coefficients values for building - soil interaction can be calculated within the geotechnical module included in ProSap. Bearing capacity of the soil can be verified, and the K- values automatically assigned to the foundation elements. Code Checking settings and design's parameters can be defined within the module.

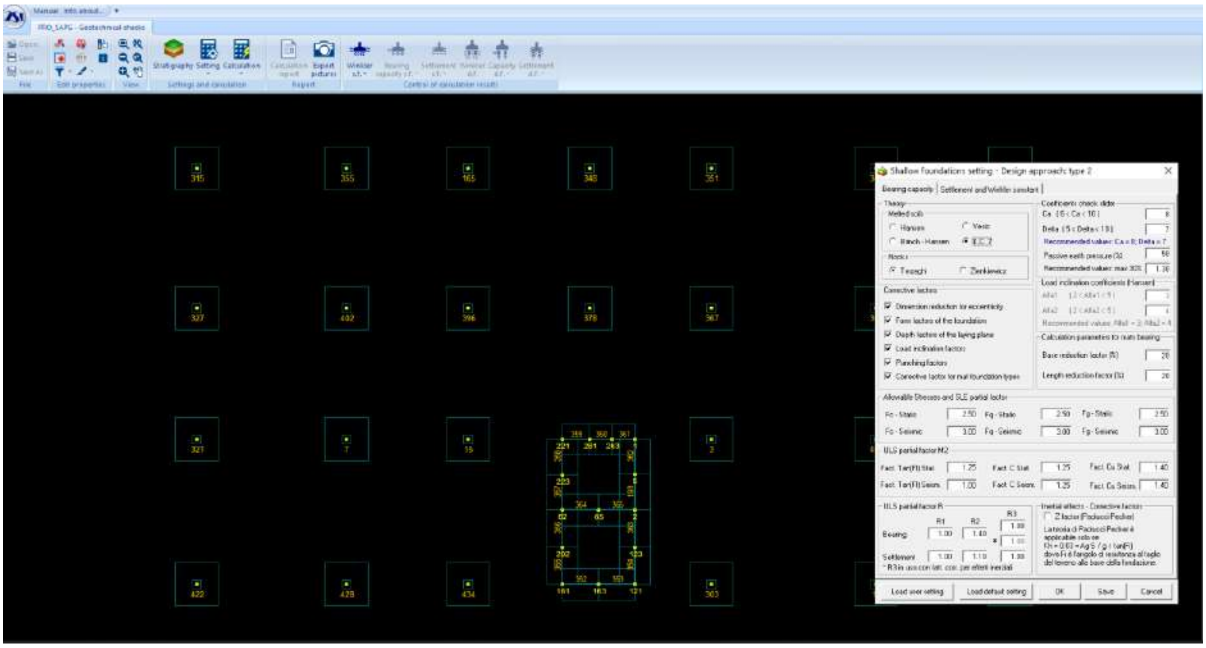


Fig. 57-Geotechnical module included in ProSap.

The next step consists in the load's application, and generation of the combinations. Wind and seismic are automatically evaluated through Code wizards. Wind loads, once calculated, must be assigned to the model, instead seismic actions are automatically applied from the software. For this Case Study, no wind or seismic load is considered for the analysis.

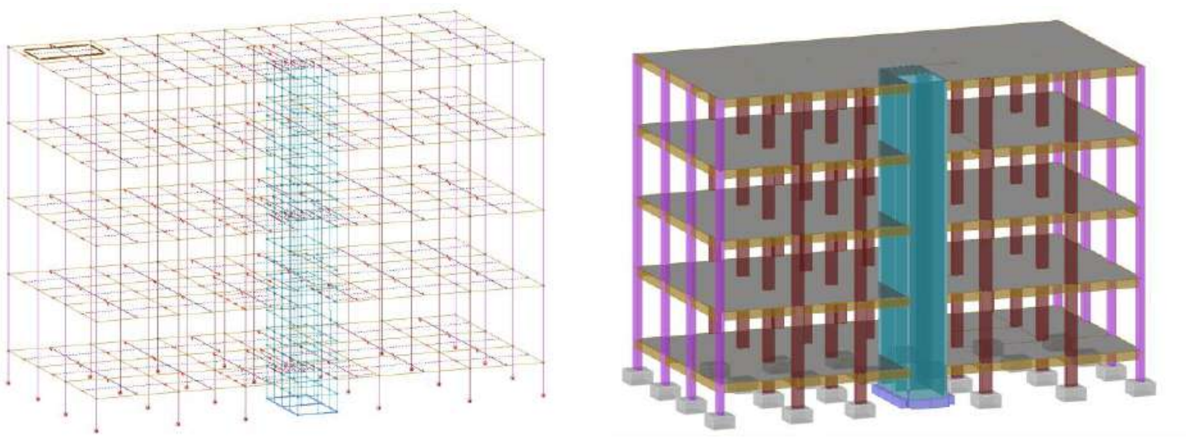


Fig. 58-Physical and analytical model corrected in ProSap.

With checking satisfied, you can start the analysis, check the results, and follow the design in Limit States. You can choose if design all elements at the same time or specify which one to run. Design's results can be checked, and if verification or drawings do not satisfy requirements or Code Checking, model and design settings can be modified, and the analysis and design run again. The process of reinforcement design is interactive with possibility to define schema as needed. The model can be exported into drawings, reports may be generated, and quantity estimations evaluated for the different structural elements.

ProSap provides interactive integrated tools to modify the parameters and reinforcement's properties, and generate automatically detailing for beams, columns, slabs, and walls. This is possible in the add-in integrated modules of PRO_CAD Beams, PRO_CAD Columns and PRO_CAD Walls and Slabs. If you make changes to the reinforcements, these are checked and verified based on the achieved analysis results. Accurate quantity estimations are included in every detailing generation.

The IFC model imported to ProSap could be automatically updated with the "*update IFC*" command. Another *IFC_rev* file is created with updated sections of the structure. The previous IFC and the updated one can be grouped in one federated model, and the coherence and reliability of the import/update IFC operation checked in a BIM Coordination Tool. The results of the analysis are evaluated good, with the structural elements respecting the previous positioning in the model.

Another operation consists in the IFC export, which will create a new IFC model. If any physical object is not correctly positioned, the "Alignment" functionalities may be applied to modify and adapt their position as required.

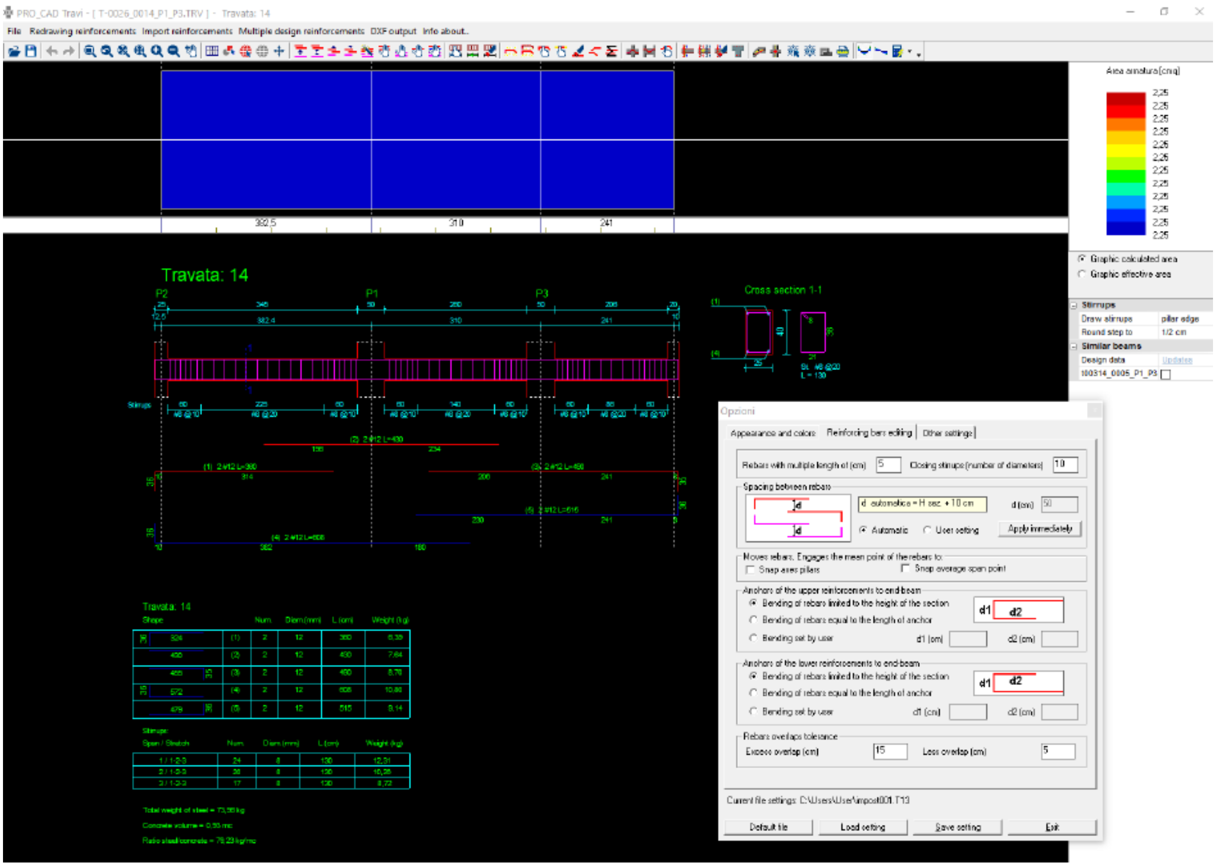


Fig. 59-PRO_CAD Travi reinforcement detailing for beams in ProSap.

A general workflow including all design and information modelling steps for this Case Study, is described as follows:

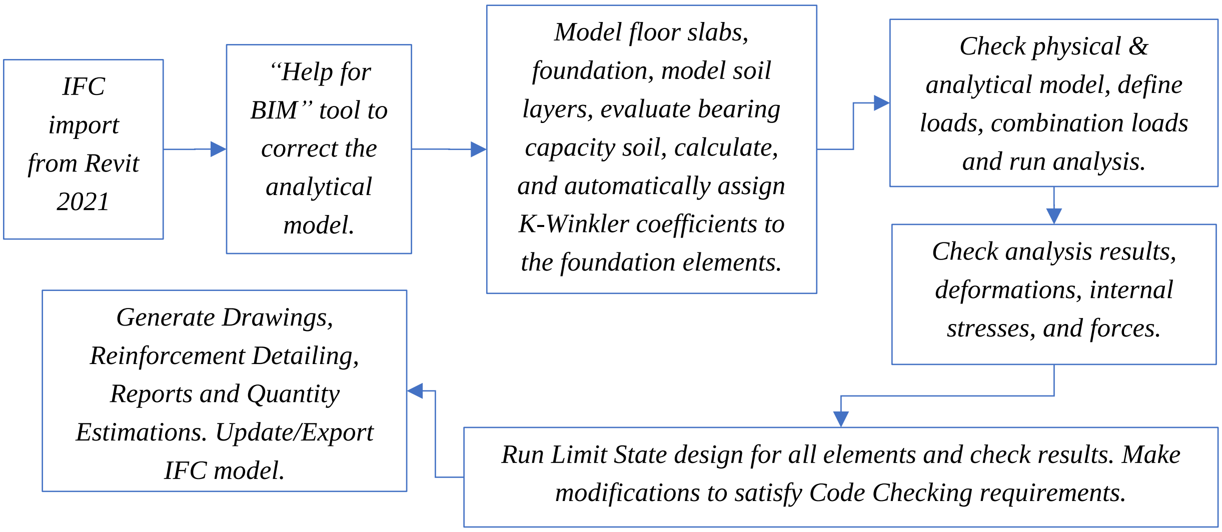


Fig. 60-Structural design and information modelling workflow in ProSap Professional v21.

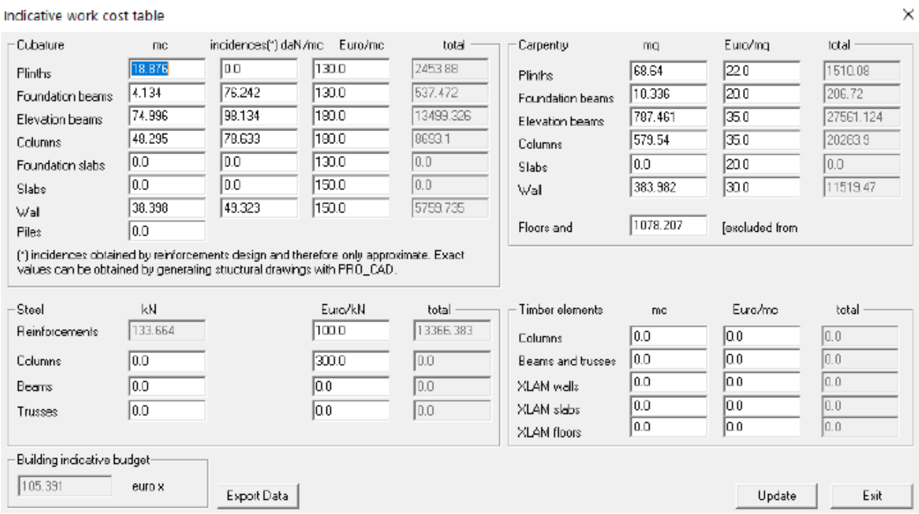


Fig. 61-Preliminary quantity and costs estimations generated in ProSap.

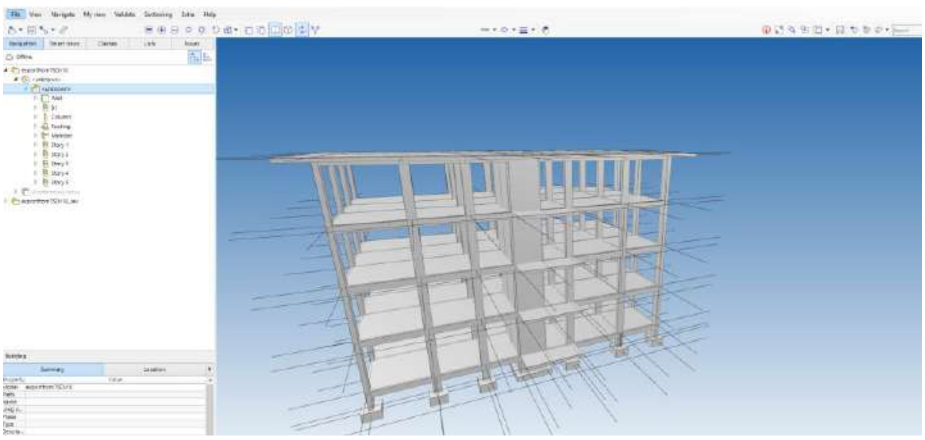


Fig. 62- Coherence and reliability of the import/export IFC operations in ProSap with BIMCollab zoom.

4.1.4.1. Discussion.

ProSap does not provide a clear distinction between the physical and analytical model, like Revit does. Once the IFC is imported in the software, you can apply additional helping tools to correct the analytical model configurations. The physical model can be modified and customized with "Alignments" functionalities as needed. These options are specific for ProSap and they may not be included in the import operations. They are assigned like properties and parameters in the model.

With a correct analytical model and a coherent physical one, you can generate and obtain accurate and reliable general plans and reinforcement detailing, without need to make further modifications. ProSap calculates initially an indicative working cost table with preliminary quantities, and accurate values once all reinforcement's detailing is generated.

The IFC import/update/export operations are generally evaluated as coherent and reliable.

4.1.5. Structural Design with Tekla Structural Designer (TSD)/Tekla Structures (TS).

The model for analysis with Tekla, is imported through Autodesk Revit 2021. The "*Tekla Structure Integrator Tool*" available for Revit, allows to directly export the model, through a. cxl format. Mapping properties can be defined in the process, facilitating, and raising the reliability of the information exchange.

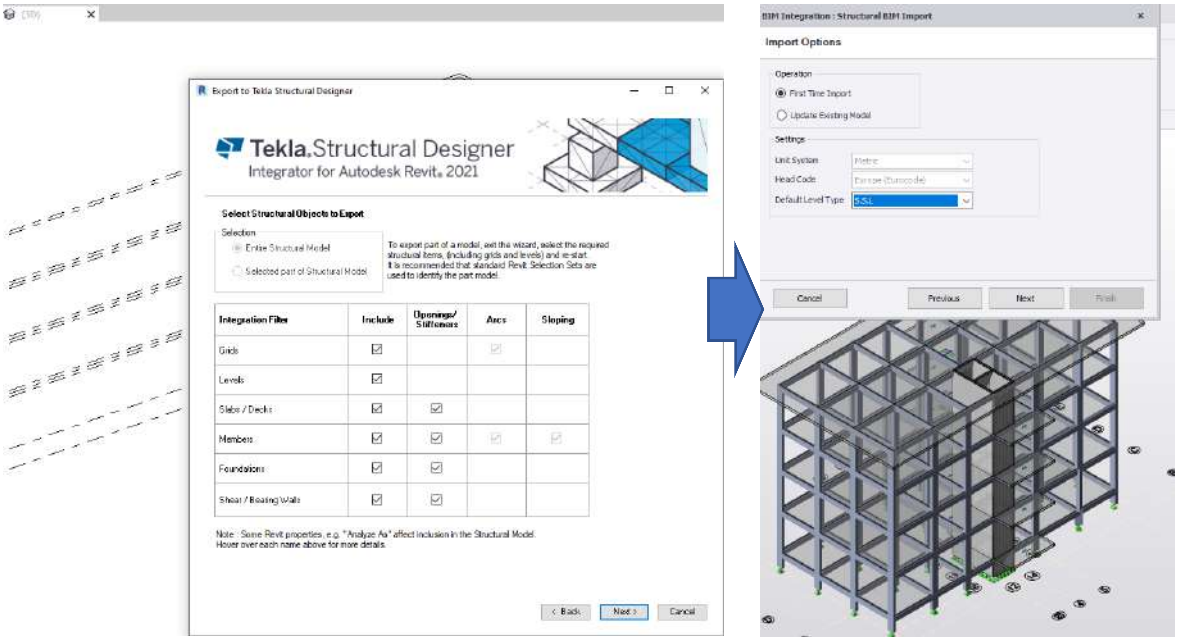


Fig. 63-Export from Autodesk Revit 2021 and import into TSD through .cxl formats.

The physical model is exported correctly together with grids, levels, and structural members. Foundation's footings require to be modelled again. Walls are imported with some issues, making it simpler to remodel them as well. A not specified rotation is identified in one of the columns, requiring some correction. Loads, combination loads, and Code Checking also required to be reapplied to the model.

The physical structural model includes exact beams and columns positioning, with calculation of eccentricities. The analytical model is automatically generated from the software. The validation tool checks and displays if there are still unresolved issues with the model.

TSD offers a quite advanced authoring tool for loads definition, including wind's wizard, generation of seismic actions based on the Code requirements, and application of some equivalent horizontal forces that consider the imperfection of the structure. Loads combinations can be added manually or generated for a "*final*", "*operational*" or "*construction*" situation. For imposed loads you can decide to apply a "*pattern load*" and so consider all possible loads configurations.

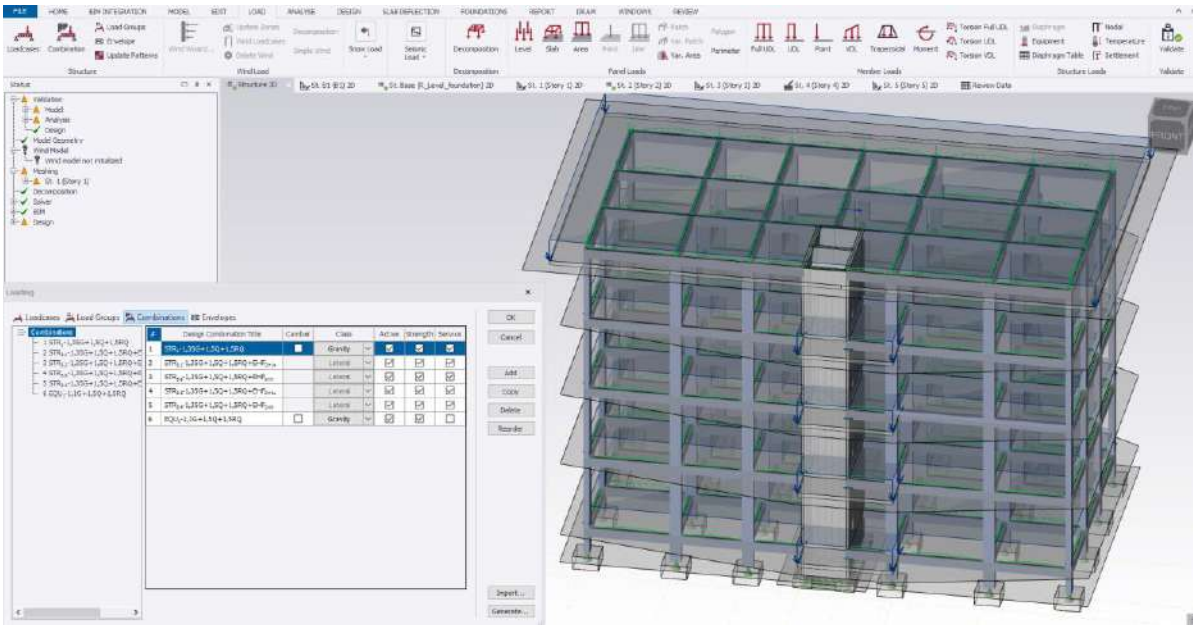


Fig. 64-TSD model correction, loads assignment and combinations.

4.1.5.1. Analysis, Design & Detailing.

Different structural analysis can be run in TSD, like 1st order linear, non-linear, modal or 2nd order linear, non-linear, buckling etc. Designer's customized preferences can be defined for design, and different analysis run for the gravity loads, all loads together, concrete, or steel elements. Structural elements are automatically designed, results can be interactively checked for stresses, internal forces, or deformations. The Drawing & Schedule Management, allows to automatically produce documentation for design, reporting and quantity estimations.

Since physical model definition is quite good in TSD, respecting all other disciplines, the final documentation generated, and the detailing designs, result accurate and reliable. Interactive design allows to customize the rebars configuration before the reinforcement's generation. Results can be checked in the "*Results*" window for all loads combinations.

The process of design is similar for beams, columns, foundation's footings, and walls. Another functionality is available for the slab's design, which allows to configure some additional areas for reinforcements.

Slab deflection check and design is run apart. TSD allows to design "patches" for the additional reinforcement of the slabs. They can be modelled and calculated next to the columns, beams, or walls, with customized parameters.

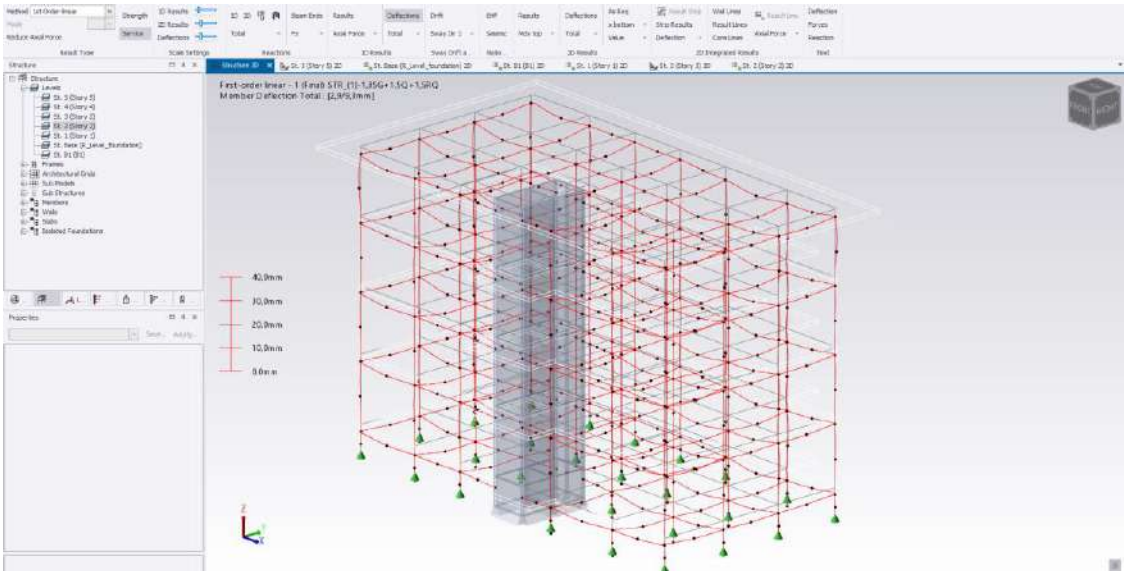


Fig. 65-Results checking in "Results" window (total deflections).

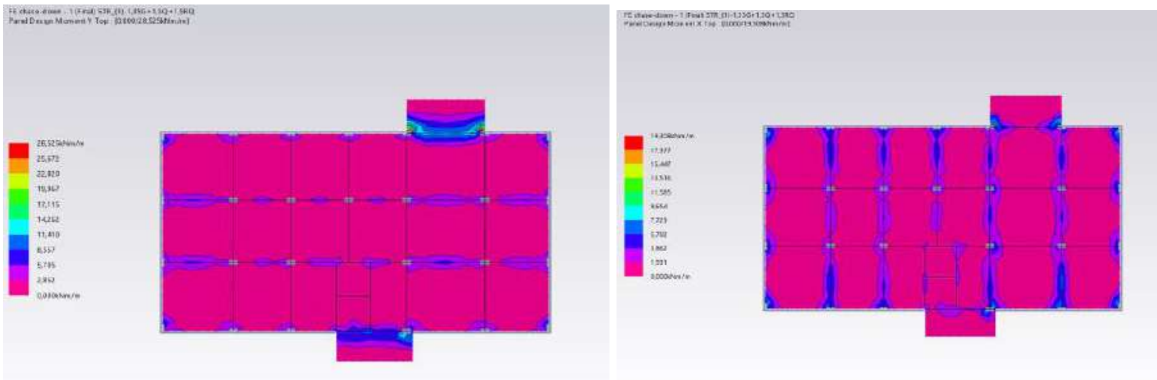


Fig. 66-Slab's analysis results for upper moment (x) distribution.

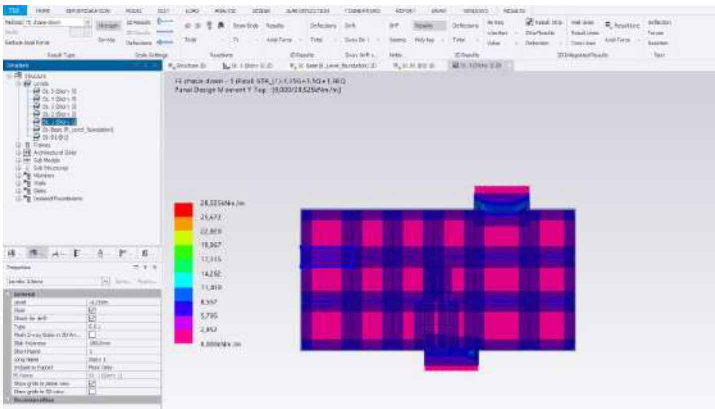


Fig. 67-Slab's reinforcement patches for reinforcement's optimization in TSD.

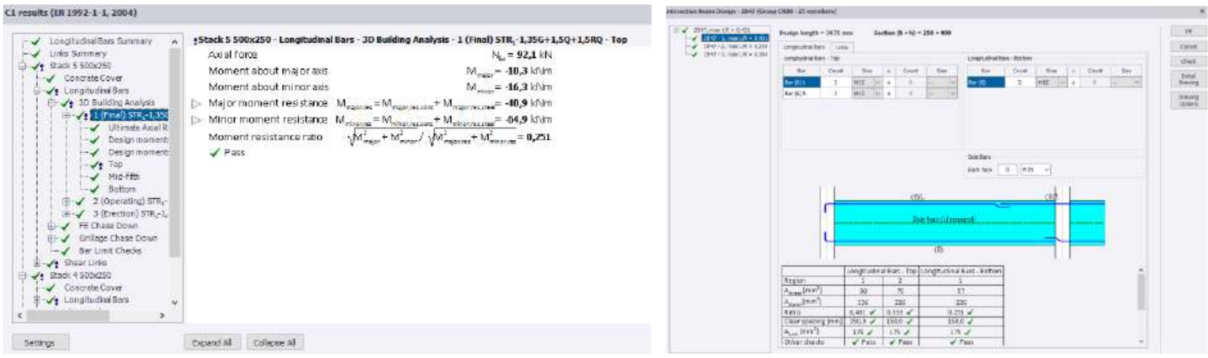


Fig. 68-Column's design check and beam's interactive reinforcements definition.

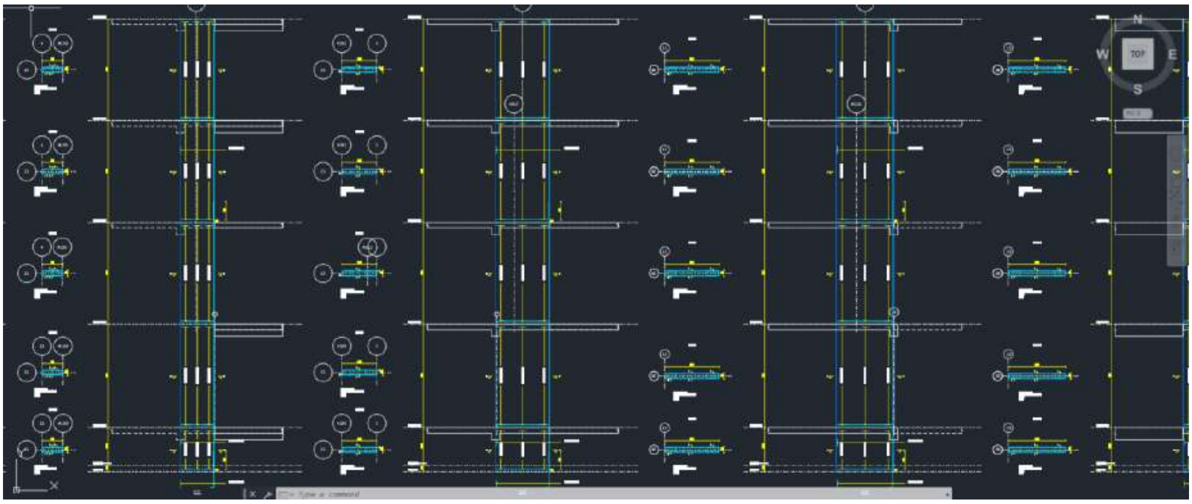


Fig. 69-Wall's reinforcement detailing.

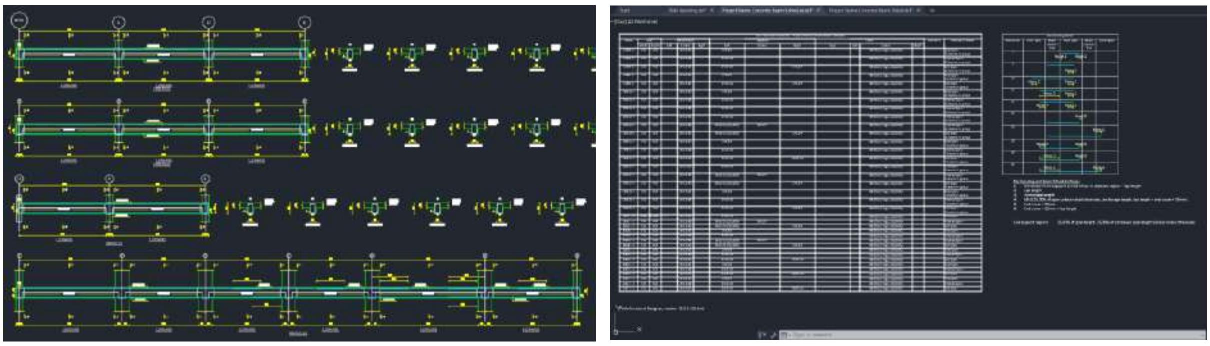


Fig. 70-Concrete beam's detailing and quantity estimations.

The process of modelling, analysis, design and 2D detailing is quite fast in TSD. Once Code Checking, user's preferences and design settings are defined, the workflow is automated with drawing and quantity estimations easily generated with possible functionality to directly upload the documentation to the CDE Trimble Connect.

Modifications can be done to the model at any time with small efforts. Since the process is automated all designs and detailing are obtained within a short time.

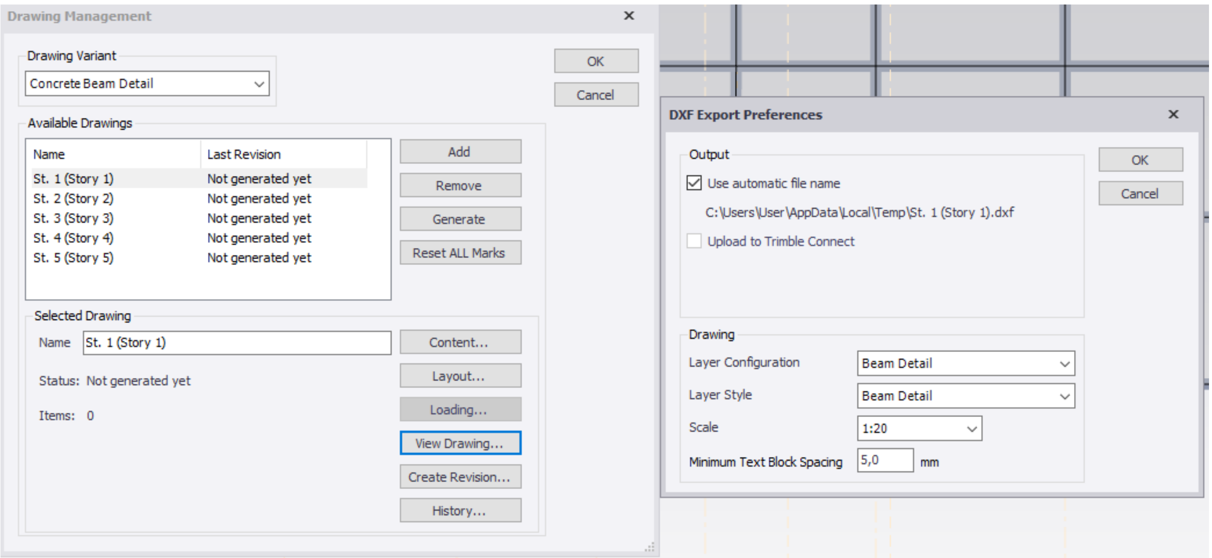


Fig. 71-Documentation production and possibility to automatically upload and update information to CDE Trimble Connect.

The advantage of TSD consists in the high interoperability with TS. The model can be imported directly to TS including results & design, with reinforcement detailing generated automatically in 3D.

In this process you can define the TSD import preferences, sections mapping, materials and rebars, and you can obtain the full building model recognized in TS with native objects. Further modifications or detailing that were not possible in TSD, can be processed in TS. It is advised to keep low manual interventions, so requiring small manual efforts in case of rework processes.

The workflow applied for the TSD / TS, consists in the following steps:

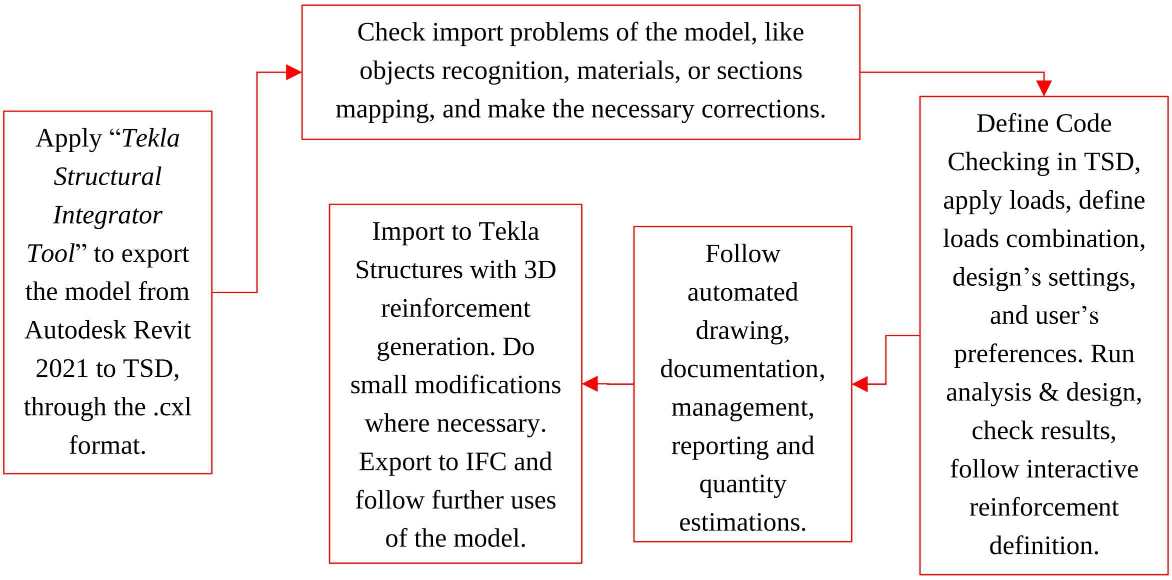


Fig. 72-Tekla Structural Designer (TSD) / Tekla Structures (TS) applied workflow.

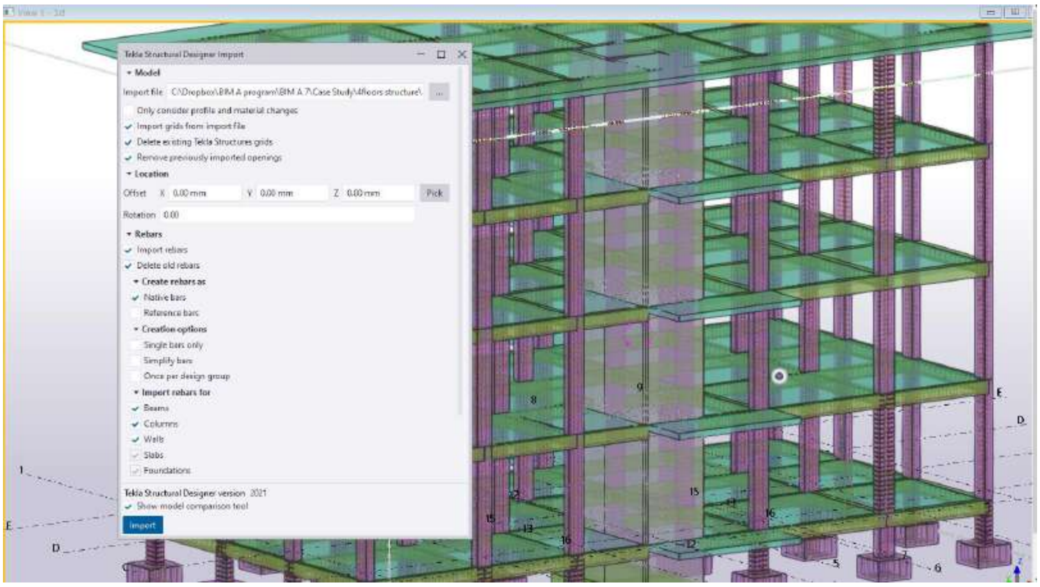


Fig. 73-TS model's import with TSD designer's parameters configuration.

4.1.6. Design, automation, and interoperability discussion.

It was observed that the IFC format can be imported and exported between all software. In some of them, are further included specific commands and tools to directly exchange the model's information.

Revit-Robot has a direct integration functionality, which allows to import and export the model together with results and the reinforcements detailing. In a few cases have been identified some problems in this direction, with full interoperability for the reinforcement's information exchange not guaranteed.

Revit is a BIM authoring tool providing modelling for structural elements like columns, beams, slabs, and walls. Properties of the objects can be defined as needed. The model can be referenced to the other disciplines with the design resulting coherent and reliable. The analytical model can be modified separately and guarantee a correct finite element analysis. The options are not very advanced to allow complex configurations for the analytical model. Some limitations were identified for the modelling of foundation beams. Footing's foundations were opted for this Case Study. Simple loads could be defined in Revit, but combinations based on Code checking and the advanced analysis must be run in Robot.

Robot is an advanced analysis, design and detailing software, allowing linear and non-linear analysis for different materials and Code Checking. Analysis results with design and detailing can be exported to Revit, but with some limitations for reinforcements, in case of wall's foundation strips and floor's slabs. The import/export process was evaluated very good for columns and beams with advanced options for the analysis, design, and detailing. The IFC export model is evaluated reliable and accurate.

SOFiSTiK FEA Analysis and Reinforcements offer great advantages in working integrated within Revit. This assures interoperable processes including correct mapping of elements and loads between the software. The model is automatically checked with warnings and visualization windows for modifications. SOFiSTiK makes use of the Revit's analytical model, which can be modified from the available Revit commands. Tolerance settings facilitate the analysis process with finite element analysis.

Some limitations were identified for the definition and automation of wind and seismic loads definition and combinations based on the Code requirements. Subsystem can be created to organize the design process. Elements can be grouped to optimize the reinforcement's design. These can be modified with interactive functionality and automatically generated from SOFiSTiK Reinforcements. All rebars are created and managed in the 3D Revit model.

The SOFiSTiK integrated tool in Revit provides analysis and design for columns, beams, and slabs. Manual reinforcement detailing is possible for all structural elements. For more advanced analysis you should proceed with the SOFiSTiK Desktop Software. SOFiSTiK external products include the SOFiCAD, which can manage and design parametrically 2D reinforcement detailing. Once full model is obtained, quantity and costs estimations can be automatically evaluated in Revit, or through other construction and management software. IFC exported is evaluated like the previous workflows as accurate and reliable.

ProSap Professional v21 allows IFC import/update/export operations. A "*Help for BIM*" tool is available to modify and adapt the analytical model. The processes in ProSap are generally automated, including the geotechnical parameter evaluations. ProSap can be applied for different material structure, allowing linear and dynamic analysis. Wind loads and seismic ones can be defined through wizards, with seismic actions applied automatically to the model. Combinations can be generated based on Code Checking. Warning notes are displayed for every model and design checking.

The reinforcement's detailing, reporting and quantity estimations are automatically generated. Initially are required some efforts to configure "Alignments" for the positioning of the structural elements, to guarantee the accuracy of the 3D model. Parametric drawings and Calculation Reporting are automatically generated in the detailing process. The reinforcements are provided only in 2D in ProSap. There is a good reliability of the imported/exported IFC model between the initial configuration and the one obtained after analysis and design.

Tekla Structural Designer (TSD)/Tekla Structures (TS) was identified to have a high reliability and accuracy for the 3D physical modelling with automatic evaluations for the analytical geometries. The "*Integration Tool for Tekla*" in Revit, allows to import a preliminary structural model from Revit with an interoperable. cxl format.

TSD is a powerful tool for modelling, analysis, and detailing. It allows to perfectly respect the physical modelling and as well to operate advanced analysis of the structure. Winds and seismic loads can be generated similarly to ProSap automatically through wizards. The design stage allows to group elements for optimization of quantities and costs. Interactive reinforcement detailing and design's preferences support detailing customization. Deliverables can be generated automatically with small efforts. TSD allows similarly to ProSap to automatically generate drawing documentation with reinforcement detailing and quantity estimations. The imported TSD model in TS recognizes all structural elements, design results obtained in TSD and automatically generates the 3D reinforcement detailing.

The final exported IFC model, the quantity estimations and general reporting obtained from Tekla, are highly reliable and accurate. The obtained IFC model can be used for clash detections and for other construction management processes.

In the following table are summarized some of the main issues identified from Case Study nr.1:

Workflow/ Analysing Criteria. **Case Study 1.**	Revit /Robot 2021	Revit 2021/ SOFiSTiK	ProSap Professional v21	Tekla Structural Designer/Tekla Structures 2021
Structural modelling capacities.	Good modelling for regular buildings. Limitations for foundation beams families in Revit. Accurate [1] physical modelling.	Good modelling capabilities. Extra reinforcement functionalities for modelling and design in the SOFiSTiK tool.	Fast and good modelling for regular concrete buildings. Physical modelling with Additional parameters for the "Alignments".	Very good functionalities for modelling. Accurate for physical & automated analytical model configuration.
Accuracy of the physical model.	Accurate physical modelling with advanced analytical model configuration in Robot.	Accurate physical model in Revit. Analytical model validation in SOFiSTiK.	The IFC imported may require applying the "*Help for BIM*" & "*Alignment*" options to satisfy required configuration.	Very accurate physical model with possibility of defining structural elements eccentricities.
Loads definition & combinations	Advanced load definition and combinations in Robot based on Code requirements.	Automation missing for loads and combinations in Revit. Advanced in SOFiSTiK Desktop.	Automated load definition and combinations following Code requirements.	Automated load definition and combinations following Code Requirements.
Analytical model configuration, reliability, and accuracy.	Separate modification of the analytical model. Analytical links in Revit & advanced link configuration in Robot.	Analytical model configuration in Revit. Model validation from SOFiSTiK.	Automated analytical model configuration. Functionalities for checking and validation.	Analytical model configuration automated in TSD. Definition from the physical model with eccentricities.
Analysis, design & detailing functionalities, and capabilities.	Robot offers advanced functionalities. Detailing reliability and accuracy depending on the interoperability processes between Revit & Robot.	Simple functionalities from SOFiSTiK. Automated design & detailing for columns, beams & slabs. More advanced analysis in SOFiSTiK Desktop.	Advanced functionalities for all designs and information modelling phases. Static & dynamic analysis. Interactive design and automated detailing	TSD is an advanced BIM authoring tool for all designs processes. 1st & 2nd order, linear & nonlinear analysis, advanced design & detailing. 3D reinforcement generation in TS.

[1] The words "coherence", "reliable" and "accurate" are used in the process's evaluation.
"Coherence" is related to the fact that the model is imported/exported correctly and consistently in the process with no relevant issues, such as no columns or beams missing, no differences in positioning of BIM objects etc. The structure of the process is generally respected.
"Reliable" is used in the way that you can trust this process as being repeatedly with similar results.
"Accurate" is meaning that the information modelling obtained has no differences compared to the expected result.

Processes automation	Highly automated processes in Robot. Time consuming for information exchange between Revit/Robot. Some manual reinforcement detailing in Revit.	Good automation for most processes in Revit. Some manual reinforcement detailing required.	High automation for all processes including geotechnical parameters evaluation, foundation's design & detailing.	All processes are highly automated in TSD, model, design's results and reinforcement detailing are recognized in 3D in TS.
Interoperability in the process.	Revit/Robot does not fully guarantee information exchange for reinforcement detailing.	Full interoperability of information exchange with SOFiSTiK working integrated in Revit	n/a	Very good interoperability, reliable and accurate exported information model.
Interoperability with other software.	Tekla Structural add-in Integrator Tool in Revit for direct information exchange with TS and TSD. openBIM software recognizing different formats.	SOFiCAD is an AutoCad similar authoring tool with advanced parametric reinforcement design interoperable with different software.	IFC import/update/ export. "Help for BIM" to support the recognition process of the analytical model & "Alignments" for eccentricities definition.	Highly accurate information exchange with Revit and ProSap. BIM friendly with a wide range of software and tools.
Automation for drawing documentation, Reporting & Quantity estimation.	Good automation with 3D modelling including reinforcements. Automation for reporting and quantity estimations.	Most processes automated. Manual reinforcement detailing for foundation elements.	All processes automated. Generation only in 2D for reinforcements. Preliminary quantity estimations and more accurate, once detailing is provided.	High automation for all processes. 3D reinforcement generation. Drawing Documentation & accurate Quantity estimation and Reporting.
IFC import/ update/ export operations coherence, reliability & accuracy	Good coherence of model in information exchange & high accuracy. Issues identified in some import/exporting.	Good coherence of model in information exchange & high accuracy. Issues identified in some import/exporting.	Reliable in import/exporting. Simple IFC structure data. Lower accuracy in importing compared to the other workflows.	Highly reliable for all IFC import/ export operations. BIM objects conversion to native elements in TS. Coherent & accurate.
3D concrete reinforcement modelling, design & exporting.	Good functionalities for the 3D reinforcement modelling, design & detailing.	Advanced functionalities for 3D reinforcement modelling design & detailing.	3D physical modelling for concrete and 2D reinforcement detailing.	Full functionalities for 3D concrete's reinforcement modelling, design, and detailing.

Table 11- Case Study nr. 1 -Summarized discussion table based on the analysing criteria.

4.2. Case Study nr.2 - Six floors governmental buildings area 4800 m^2.

For this Case Study are taken into consideration two governmental buildings each one with an area of 4800 m^2. They are named "*Building A*" and "*Building B*".

For Building A, the construction has already started, and all structural concrete works have finished. "*Traditional workflows*" were applied for the design including manual detailing. The process of clash detections was done by simply overlapping designs between the architectural, structural and MEP discipline. Some problems were identified during the structural works.

Fig. 74-Building A – Structural works already concluded - "Traditional workflow", manual clash detections by overlapping designs.

For Building B is applied an "*IFC exchange*" workflow. Since both buildings have similar areas and same technology of construction, comparisons can be done for the structural design and construction works.

Fig. 75-Building B - 3D preliminary simulation view of the project, use of "IFC exchange" workflow.

4.2.1. Organization's information exchange workflows.

The planning process for the building includes the coordination and management between different Institutions, Organizations, and Private Companies. A general schema of the Parties involved, with focus to the structural design, is given as follows. This schema has been generally applied for Building A.

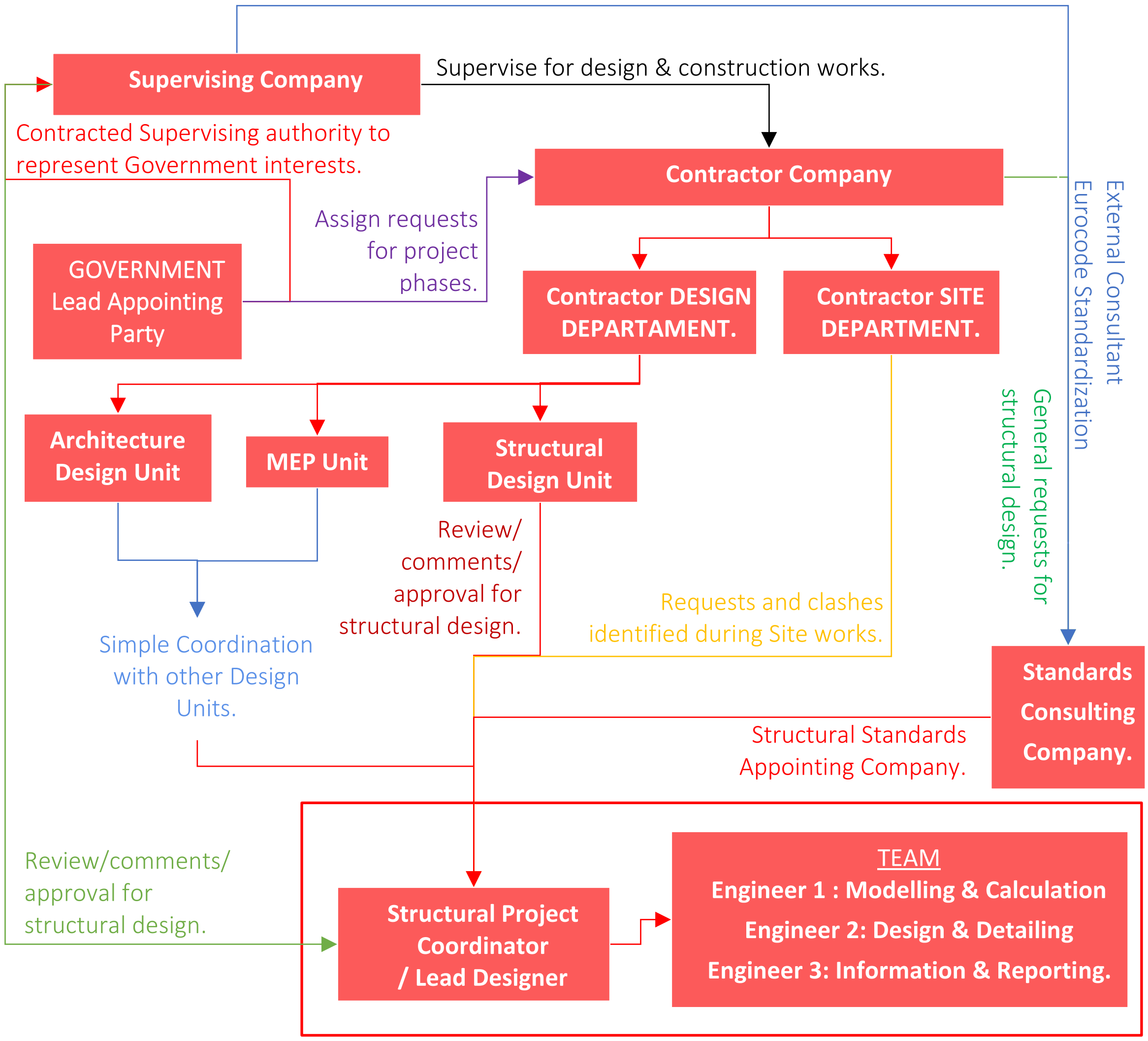


Fig. 76-Organization's information exchange workflow.

It was observed that the information requirements were not standardized and very clear. Each Party could get confused in their duties and the kind of deliverables to produce. The communication was done electronically and in local site meetings. Information exchange between Contractor, Designer and Construction company was based on 2D drawings. 3D simulation was produced only to give an idea of the design to the Lead Appointing Party. There was no BIM methodology applied with low interoperability between the processes.

Different problems identified for the structural design and construction for this building consisted in:

- Information received for the architectural and MEP only in 2D format pdf or .dwg.
- Structural modelling with low referencing and clashes done manually by overlapping the designs.

- Clashes identified late on Site between the structural and the MEP model, consisting in delays and higher costs for construction.
- Small incompatibilities with the architectural model, forcing changes to the design after construction works started.
- Problems in communication for the design's updates, bringing to situation where an old version of design is still being applied on Site.
- Difficulties in explaining the concrete's reinforcement detailing, where different elements intersect, considering possible bars overlapping.
- High manual reworking required for the modification of the structural design due to low automation of the detailing processes. Small changes required time consuming processes and higher costs for updated versions.

For these reasons and others, it was proposed for the next building to make use of more interoperable processes and BIM friendly workflows.

4.2.1.1. Building B organization's structural design information exchange.

Following the problematics faced during the Building A, the "*Traditional workflow*" was re-engineered to have lower costs, higher efficiency, and efficacy, by improving communication and collaboration and making use of IFC format exchange. The "*IFC exchange*" workflow allows a more fluid work between the Parties, better deliverables, higher quality of design, less costs and enhanced management of the facility. The general detailing and description of the workflows is given in *3.3-Workflows. page 41*.

OpenBIM software facilitate higher standardized documentation and better communication. Information requirement (ISO, 2018) better define what is required for the project. IFC format information exchange facilitates early clash detection. 2D drawings for concrete reinforcement can still be considered acceptable, but automation of processes is required to be higher. A more user-friendly BIM workflow for the structural design and information modelling organization is defined as follows:

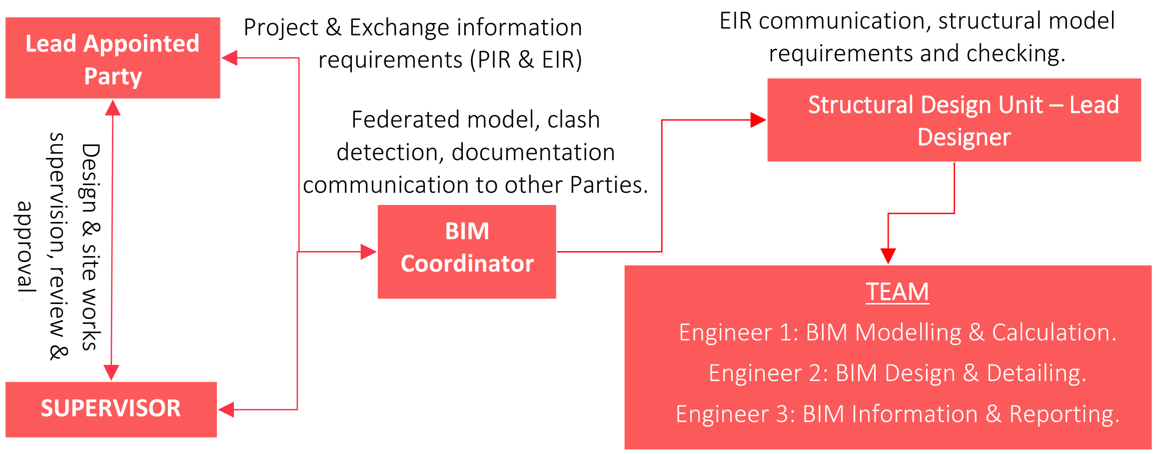


Fig. 77-Structural Design Unit focused, Organization's workflow.

The modelling should start from referenced models, and final drawing documentation and Reports include a structural, reliable IFC model to be checked for clash detections. Processes and workflows should be automated to allow a shorter time and less costs for updates. The potentials of the different software and workflows previously presented, can be applied to the Case Study.

4.2.2. Modelling and import/export operations.

It was opted to start the modelling of the building B, initially in ProSap Professional. It is fast in defining objects and it accepts IFC import/update and export operations. The model can be checked towards other disciplines and for the interoperability of information exchange with the other software.

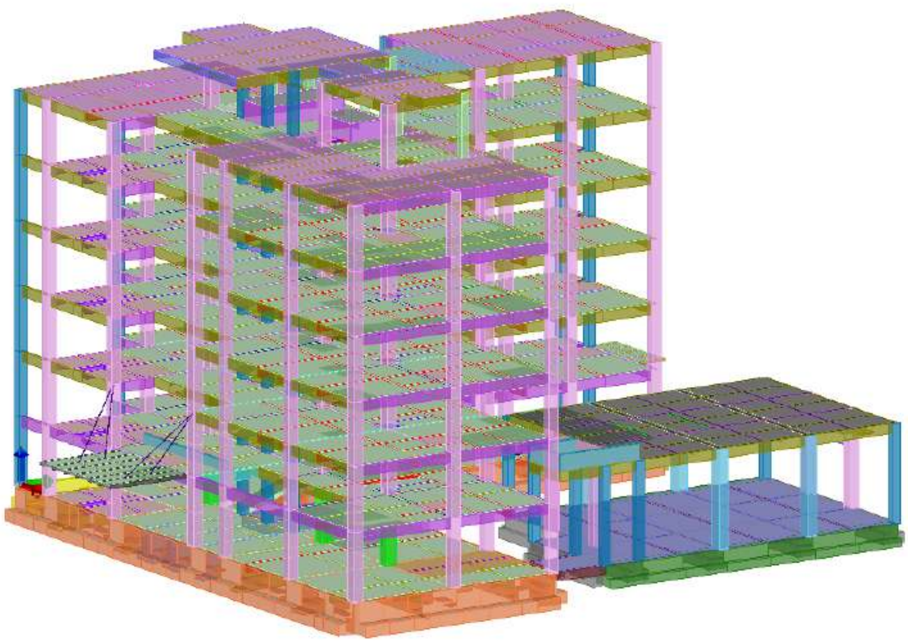


Fig. 78-Building B - structural model in ProSap Professional.

The analytical and physical model in ProSap, in default are defined within the same central axes. The physical object's (seen in the solid view) can be modified respectively to the analytical geometry applying the "*Alignments*" properties or "*Fili fissi*". It is possible to parametrize, respectively to the analytical lines, assigning values and adjusting the distances in the different directions. The transport moments for the eccentricity of the structural elements can be considered or not considered in the calculation, based on defined options from the designer.

The "*Help for BIM*" and the "*Alignments*" command tools in ProSap guarantee the coherence of the model and the interoperability of the software in dealing with IFC formats, allowing more reliable and accurate design.

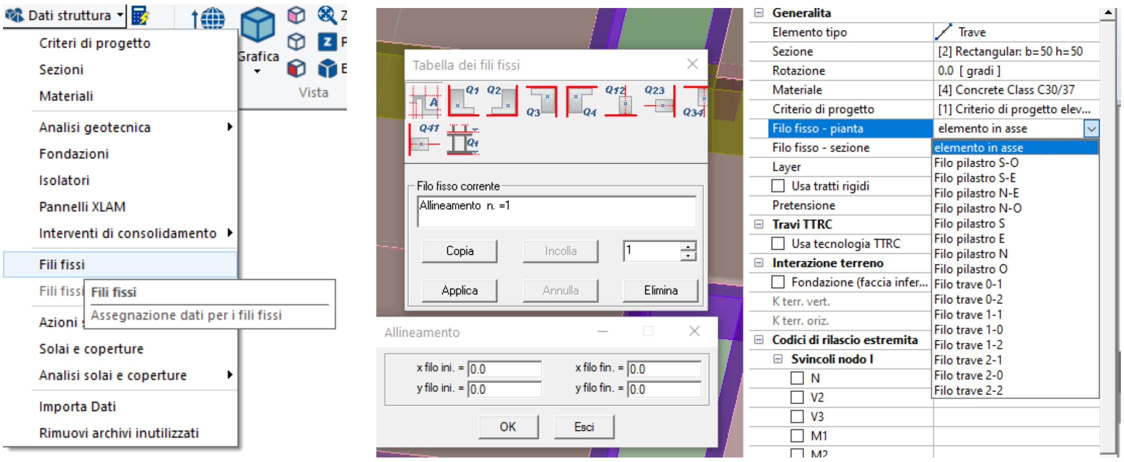


Fig. 79-Table of "*Alignments*" or "*Fili fissi*" in ProSap for better defining the position of the structural elements respectively to the physical model.

4.2.2.1. Tekla Structures (TS) - IFC importing and conversion to native objects.

TS presents some good optionality for IFC importing and conversion of the model's objects to native elements. To follow structural analysis, you should deal with native elements and a fully recognized analytical model. The process in TS consists in importing the IFC and converting the IFC objects to native Tekla ones. Mapping properties can be defined in the respective windows.

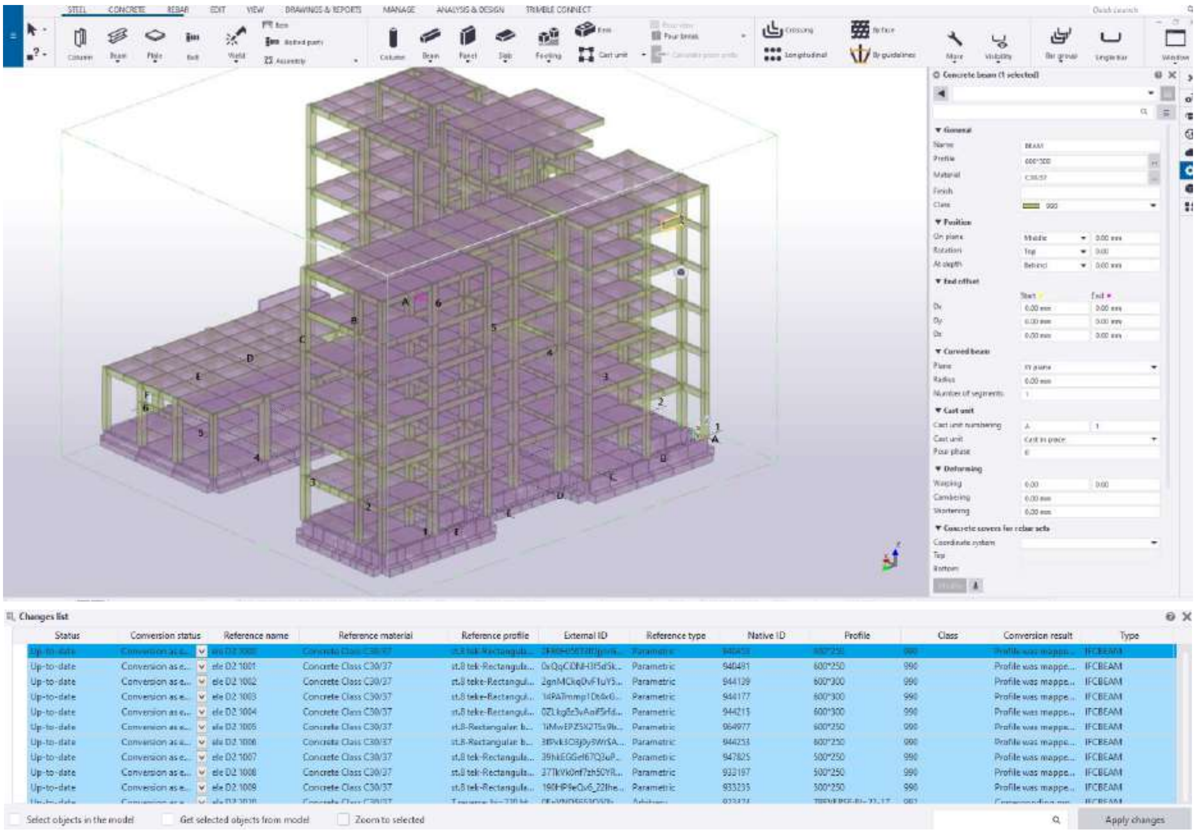


Fig. 80-Import IFC into Tekla Structures and conversion to native objects.

4.2.2.2. Revit importing.

For the conversion and recognition of the model into Revit, two different approaches may be applied:

a. Apply add-in tools for conversion of the IFC objects to native elements. Revit itself does not recognize automatically the IFC objects as parametric ones. Different tools may be applied, like the openBIM project Cype Revit interoperability (BIMserver.center, 2020), the AGACAD tools (AGACAD, 2014) or the IFCtoRevit tools (Ibrahim5aad, 2020).

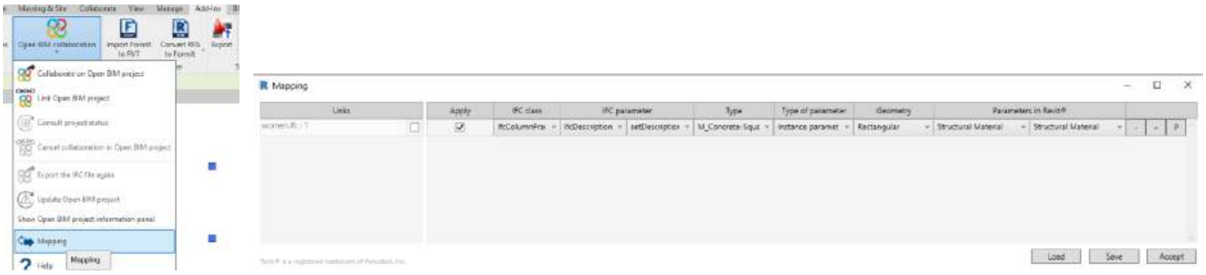


Fig. 81-OpenBIM collaboration mapping process for imported IFC objects.

b. Import the model from Tekla Structures/Tekla Structural Designer, making use of the Tekla Integrator Tool through the cxl format. The workflow is simple, and all structural elements are automatically recognized with an analytical model configuration in Revit. New families may be created for the mapping process if the Revit default ones are not appropriate (example T reversed foundation beams).

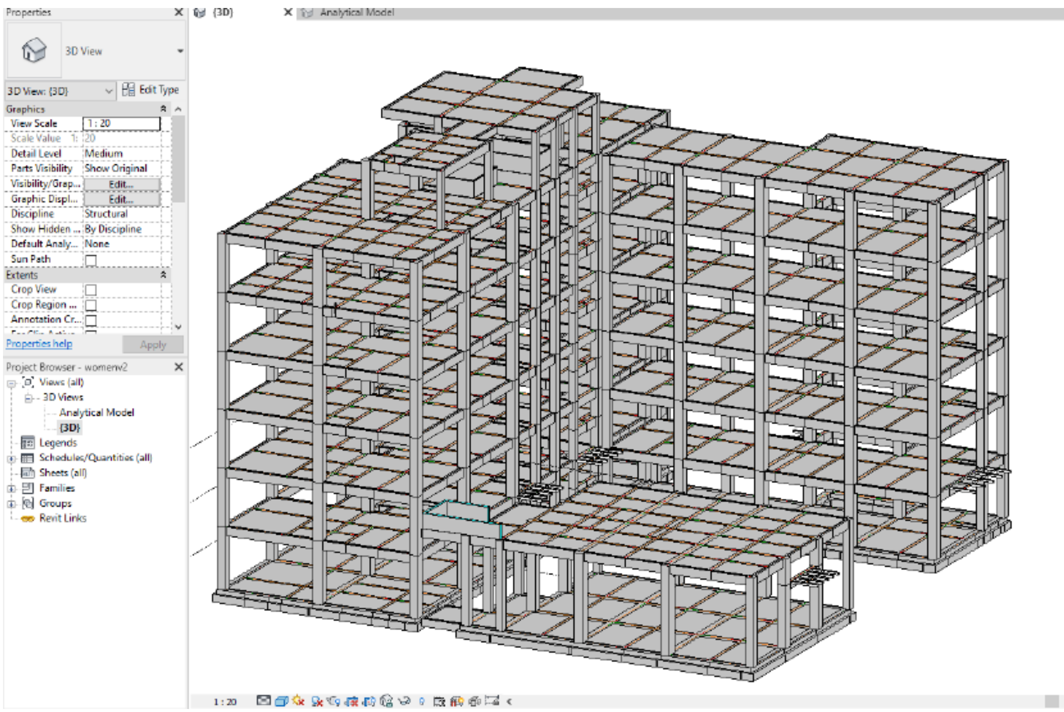


Fig. 82-Imported model, making use of the Tekla Integrator Tool in Revit 2021, through the cxl format.

4.2.3. Analysis and design.

Since the project has been modelled in ProSap Professional v21, analysis will run initially in this software. We will neglect wind actions on the structure and consider a low seismic action with PGA reference of 0.075g. Design will be done with low ductility, and importance factor 1.0. Due to the low seismicity present, the Spectral Shape will be considered as type 2.

After all design's parameters and preferences are defined, it is run the structural analysis. Following different iterations with results checking, a final configuration is decided for the elements.

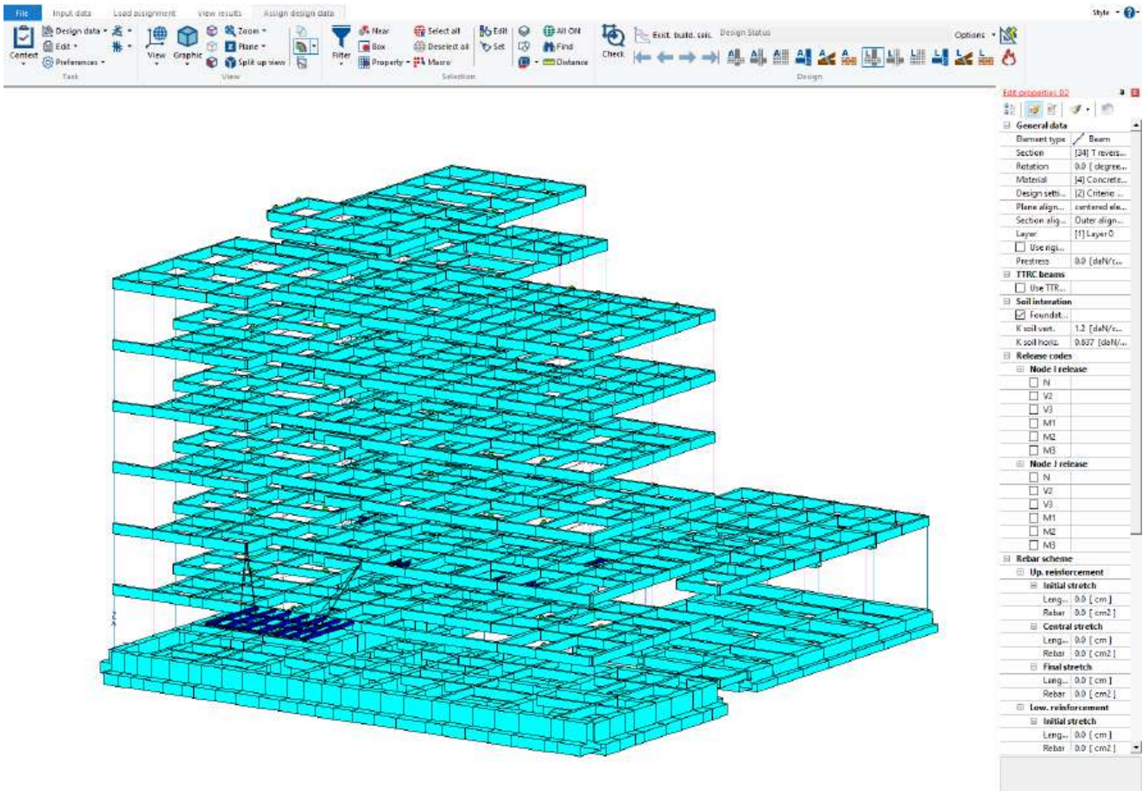


Fig. 83-Structural analysis & design model checking for concrete beams in ProSap.

In ProSap, you can check analysis results and reinforcements detailing for every element, and as well generate the 2D parametrized drawings, in the integrated add-in tools, like the PRO_CAD Beams. The generation of detailing is automated and can be done at the same time for all the elements. Parametrization and groups creation can be customized to facilitate the construction works.

Reinforcements can be also modified manually. Parametrization and automation of processes with small manual modifications is advised. For each structural element, or group of elements, it is available a reinforcement scheduling with all rebars dimensions and automatic quantity estimations. The process is similar for columns, walls, and meshed slabs. Structural analysis can be done by considering or not considering the floor's slabs rigidity in the global structure's stiffness matrix calculation.

The accuracy of design is strongly depending on the 3D modelling. If there are applied too many approximations, these will be reflected also in the detailing documentation. ProSap provides some optionality for beams and columns positioning with “*Alignments*” commands, that if configured correctly can assure coherence, reliability, and accuracy of the model.

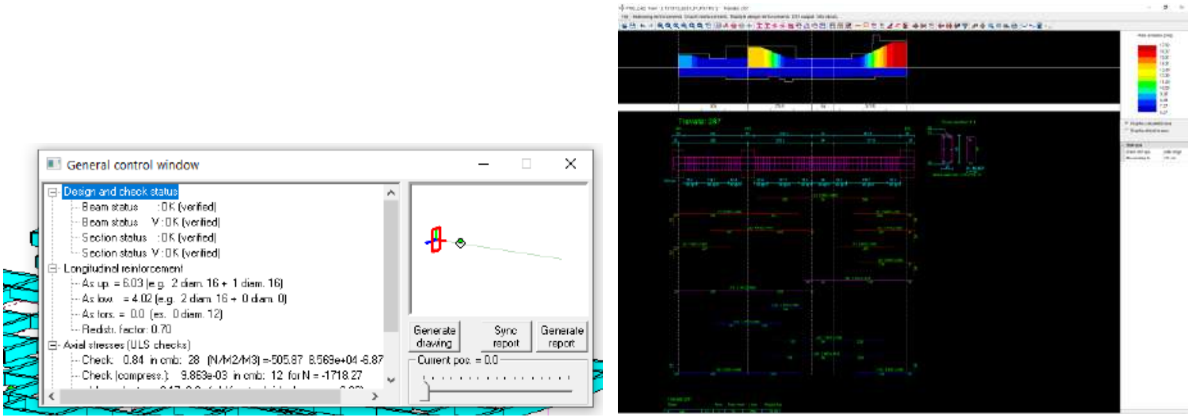


Fig. 84- Design’s results check, parametrization and automated reinforcement detailing for a concrete beam.

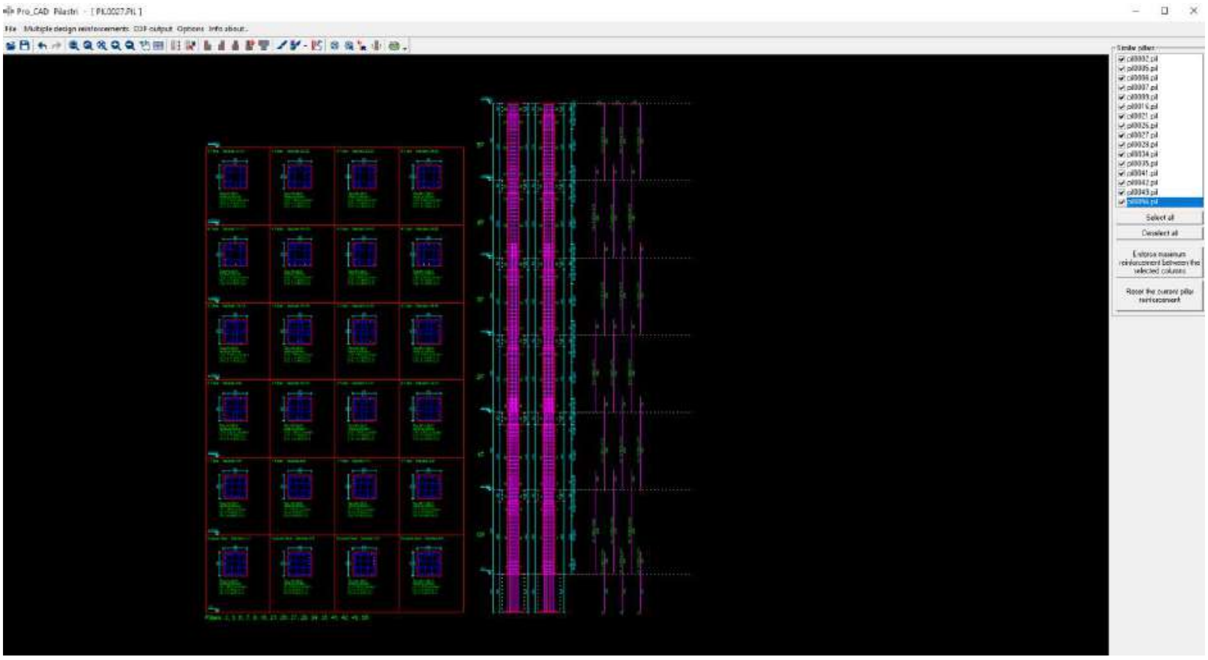


Fig. 85-Automated multiply design reinforcements for grouping of similar columns.

ProSap generates automatically general floor plans with structural elements positioning, dimensions, and slab’s reinforcement. It produces automatic drawings with grouping of elements for columns, beams, and walls. The drawing can be exported for further modifications, for layouts, and for the release of the drawing’s documentation.

ProSap provides initially indicative working cost table, and accurate quantity estimations obtained only after all reinforcements detailing is generated. Structural Calculation Reporting can be customized with designer’s preferences and produced in one click. IFC exported includes the concrete material without the 3D reinforcements. The model can be used for clash detection, and for further uses in the next phases of the project.

4.2.4. Structural Design with Revit-Robot.

Before starting design, you need to import the model to Revit with native objects, so every structural element includes the physical properties together with the analytical configurations. This is possible, following the previous discussed options, with add-in conversion tools from IFC objects, or by importing the model from TS/TSD with the Tekla Integrator Tool.

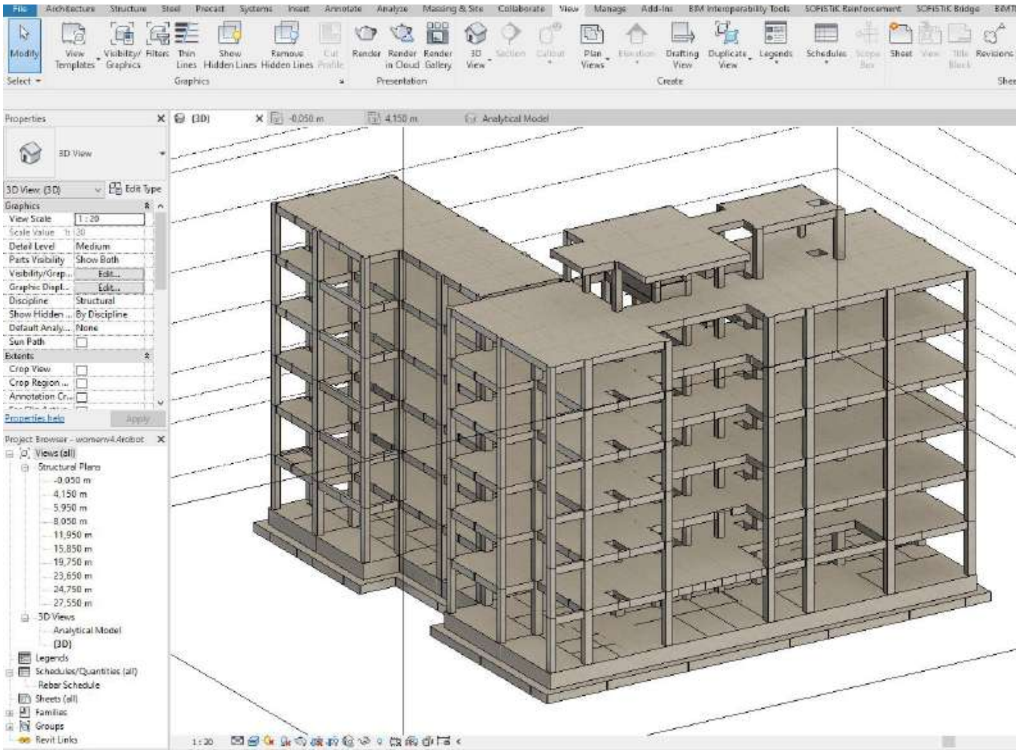


Fig. 86-3D IFC structural model in REVIT

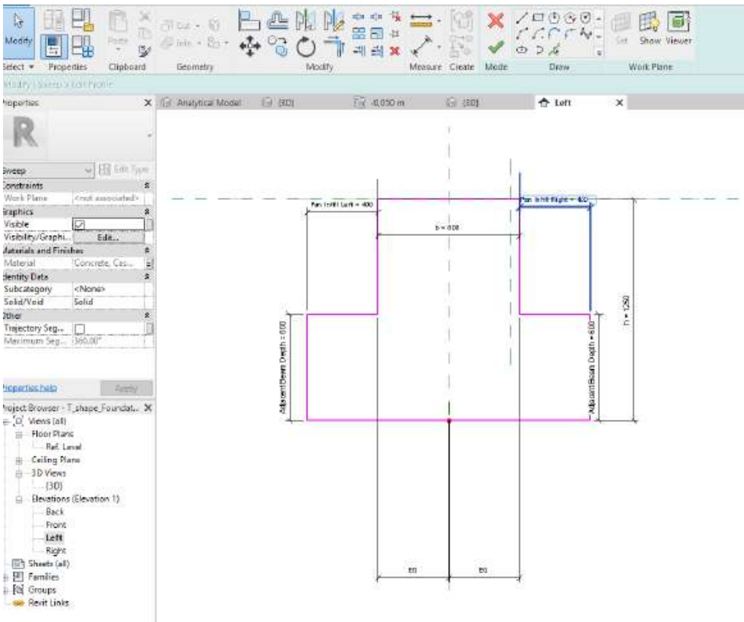


Fig. 87-T foundation reversed beam modelling.

It was observed that in the importing process, Revit does not provide default foundation families for T reversed concrete beams. It is accepting only footings, wall's foundation strips or slabs. The T foundation beam was decided to be applied due to expected better results compared to the footing's configuration, in having lower costs and producing optimized quantities compared to the slabs foundation. It is not present in Revit and it was necessary to be modelled as a new object family. Once created, it can be assigned in the mapping process during the importation of the model. [1]

A suggested procedure for the model validation and design consists in the following steps:

- Check the physical model to be correctly imported.
- Check the analytical model to be correctly defined. Make use of the analytical adjust command to make some modifications where necessary.
- Model boundary conditions. You can apply initially fixed boundaries, but this will not represent the real soil-structure interaction. To have a better definition, it is necessary to do some calculations for the K-soil-structure interaction based on the soil's layers and the foundation configuration. This can be done in Robot and the values may be applied after in the calculation.
- Another option consists in defining the elastic ground coefficients, and automatically assign them as properties for the ground foundation beams as a property in Robot. For this option no boundary conditions shall be applied in Revit, and the properties must be assigned in Robot. It can be a more accurate and automatized procedure.
- Define principal load types and apply them to the structure. For faster modelling, the seismic loads can be defined in Robot. The load combinations can be generated automatically based on the assigned Code Checking.
- Import/export operation of the model with Robot.

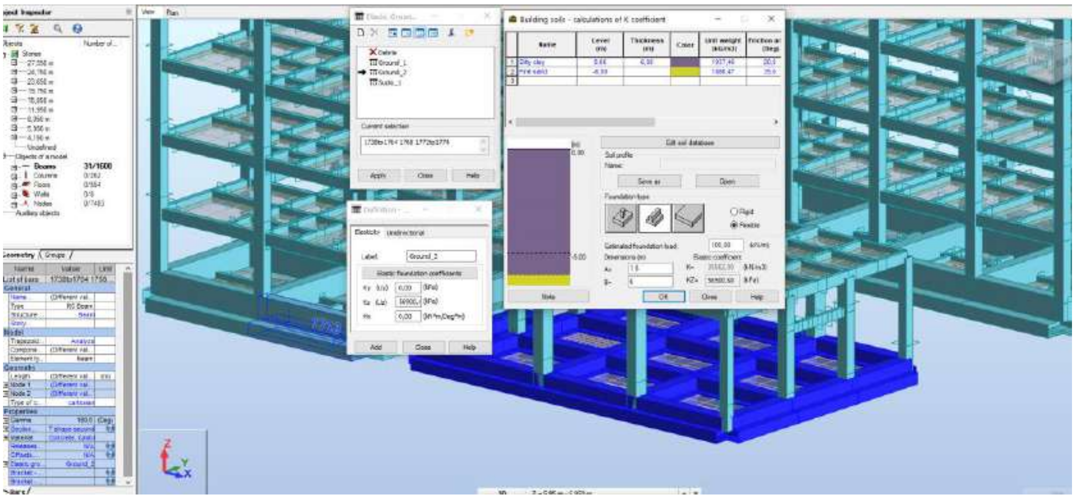


Fig. 88- Elastic ground coefficient evaluation and automatically assignment of the values to the foundation beams.

After importing in Robot, you can apply model checking and run the analysis. Based on the warnings, you can follow further modifications, update the model, and then iterate the import/export operations

[1] This is a functionality that can be improved in Revit, by providing more alternatives for the foundation's modelling.

with Revit.[1] After running the analysis, you can follow the calculation for the "required reinforcement" for all structural members and check that elements are correctly verified. The "provide reinforcement" with Code Checking parameters and "user's preferences" schemas, define the final reinforcement configuration for the elements.

The process of analysis and design in Robot is like the Case Study nr.1. For Case Study nr.2, the structure is bigger, and may require more time for calculation and design.

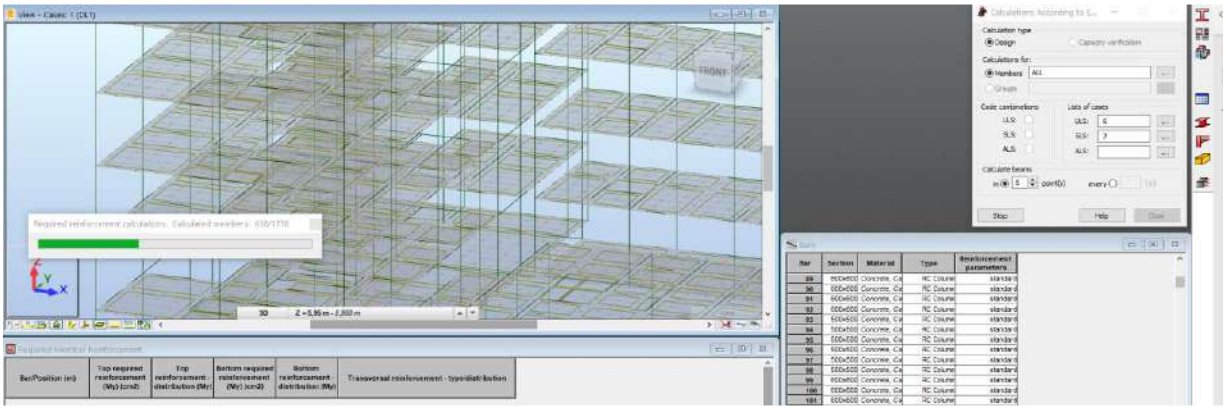


Fig. 89-"Required reinforcement" calculation for all structural members.

It was observed that Robot is fast in the general model checking and structural analysis, but requires *too much time and high computation resources for the design and detailing calculations*, compared to other software. *The process of sending/receiving the model between Revit and Robot*, with results and reinforcing configuration, is a time-consuming process. This may be an area of further investigation for the software vendor to check how it can be optimized.

2D drawing documentation and reporting can be obtained directly from Robot. The 3D model with reinforcement detailing is exported with results and reinforcement detailing to Revit. Further modelling modifications, that were not possible in Robot can be done after exporting into Revit. Final drawing documentation, quantity estimations and IFC exporting for clash detection can be produced for the further uses of the model.

4.2.5. Structural Design with Revit-SOFiSTiK.

To start the analysis in Revit-SOFiSTiK, it is necessary to assign initially the boundary conditions, loads and loads combinations in Revit. Seismic actions cannot be evaluated in Revit but are required to be defined in SOFiSTiK Structural Desktop (SSD).

The workflow for analysis and design is like Case Study 1. Once the general settings are defined with Code Checking, it can follow the mapping of materials, sections, and load cases. Model checking and

[1] This Case Study has been verified initially in ProSap Professional 2SI. There is a high probability that only few warnings and notifications will be displayed, and most of structural elements shall be verified.

validation in SOFiSTiK displays notifications and warnings with visualization windows to check and modify incongruencies in the model that can be modified, updated, or ignored if not relevant.

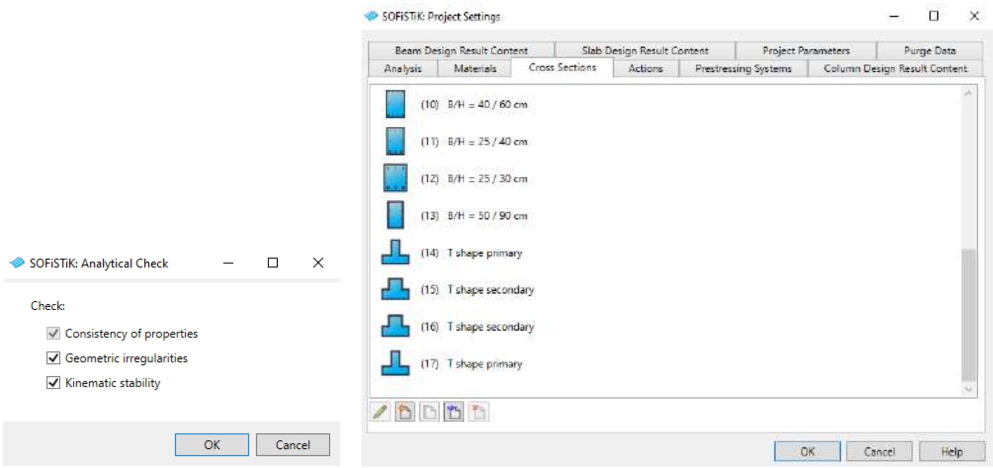


Fig. 90-Analysis check and Project's Settings in SOFiSTiK tool integrated in Revit.

Structural analysis results can be graphically and analytically visualized for internal forces, stresses, deflections and reaction forces for different load cases and combinations.

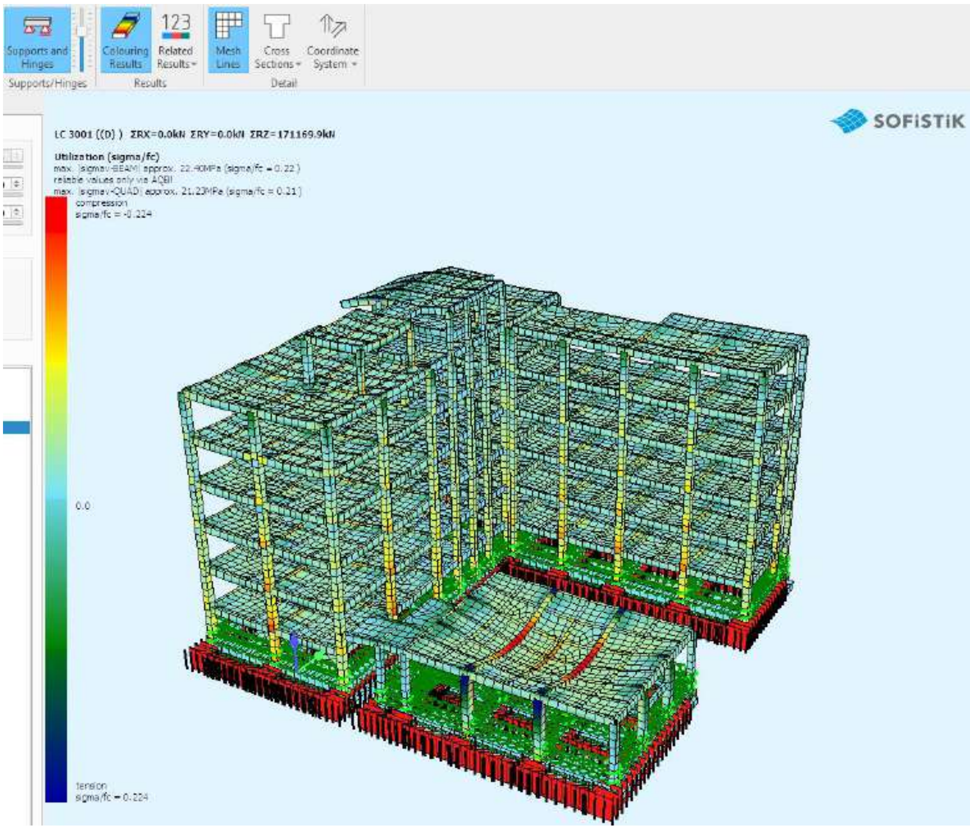


Fig. 91-Analysis results visualization.

With analysis verification, the structural elements can be grouped following similar geometry and expected reinforcement detailing. Code checking settings and designer's preferences can be defined case by case.

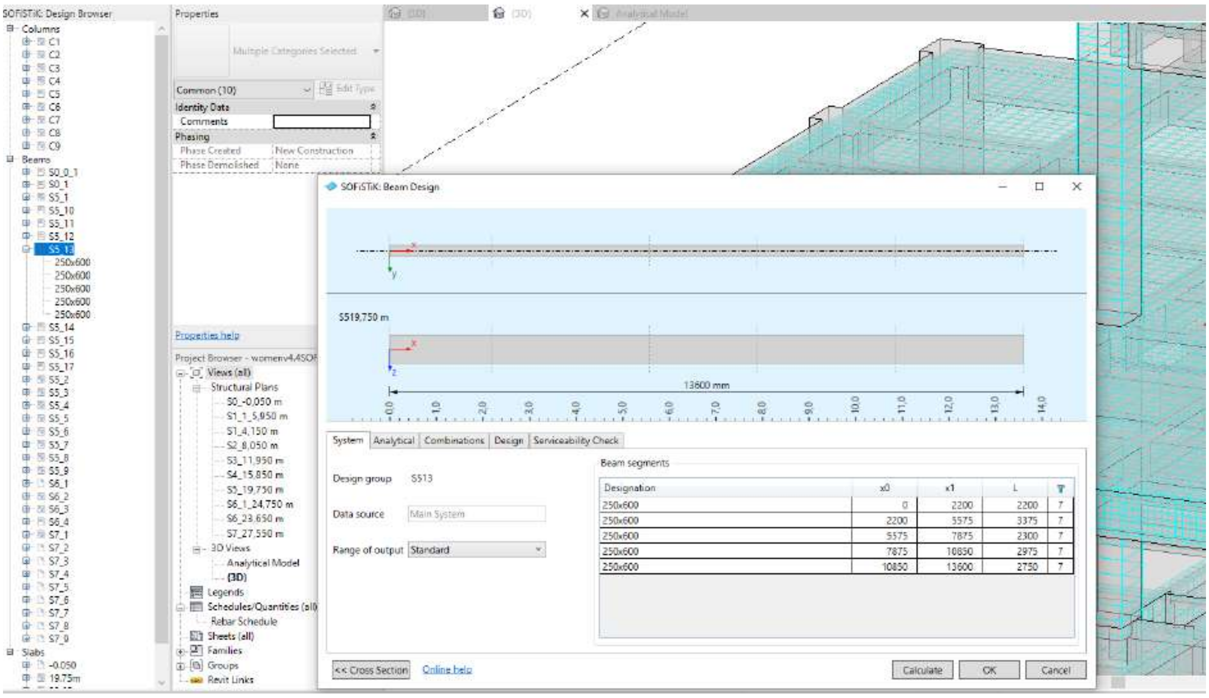


Fig. 92-Revit-SOFiSTiK elements grouping for design (beams).

With structural elements verified, you can proceed with automated reinforcement generation based on the design's requirements. Reinforcement schema can be assigned automatically based on the designer's preferences.

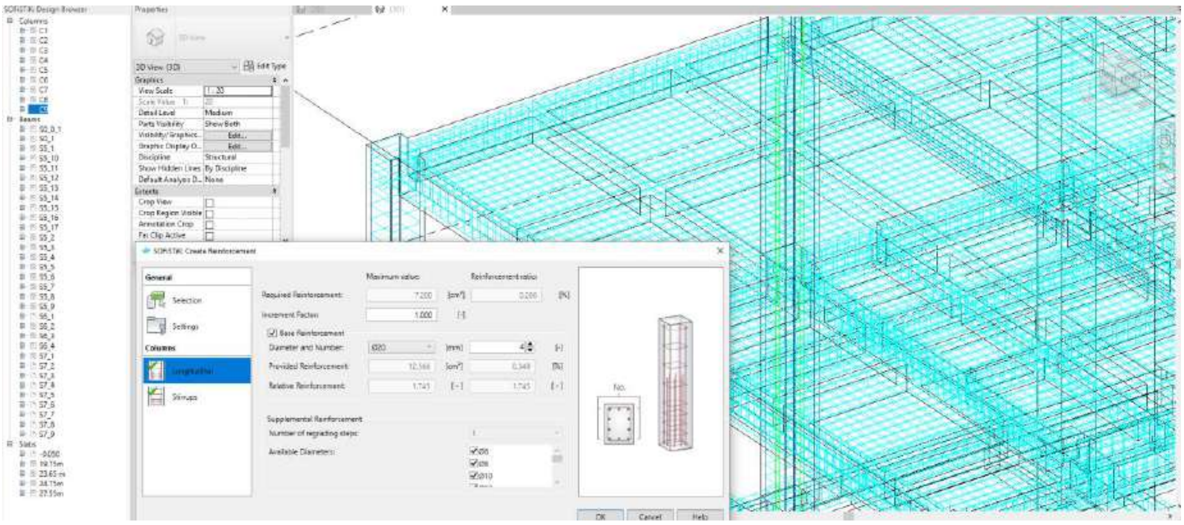


Fig. 93-Automated reinforcement for structural elements in Revit – SOFiSTiK (columns)

Once the full model is correctly verified and reinforcements are fully generated, further manual modifications can be done for the rebars in Revit. Drawing documentation and Scheduling of quantities can be generated from Revit, with Calculation's Reporting from SOFiSTiK. IFC can be exported from Revit, evaluated for information exchange quality, and then used for clash detections with the other disciplines.

4.2.6. Structural Design with Tekla Structural Designer (TSD) /Tekla Structures (TS).

For the analysis and design in TSD / TS, the superstructure has been separated from the foundation. TSD offers advanced configuration for the foundation's modelling with footings, slabs, and strips, but does not directly give functionalities to model T reversed foundation beams. Boundary conditions can be specified by applying springs for the soil-structure interaction.

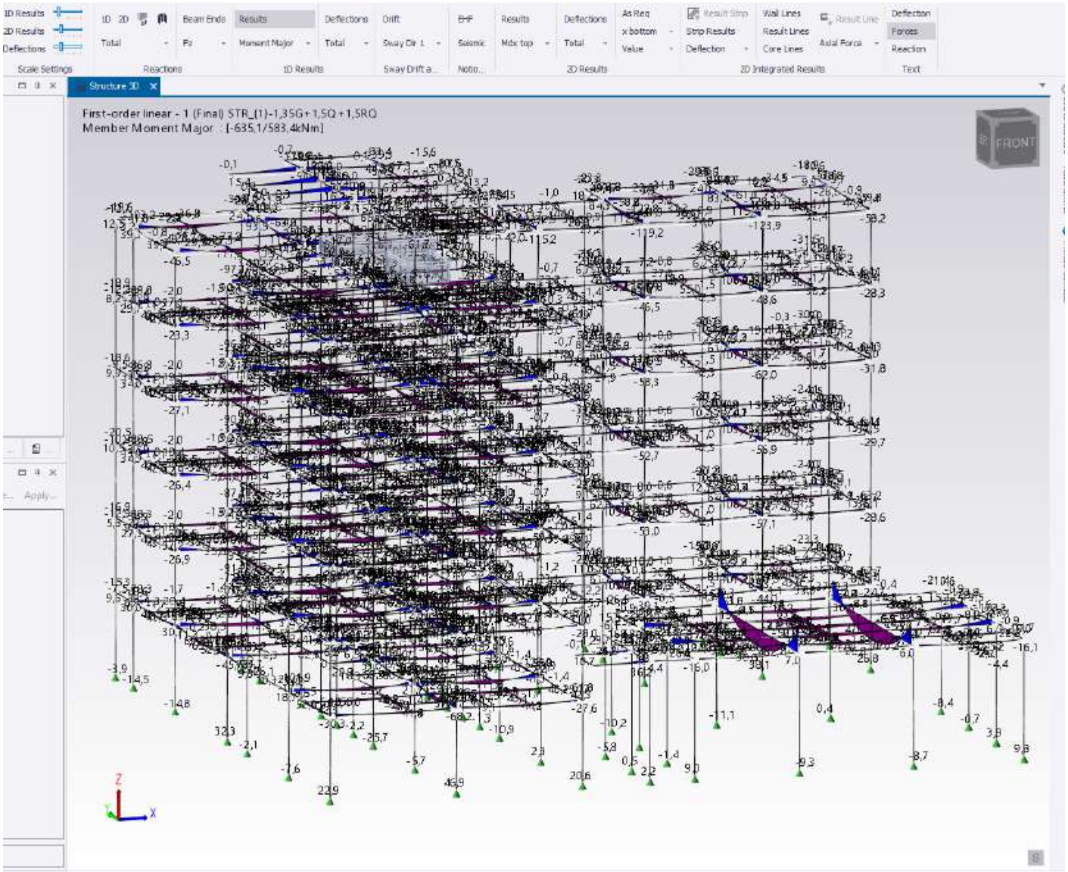


Fig. 94-Major bending moments visualization for all structure for a given combination.

TSD requires less computer calculation resources than Robot SA, with faster analysis, design, and detailing. Seismic actions can be modelled automatically, and structural analysis results can be checked in the advanced results window.

All elements can be designed, and parameters checked versus Code Checking and user's preferences. Documents management commands generate drawings for reinforcements for all structural elements. Quantity's estimations and Reporting for Calculation are also automatically produced.

The structural model saved in TSD can be imported in TS with design results including recognition for 3D reinforcement detailing. Tekla Structures offers an advanced BIM authoring tool for modelling. Possible modifications that were not possible to be made in TSD, can be done in TS. Final model can be exported in IFC with all 3D reinforcements from TS. Automatic updates are possible to be made directly in Trimble Connect CDE. IFC can be exported for clash detections with other disciplines and for the next phases of the project.

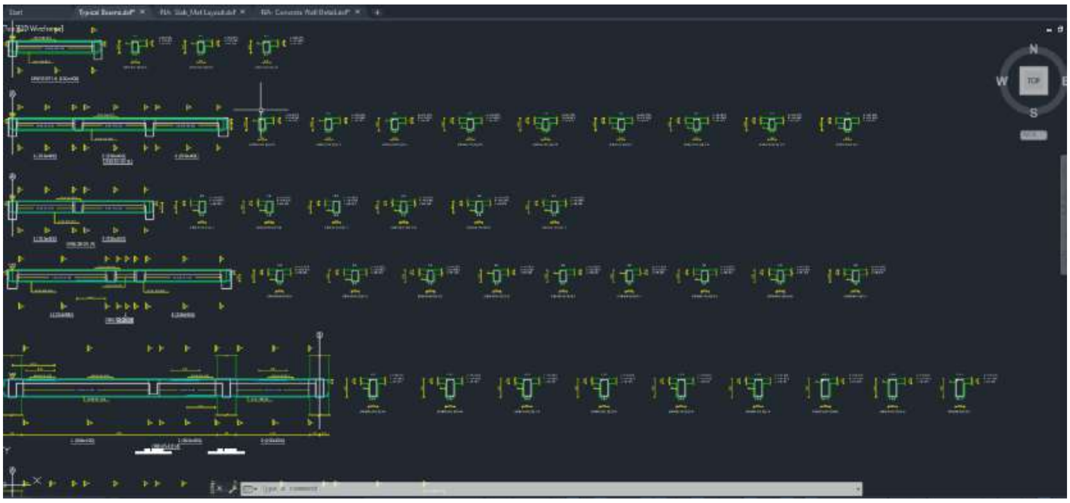


Fig. 95-Concrete beams drawing generation in TSD.

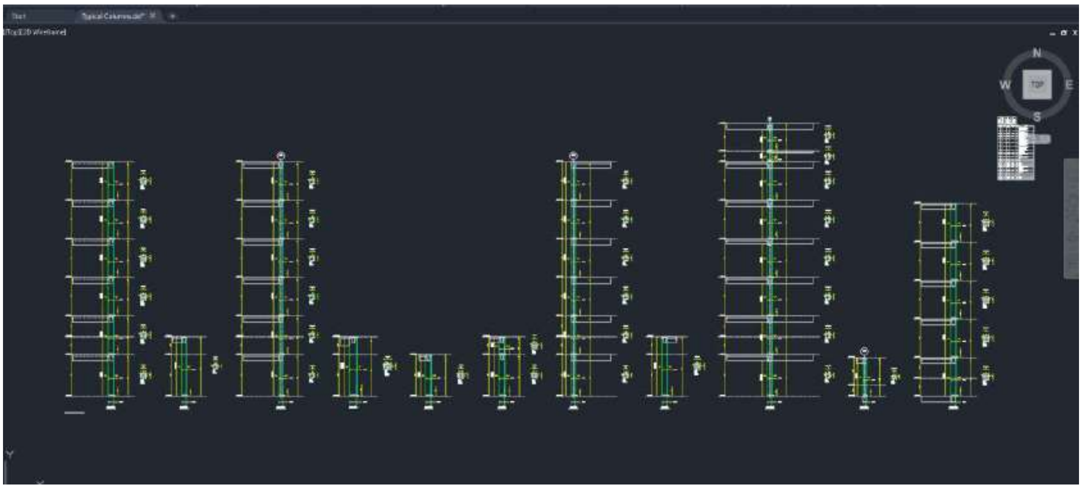


Fig. 96-Concrete columns drawing generation in TSD.

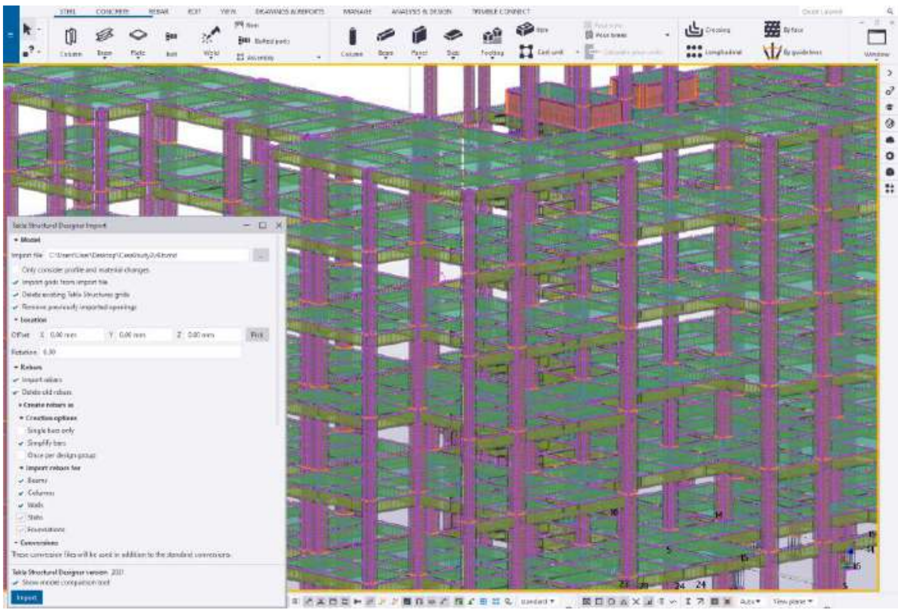


Fig. 97-TS model with 3D reinforcements imported from TSD.

4.2.7. Design, automation, and interoperability problems between the software.

The application of the workflows is summarized and analysed based on the chosen criteria. BIM adoption evaluation involves structural engineering design issues (conception, modelling, analysis, design, detailing and reporting), automation of the processes, and interoperability operations between the different software.

Design.

The structural modelling, analysis, design, and detailing are simply considered as part of the "information modelling" process in BIM. For this Case Study, it started in ProSap Professional and continued by exporting to the other Software. The quality of information exchange was checked case by case.

Structural analysis could run in all software with wide options for the job preferences with linear or non-linear, static, or dynamic analysis. Analysis results are accompanied with interactive visualization for stresses, displacements, internal forces, and reaction forces.

Design can be done individually for each element, by manual or automatic grouping and by applying user's preferences. The approach may differ from one software to another, the functions may change, but Code Checking is generally comparable. Passing, failing or warnings are displayed for the design's results of the elements in TSD, verified or non-verified checking elements are provided in ProSAP, and with Reporting in Robot and SOFiSTiK.

Detailing is generated automatically in all workflows. 2D reinforcements are produced from TSD and ProSAP Professional, instead TS imports the rebars from TSD and generates them as 3D elements. In SOFiSTiK, reinforcements are generated and displayed automatically in 3D in Revit. In Robot it is including in the 3D configuration also quantity estimations and 2D drawing layouts. The quality of detailing depends on the physical modelling. Higher is the accuracy, better will be the quality of the drawing documentation and the 3D model.

Quantity estimations are automatically evaluated in all workflows. ProSap initially gives only indicative work quantities and more accurate values are provided only after reinforcement's detailing generation. TSD provides quantity predictions, with accurate values obtained from TS.

Drawings, documentation management and IFC exporting are guaranteed in all workflows and software. ProSap Professional exports the IFC only with concrete material without the steel reinforcements. General plans, detailing drawing documentation, and reporting are produced with good quality in all workflows.

Automation.

BIM friendly workflows and software provide good automation between the different processes. ProSap automatically evaluates the geotechnical parameters with add-in tools and assign them to the foundation elements. Parametric drawings generated from ProSap may require some manual re-working for layout's configuration. Reinforcements are not exported in 3D in the IFC model, with some limitations to clash detection of rebars in the intersecting nodes. Accurate quantity estimations for all structure are not automated, requiring some manual updates of the indicative works costs table. Most of the other processes resulted with a good automation.

In TSD similarly to ProSap, wind and seismic loads, are generated through wizards. Analysis, design, and detailing proceeded through interconnected operations. The TSD model is recognized together with the design's results and the 3D reinforcements in TS. A limitation was identified for the modelling of the T reversed foundation beams. TSD offers wide functionalities and in general high automation in all design's stages.

Revit-Robot operations are also evaluated positively for the level of automation. The main issues and limitations identified in this workflow, were the time-consuming operations in the importing and exporting of the model between the software, including the design's results, and the rebars reinforcements. The software required high computation resources.

In Revit-SOFiSTiK workflow, was observed a good interoperability, with the analysis software coming integrated as a tool in Revit. Analysis runs based on the Revit analytical model, with possibility of elements grouping for the design. This process may require some time to be organized offering a lower automation. This has positive and negative effects. It allows the designer to check and group individually the elements and so to understand and organize the design with expected analysis and design logic. From the other side it may be a repetitive operation once the structural model configuration is clear. The reinforcements generation, based on the design's requirements, resulted in an automated operation.

Interoperability.

The model for this case study was created in one software and then imported and exported between the others. A good interoperability was observed in general between the software. For Revit, it was necessary to create a new family for the T reversed foundation beams, as were not configured in default in the software.

Loads and combination loads are not imported and exported in the IFC information exchange. To follow structural analysis and design, it is necessary for all software to recognize the analytical geometry of the structural elements. The physical model was initially built in ProSap and exported to an IFC format. Tekla Structures (TS) allows to convert the objects from IFC to native BIM elements. Tekla Structural Designer (TSD) and Revit could recognize and convert automatically the exported. cxl formats from TS, reading the physical model together with the analytical geometries. The conversion process in Revit, from the IFC objects to native ones, could be done also by applying some additional tools, as previously described during this Chapter.

Robot and SOFiSTiK work in collaboration with Revit. Robot applies some send and receive information exchange with Revit, and SOFiSTiK comes integrated as an add-in tool in the software. The interoperability is higher in the SOFiSTiK case and a bit lower for Robot. For example, if you make too many modifications in the Revit or Robot model, you may encounter errors during the import and export processes between the software.

The discussed issues are summarized in the following table:

Workflow/ Criteria. Case Study 2.	Revit /Robot 2021	Revit / SOFiSTiK 2021	ProSap Professional v21	TSD/TS 2021
Modelling	Limitations for T reversed beams in default foundation family configurations.	Like Revit/Robot.	The model was initially built here. The process is fast and accurate applying "Alignments" options.	Accurate in TS and with some limitation for T reversed foundation beams conversion in TSD.
IFC importing and conversion to native objects.	The importing is correctly applied from TS/TSD with the Integrator Tool or through additional tools for IFC conversion.	Like Revit/Robot.	n/a	The IFC is fully recognized and converted to native objects in TS.
Analytical model configuration and boundary conditions.	A few adjustments were done after model's importing. Boundary conditions applied in Robot through automatic K-coeff. evaluations.	Spring boundary conditions to be applied in Revit. Analytical model validated through notifications in SOFiSTiK.	The physical and analytical model have a similar spatial configuration with some differences from the "Alignments" of the physical model.	The designer defines the physical model, through exact positioning. Analytical model automatically generated.
Structural Analysis functionalities and capabilities.	Robot is an advanced structural linear, nonlinear, static, dynamic, analysis software applying finite elements.	SOFiSTiK is an advanced analysis software with wide functionalities in SOFiSTiK Structural Desktop (SSD)	ProSap allows Eurocode checking, with linear, nonlinear, static, dynamic, pushover analysis, applying finite element analysis.	TSD applies different order analysis with FE and advanced results exploring. There are no crucial differences with the other software.
K-Winkler soil-structure interaction and values applications to the foundation's elements.	The values are automatically calculated and applied in Robot through the assignment of soil layers as element's properties.	The values should be calculated separately and applied as boundary conditions in Revit.	ProSap has an integrated tool that automatically calculates and assigns to the elements the K-values. Also, it calculates the bearing capacity of the soil.	Assigned manually since modelled only superstructure with boundary conditions. Foundation modelled separately.
Design grouping and interactive functionalities.	Robots automatically groups elements based on floor's level. There are good functionalities for the interactive design of reinforcement.	The grouping can be done from the designer as required. Functionalities for interactive design of the elements.	The grouping is done automatically from the software. Interactive design of elements with Code Checking verification.	TSD automatically groups the elements. Interactive design of elements with wide Code Checking verification.
Detailing quality and accuracy.	Physical model depending on the Revit accuracy, which is generally good. There may be some incompatibilities in the importing of reinforcement from Robot.	Modelling with precision in Revit, good accuracy of the physical model. Quality for reinforcement generation with possibility of further modification.	Detailing quality depends on the quality of the physical model since processes are automated. Reinforcement generation can be parametrized and further modified.	Very good detailing quality and accuracy. Model with reinforcements can be imported in 3D in TS. Advanced BIM authoring tool for further modelling in TS.
Reinforcement generation.	Reinforcement is automatically generated. Delays in	Reinforcements are automatically generated. Manual	Reinforcement is automatically	Fully automated processes for reinforcement

	the import process in Revit.	grouping of elements.	generated through automated processes.	generation including 3D importing in TS.
3D reinforcement	It is available.	It is available.	Will be available in future editions.	Generated in the importing process in TS.
Processes automation.	Generally automated processes.	Generally automated processes.	Very Good automation of processes.	Very Good automation of processes like ProSap situation.
Interoperability and required time for the processes.	Time-consuming for sending and receiving model's information including results and reinforcements detailing.	Low time requiring for information exchange, SOFiSTiK integrated in Revit.	n/a since only one software.	Acceptable time required for importing and exporting information between TS/TSD.
Interoperability with other software.	Good interoperability, not included IFC conversion options to native objects.	Like Revit/Robot.	Import/update/export operations with IFC format. "Help for BIM" and "Alignment" options for model correction.	High interoperability with a wide range of format files and other software recognition.
Automation for drawings documentation, Reporting & Quantity estimation.	Good automation in Revit. Some drawing documentation & Reporting can be generated in Robot.	Good automation in Revit. Reporting available from SOFiSTiK.	Good automation for all drawing & Reporting. Some manual work for layouts and quantity estimation correction.	High automation for all documentation.
Quantity estimation accuracy.	Depending on concrete objects accuracy.	Depending on concrete objects accuracy.	Accurate values obtained after reinforcement detailing.	Good predictions in TSD and very accurate in TS.

Table 12-Design, automation, and interoperability between the different analyzed workflow/software in Case Study nr.2

4.2.8. BIM adoption improvements from Building A to Building B.

Building A design was done mainly following "*Traditional workflows*", with some issues identified at the beginning of the Chapter and reported below. *Building B* design was done applying BIM friendly software and "*IFC exchange*" workflow, so it is expected to produce better results for the next phases of the project. The issues described from Building A and the expected improvements in Building B are analysed and summarized in the following table:

Building A	Building B	Evaluation
Information received for the architectural and MEP in 2D format, only in .pdf or .dwg.	"IFC" exchange workflow applied. Model can be imported and exported within IFC format.	√
Structural modelling with low referencing and clashes done by manually overlapping the designs.	Clashes can be checked within the same workflow or other BIM Coordination tools based on IFC federated models.	√

Clashes identified late on Site between the structural and the MEP model, consisting in delays and higher costs for construction.	It is expected to not have clashes, except the ones coming out from possible human or computer error.	√
Small incompatibilities with architectural model, bringing to the need to make changes to the design after construction works started.	The structural model is expected to have a high coherence, reliability, and accuracy with the other disciplines.	√
Problems in communication for the design updates, bringing to a situation where an old version of design is still being applied on Site.	This is not completely solved in this Case Study, since it may require the use of a Common Data Environment, better workflows & technologies for Site Coordination.	√*
Difficulties in explaining the concrete's reinforcement detailing, where different elements intersect, considering possible bars overlapping.	The 3D reinforcement model fully explains the configuration of the rebars and the respective positioning to intersecting nodes.	√
High manual working required for the modification of the structural design due to low automation of detailing processes. Small changes required long time of processing and high costs for updated versions.	Small manual reworking in case of modifications or updates due to a good automation guaranteed from the openBIM workflows.	√

Table 13- Comparison Table between Building A issues and Building B improvements.

4.3. Case Study nr.3 - Six floors building (4800 m^2) governmental use.

Case study nr.3 comes with a similar building area to the previous project, but with more complexity for the design. The preliminary architectural model is composed in an irregular geometry and defined in some axes with curved shapes. The building is developed in 7 floors with a height of around 30 m.

Fig. 98-3D visualization of the project.

The project is based on a real case and is currently on the planning and design stage. Some architectural plans have been developed and are under evaluation for the structural design.

4.3.1. Project’s modelling.

For this project have been chosen two of the workflows: *ProSap Professional v21* and the *Tekla Structural Designer (TSD) - Tekla Structures (TS) 2021*. An integration with *Revit 2021* is also discussed in the process.

Most of the issues for the modelling stage have been presented in the previous Case Studies. The difference of this project is related to the higher complexity and irregularity of the model. The columns are not positioned orthogonally to the main axes, but they are in a rotated position and together with the beams follow an undulated configuration.

4.3.1.1. Modelling with ProSap Professional v21.

In ProSap the modelling process can start from some referenced .dxf, by automatically generating some part of the model. The position and rotation of the columns can be defined with default commands and the beams designed for every floor with referenced “*Alignments*”. ProSap also reads 3D .dxf and automatically generates from its lines the 3D model. Properties and parameters of the structural elements can be defined subsequently. The workflow is described as follows.

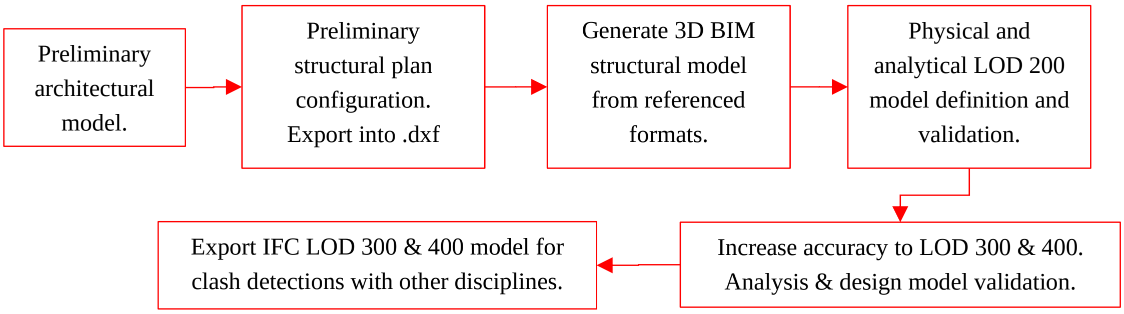


Fig. 99-Case Study nr.3 - Project’s modelling in ProSap – Workflow A

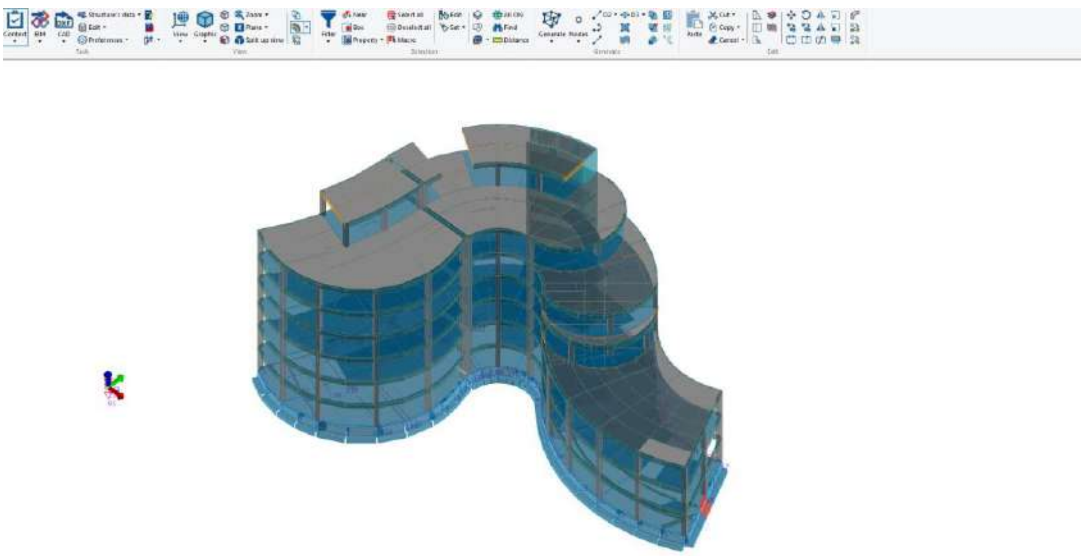


Fig. 100-Case Study nr.3 - 3D model in ProSap Professional v21.

Another proposal starts from an *.IFC exported* model from Revit 2021. The preliminary structural model is defined in Revit in coordination with the architectural one. The .IFC is imported to ProSap and corrected through the "*Help for BIM*" tool. It automatically recognizes the structural elements and converts them to native objects.

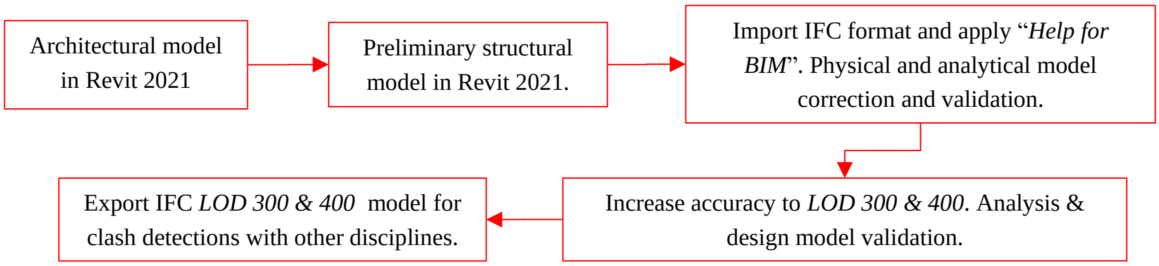


Fig. 101-Case Study nr.3 - Project's modelling in ProSap – Workflow B.

ProSap does not provide a default option for the modelling of arch beams, so they need to be divided into smaller finite elements. "Alignments" are applied to respect the architectural model.

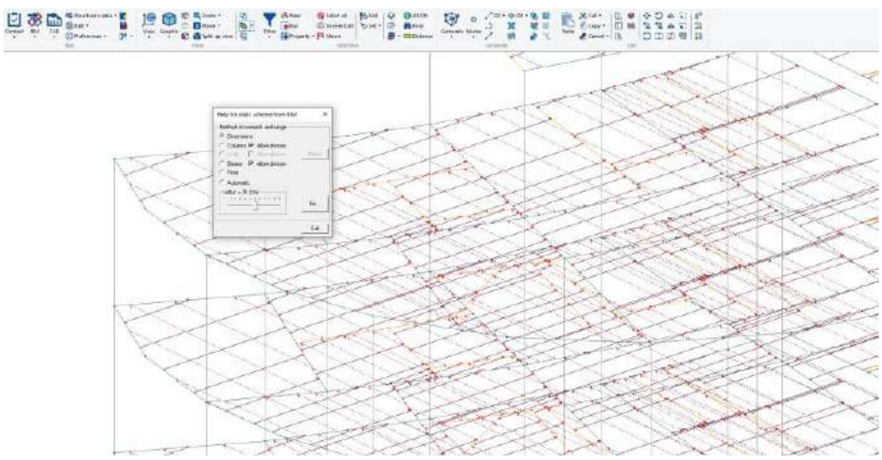


Fig. 102-Workflow B - IFC importing of preliminary structural model for analysis and design.

4.3.1.2. Modelling with Tekla Structural Designer (TSD) - Tekla Structures (TS).

TSD requires to start the modelling with grids and construction lines. These can be designed separately, generated through Wizards, or imported from referenced .dxf files.

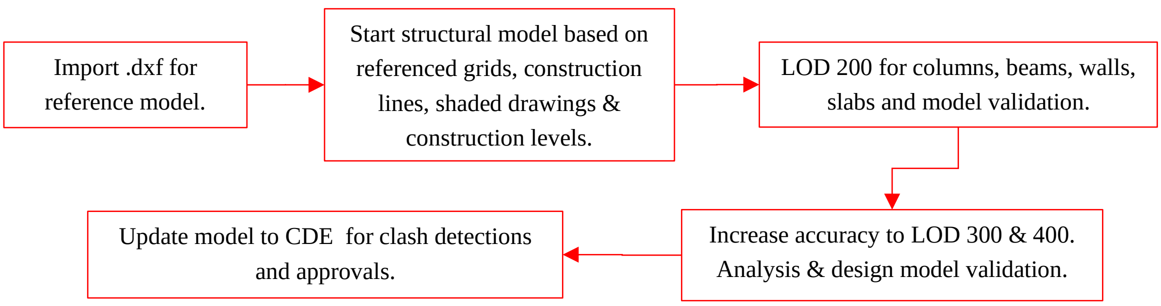


Fig. 103-Case Study nr.3 - Project's modelling in TSD – Workflow C.

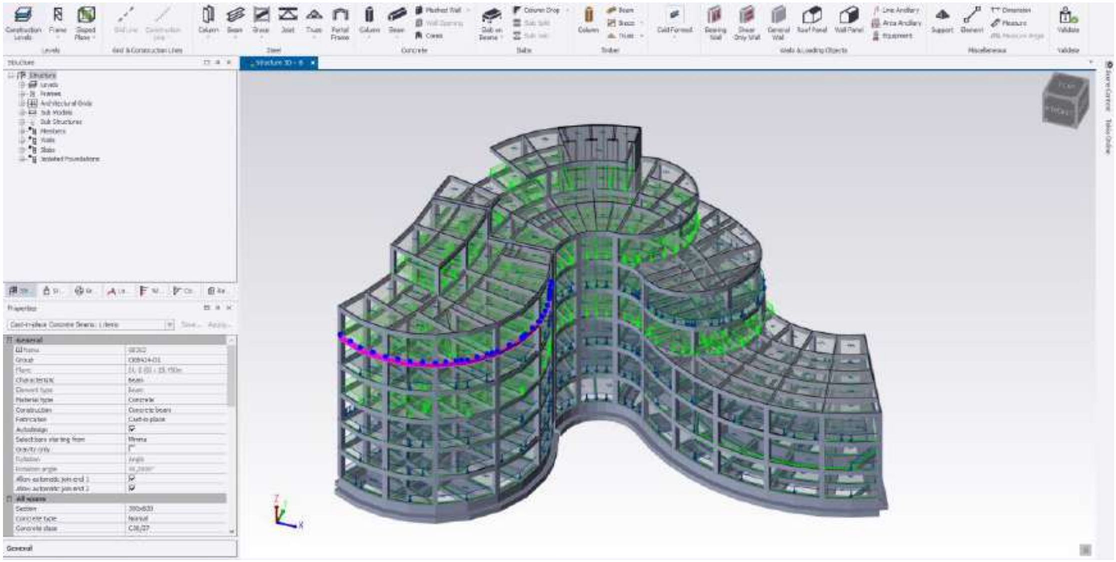


Fig. 104-Case Study nr.3 - TSD model.

As in the ProSap Case study, it is also possible to import a preliminary structural model as a. cxl format from the "*Structural BIM Import*". This format can be generated from several openBIM software including the Revit "*Tekla Integrator Tool*". The preliminary structural model can be configured in *Revit 2021* together with the architectural model and then imported for analysis and design in TSD.

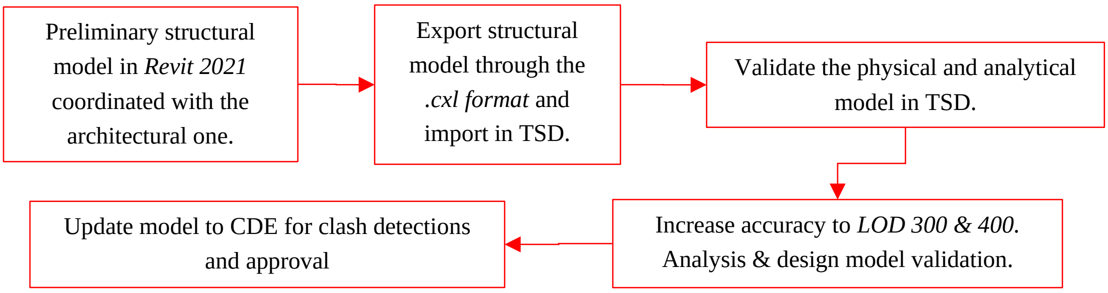


Fig. 105-Case Study nr.3 - Project's modelling in TSD – Workflow D

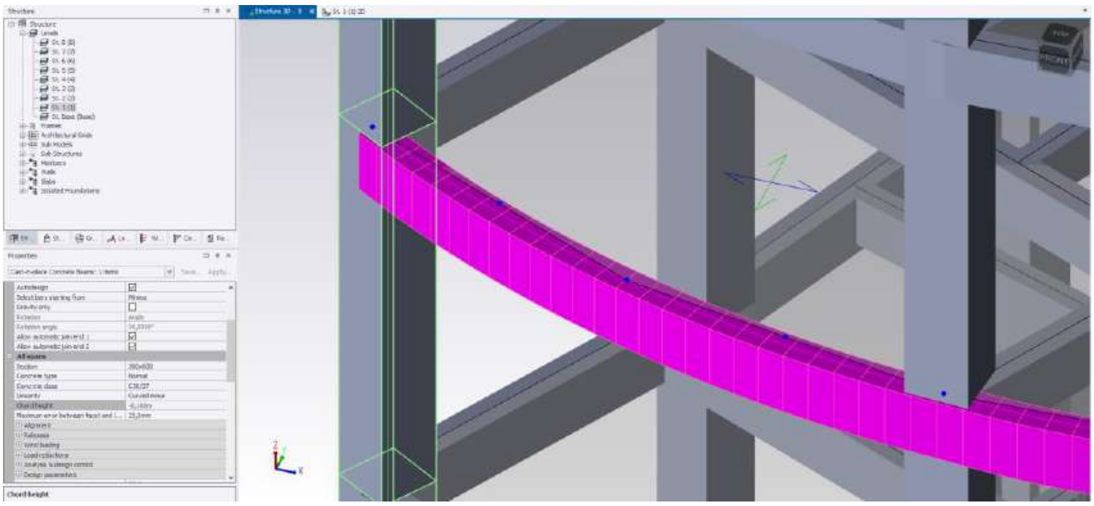


Fig. 106-Parametrized curved beams in TSD

TSD can make use of curved beams with parametrized chord's heights, allowing to obtain an accurate model. This process is more automated compared to ProSap, where the small 2D pieces composing the arcs shall be modelled manually with referenced lines. TSD, as discussed in the previous projects, comes with a limitation for the foundation beams. You can model as foundation elements, footings, mats, strips, openings, but not cast in place T reversed foundation concrete beams.

4.3.2. Analysis and design.

Preliminary analysis & design can be run from the LOD 300 definition, to check warnings, notifications, and that the model is correctly configured. Once all structural elements are correctly modelled, and there are no clashes for the LOD 300 model, accurate loads and loads combinations may be defined. These cannot be imported and exported between the different software and must be configured specifically in each one of them. Results for internal forces, stresses, deformation, and reaction forces are available graphically and analytically.

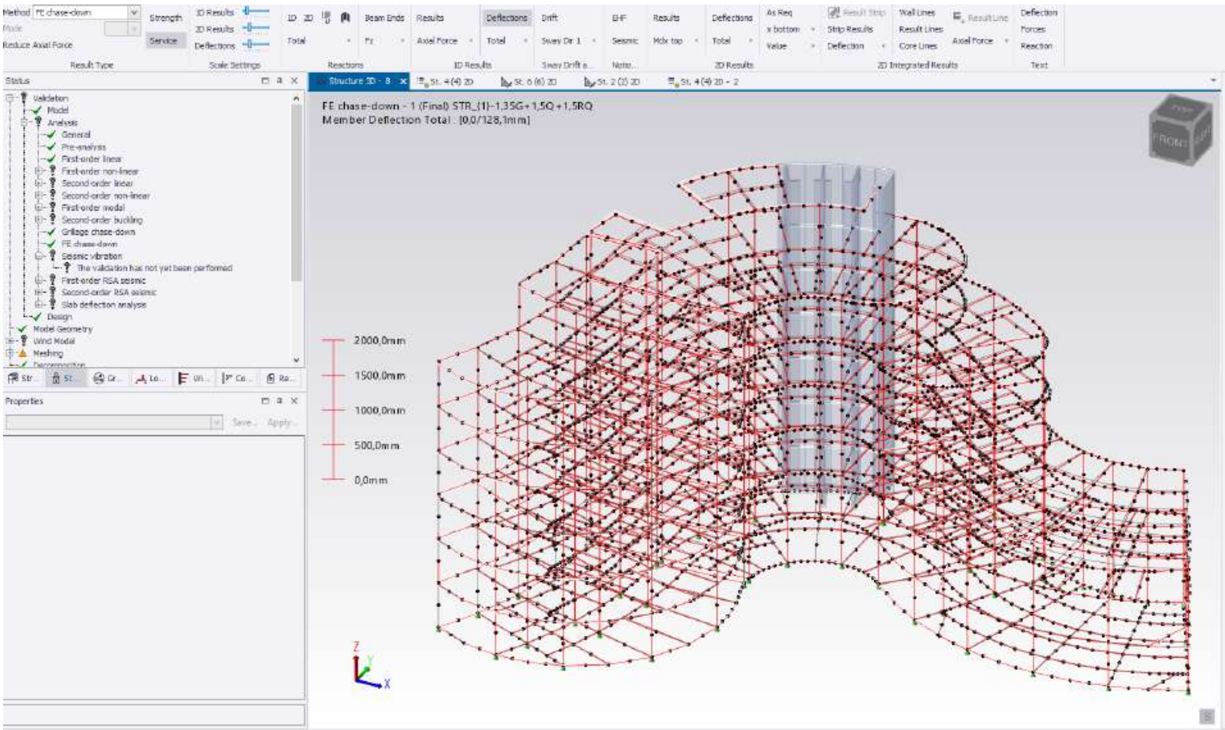


Fig. 107-Different analysis method results view for deformation, internal forces, stresses, and reaction forces in TSD.

Analysis, design, and interactive results checking is possible both in *TSD* and *ProSap*. In TSD you can change within the same software the reinforcement bars and see in real time the verification values. In ProSap, the interactive design follows with the integrated tools of "*Pro_CAD Travi*", "*Pilastri*", "*Setti c.a.*", "*Carpenterie di piano*" etc.

Structural elements can be grouped automatically for multiply design reinforcements. Manual grouping can also be done for specific elements from the designer.

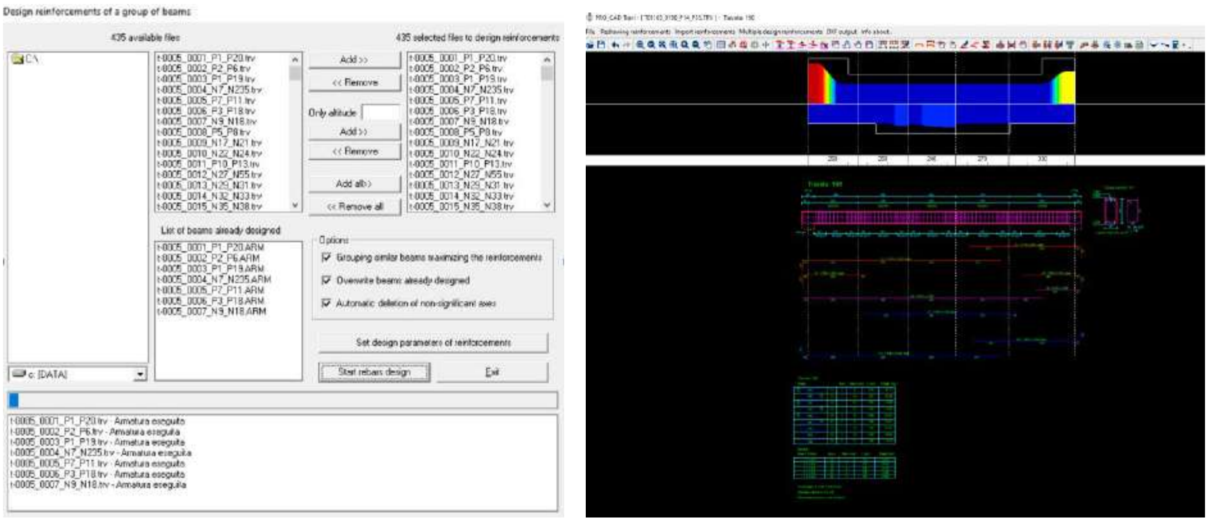


Fig. 108-Multiply design reinforcement for beams in ProSap, and user's settings and design's parameters in "Pro_CAD Travi".

4.3.3. Detailing and Documentation.

ProSap generates 2D reinforcement drawings for all structural elements. They can be configured in advance with user's preferences and parametrization, and after postprocessed for layout and final documentation. Calculation Reporting is automated with small efforts. Quantity estimations may require manual updates of the values after the production of the final reinforcements detailing. Overlap of concrete material between the different elements may not be considered in the estimation. ProSap exchanges information for the IFC model without the reinforcements rebars. The IFC can be used for clash detections and in the future steps of *construction & facility management*.

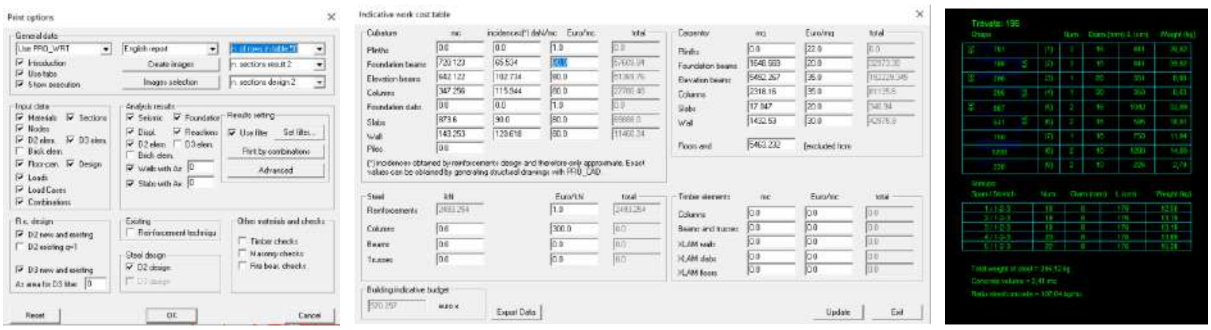


Fig. 109-Calculation Reporting, indicative working costs table with exporting option to .csv format, reinforcements scheduling and quantity estimation for a beam in Pro_CAD Travi.

TSD provides very good quality of the drawing documentation. The model can be imported into TS and the reinforcement bars recognized as 3D elements. Further processing of the elements and enrichment with properties and parameters can continue in an advanced BIM authoring software. IFC exporting includes all elements together with the 3D reinforcement bars at a good quality. Final quantity estimations are highly accurate.

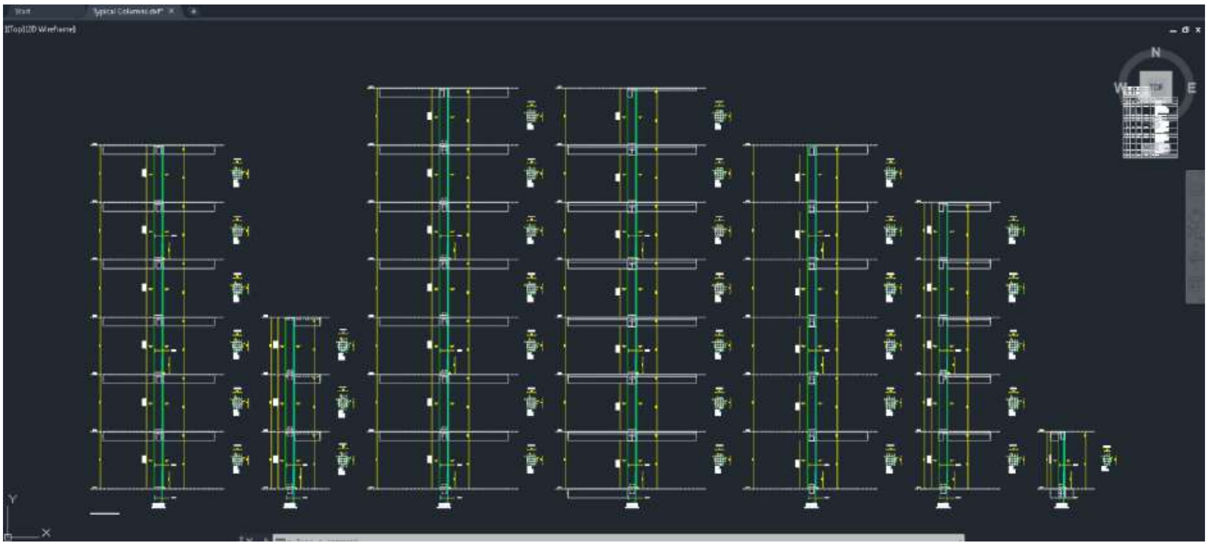


Fig. 110-Typical columns reinforcement generation with quantity estimations in TSD.

In both cases of TSD and ProSap, the general documentation and 2D reinforcement drawings are generated at a good quality. The TSD model can be exported to TS including design's results and reinforcements. TS provides more functionalities for the 3D post-processing of the model, for quantity estimations and the construction & facility management.

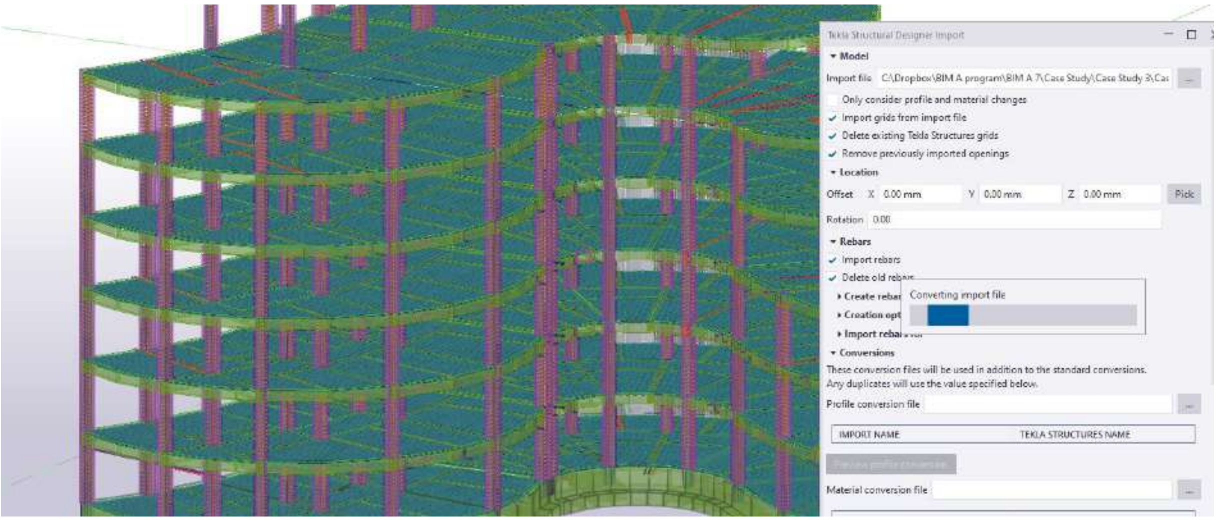


Fig. 111-Import 3D model with reinforcements into TS from TSD.

4.3.4. CDE collaboration and workflows.

To enhance and facilitate the collaboration of the project you need to make use of a CDE – "*Common Data Environment*". This does not depend only on the Structural Design Team but must be settled at the beginning of a project. All actors involved shall access the database, and with customized rights, create, insert, modify, review, check for clash detection or approve the models. CDE are provided from different vendors, like Oracle Aconex, BIM 360 etc.

Tekla offers an own CDE for collaboration, the "*Trimble Connect*". You can share not only Tekla formats but also other openBIM formats like Revit or IFC files. "*Trimble Connect*" comes with functionalities also for clash detection. The advantage of Trimble for Case Study nr.3, is presented in the case of application of the workflows making use of Revit and Tekla, which can directly integrate the model and documentation from the Trimble products and the Partner applications.

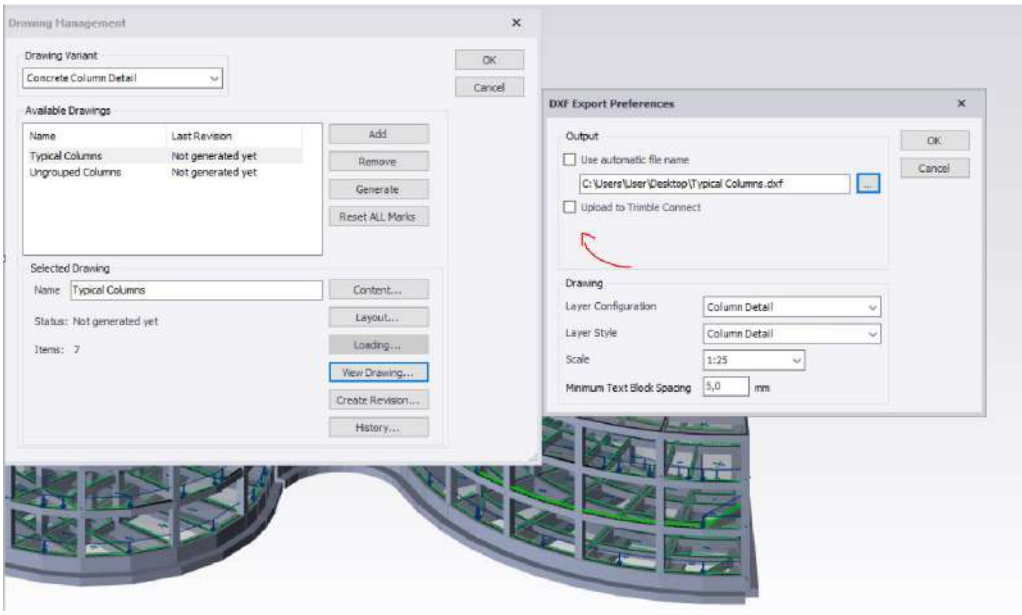


Fig. 112-Case Study nr.3 - Update of drawing documentation from TSD.

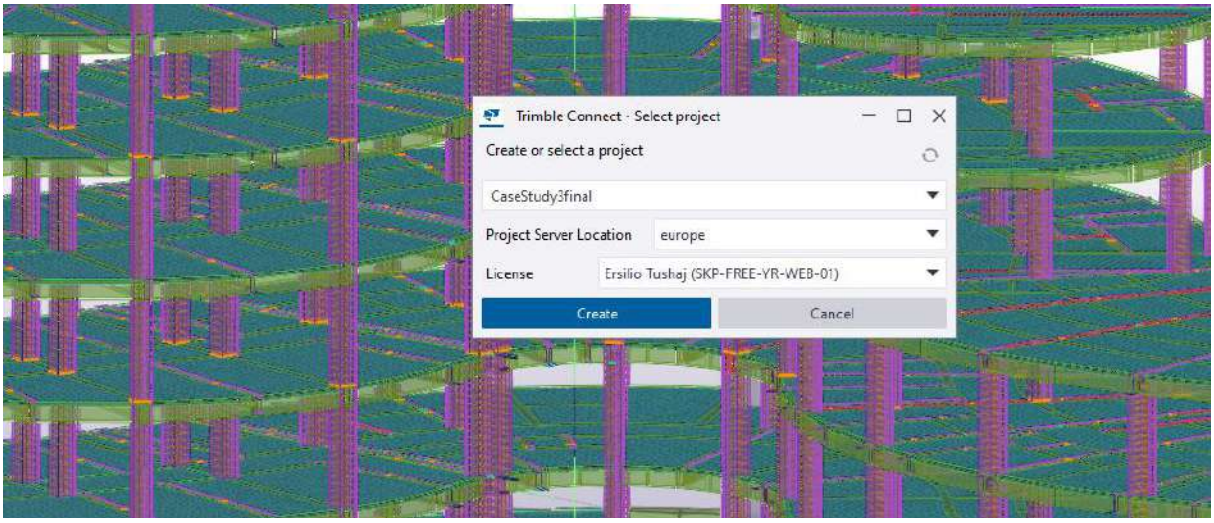


Fig. 113-Export model from TS to Trimble CDE.

Oracle Aconex is a highly developed and widely used CDE in the market. It allows multi-user operation, structured database, project's information sharing, costs, documentation, and field's management. It secures advanced communication forms, models coordination in CDE, integrated cost management, quality and safety processes, customized reporting in online viewers etc.

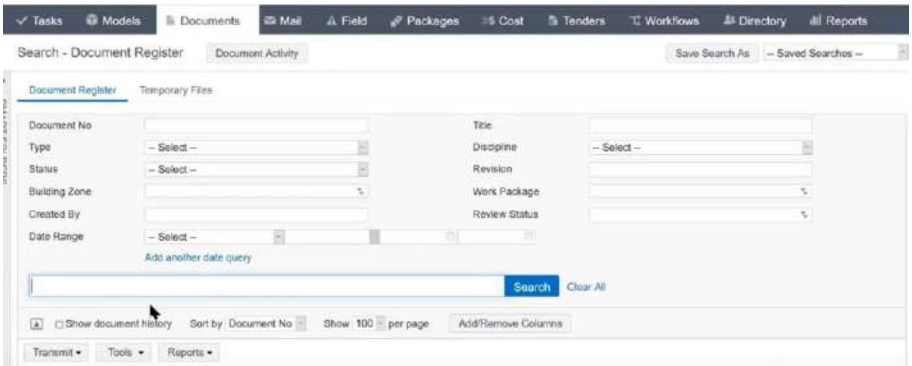
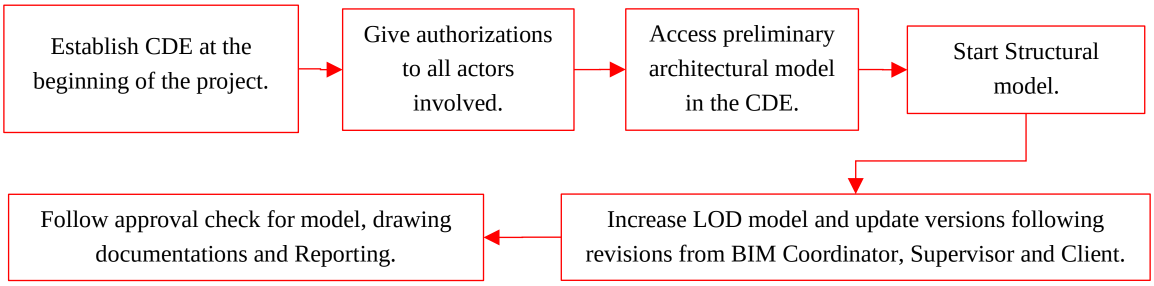


Fig. 114-ORACLE Aconex – Documents management. (Oracle, 2021)

Both CDEs can be used for the case study. Collaboration, communication, information sharing, and management can proceed through the *central cloud-based environments*.



The full workflow with activities for the "*integrated modelling*" applied within the CDE, are detailed in in *Section 3.3.1. Workflow's detailing (page nr.42, Fig. 14).*

4.3.5. Discussion.

For this case study have been applied two of the workflows, ProSap Professional v21 and the TSD/TS 2021. Each one of them has been detailed in two scenarios, one starting from referenced .dxf formats and the other from an imported preliminary structural model in Revit 2021.

Modelling.

This project comes with a higher complexity for the modelling compared to the previous ones. It was observed that TSD and Revit can deal with and automatically import/export arch beams, instead ProSap requires a manual definition of the smaller finite elements. Detailing and reinforcements are automatically generated in both cases at the end of design, respecting the structural physical geometry.

ProSap comes with a simpler configuration of the structural elements and allows to assign as a property the soil-structure interaction. Elastic coefficients are automatically calculated and assigned to the elements. In ProSap you can model a beam with different sections and assign it as a foundation element. Instead in TSD and Revit, you should make use of default families for the foundation's configuration. In case of T reversed concrete foundation beams, this becomes complicated as they are not provided from the software as an alternative option. You can model in TSD isolated footings, mats, strips, openings, but not T reversed concrete cast in place beams.

Interoperability.

From the case study analysis resulted that in both workflows there is a good interoperability. ProSap makes use of IFC import/update/export operations, instead Revit, TSD and TS can exchange information with the use of a cxl format. This type of format imports/exports not only the physical model, but also the analytical geometry, including analysis and design results with reinforcement detailing.

When using IFC for information exchange, you should check the integrity of the analytical model. Issues have been identified both in ProSap and in TSD. Each of the software provides checking and correction functionalities for the validation of the model.

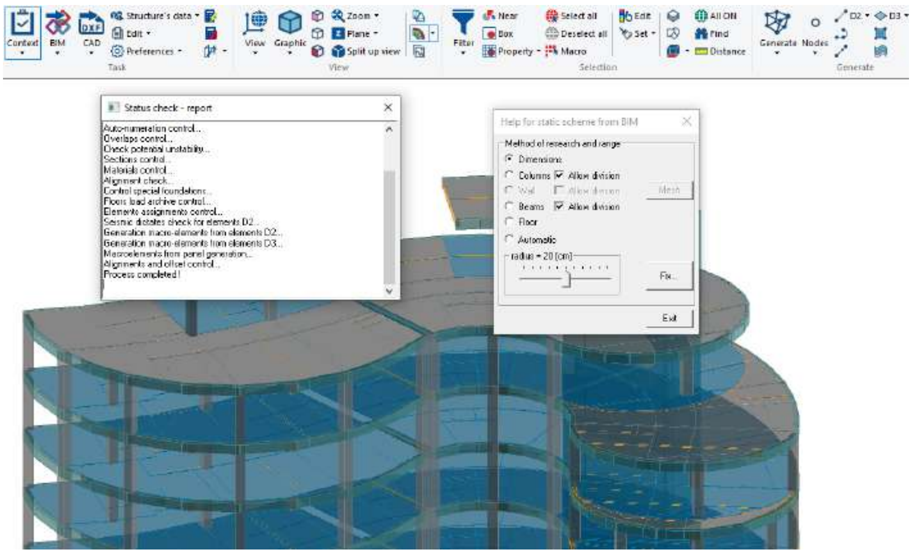


Fig. 115-Notification for model status check and "*Help for BIM*" command tools in ProSap.

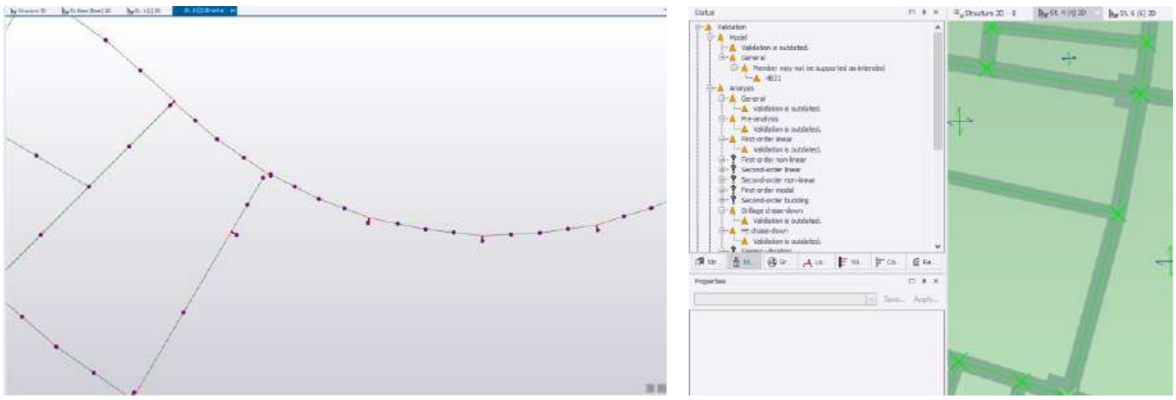


Fig. 116-Disconnected analytical elements and notifications from the validation model in TSD.

Analysis and Design.

Structural analysis functionalities and results view are provided at a high level in both software. They can run linear or non-linear, static, or dynamic, pushover, time history, 1st order, 2nd order or buckling analysis. In TSD you can check results for FE or grillage chase-down, considering or not considering the rigidity of slabs. In ProSap these considerations are done by modelling the slabs as meshed finite elements together with the other part of the structural elements, or by simply modelling slabs as loading into beams.

Design's results can be checked analytically and graphically for stresses, internal forces, deformations, reaction forces etc. The process is automated. Interactive design within TSD or the integrated tools in ProSap simplifies and involve the designer to decide specifically for the reinforcement's options.

Detailing and CDE collaboration.

ProSap provides reliable detailing for the general plans and all the structural elements. It allows IFC exporting of the concrete model, but it does not include the 3D reinforcements detailing. TSD instead, by exporting the model to TS, can also generate the 3D rebars.

CDE collaboration is guaranteed for ProSap through IFC formats and drawing documentation sharing. Instead, Tekla can directly update the model and documentation to a CDE in case of using the "*Trimble Connect*". Tekla formats are supported also from different CDE providers. Design's workflows proceed by making use of a single updated source of information.

Since most of the issues involving the workflows/software, have been discussed in the previous Case Studies, here are reported mainly the new ones from Case Study nr.3.

Software/ New issues Case Study 3.	ProSap Professional v21	TSD/TS 2021
Modelling	Model is almost accurate. Structural arch elements need to be manually defined into smaller finite elements.	TSD can automatically define arch elements with parametrized chord's heights. Identified some limitation for T reversed foundation beams modelling.
Interoperability.	Good interoperability. Requires application of correction and validation helping tools integrated in the software, like the "*Help for BIM*" and the "*Alignments*" commands.	In case of IFC importing is required manual correction of the analytical model. When using cxl formats, are also imported/exported, the analytical geometry, analysis results, and the reinforcement detailing.
Analysis and Design	Linear or non-linear, static, or dynamic, pushover, time history analysis. EuroCode Checking and user preference settings for design. You can consider/not consider the slab's rigidity, by modelling them as meshed finite elements, or as simply loading into the beams. Design's results can be checked analytically or graphically by different functionalities.	Very reliable analysis and design. You can check results for FE or grillage chase-down cases, considering or not considering the rigidity of slabs. Design results available analytically and graphically. All processes are automated. Interactive design involves the designer to decide specifically for the reinforcement options.
Detailing and CDE collaboration.	Detailing is automatically provided like the other projects following designer's settings and parametrization. CDE collaboration is not provided in default from ProSap but it is guaranteed through reliable IFC model exchange and automated drawing documentation.	Detailing is very accurate in TSD/TS workflow. Reinforcement is generated in 3D when importing to TS. Recognition of Tekla formats from different CDE providers. In case of applying *Trimble Connect*, you can automatically update the models and drawing documentation to the CDE.

Fig. 117-Summary of the new issues from Case Study nr.3

4.4. Survey.

To take in consideration the opinion of other professionals working in the field, a Survey was done for the BIM adoption for structural engineering design, making use of the mentioned workflows and software. It was prepared with the help of Google Forms.

The interviewed are civil engineers, specialized in structural engineering, architectural engineers, architects, and similar professionals with expertise in the structural design of concrete buildings. Their knowledge in BIM, by frequenting postgraduate courses, academic programs or with practical experience, is in a range from 3 months to a maximum of 10 years. They have been using BIM workflows and software in their work starting from 3 months to 5 years, which shows that BIM uses are quite new, compared to the profession.

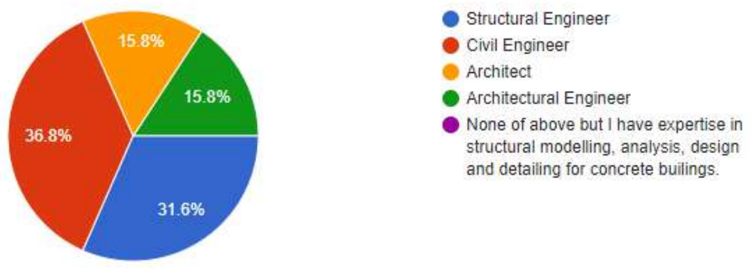


Fig. 118-Experience in using BIM friendly workflows for structural engineering design.

The survey resulted with an equal distribution in the uses of the different workflows/software. The modelling capabilities of the software integrated in BIM workflows are generally evaluated from good in Revit/Robot to good-very good in Revit/SOFiSTiK and ProSap Professionals, to very good-excellent in TSD/TS.

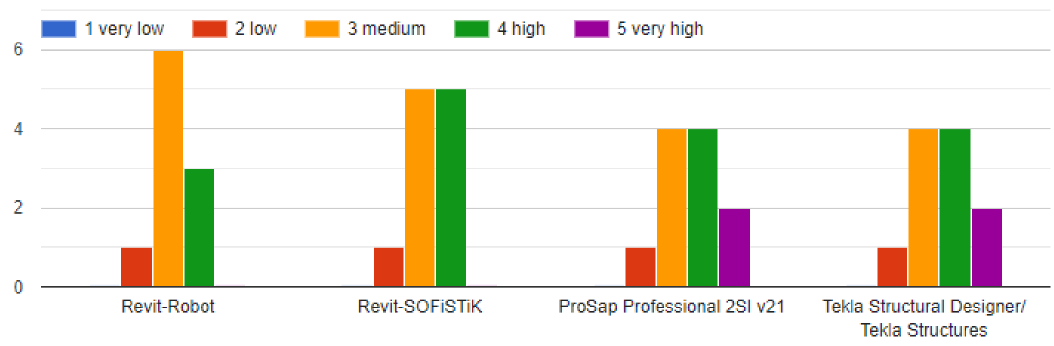


Table 14-Analytical model configuration, necessity of modification and automation.

Different opinions are given for the analytical model configuration, starting from a medium appreciation to higher ones. Better results are obtained for ProSap and TSD/TS. The structural physical modelling reliability and accuracy is evaluated generally good in all software with higher appreciation in Revit/SOFiSTiK, ProSap and TSD/TS.

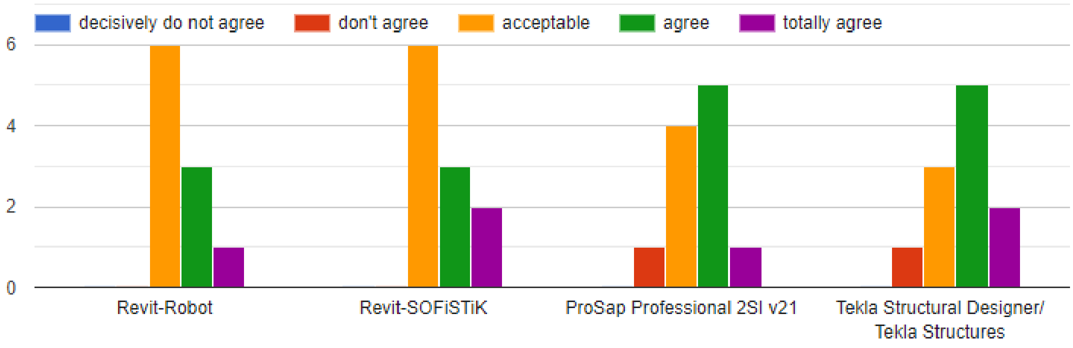


Table 15-Structural physical modelling reliability and accuracy.

TSD/TS workflow also results with higher values for the analysis and design's processes. General drawing management and Reporting is evaluated with good potentials and capabilities increasingly from Revit/Robot to TSD/TS. Quantity and Costs estimations are presented with better results for Revit workflows and TSD/TS.

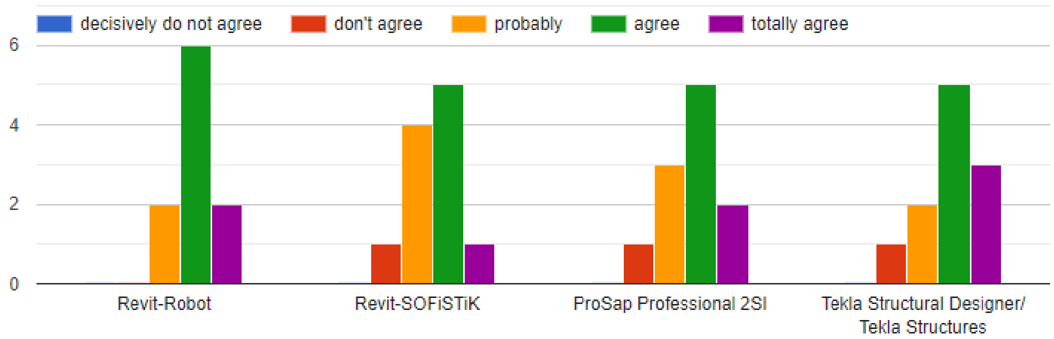


Table 16-Analysis & design's functionalities.

Automation of processes are considered very good in ProSap and TSD/TS, with small manual efforts between the different steps.

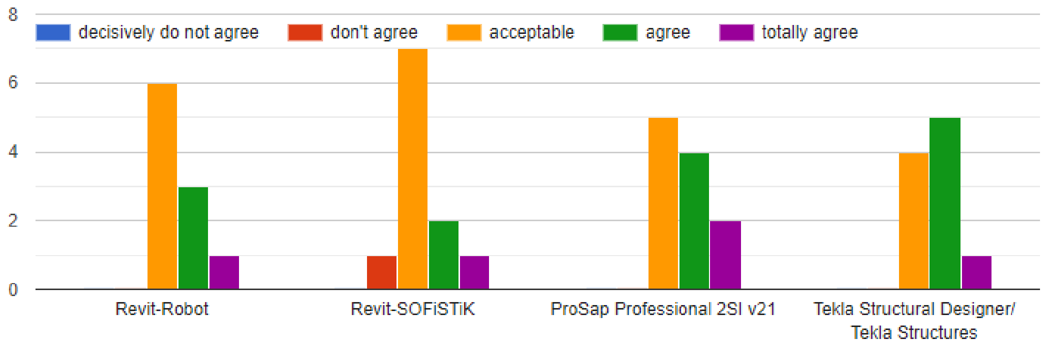


Table 17-Automation of processes.

Interoperability is evaluated good in Revit/Robot, good-very good in Revit/SOFiSTiK and very good in TSD/TS. The Survey was not done for ProSap since it is dealing only with one software and the reinforcement design tools are integrated within it.

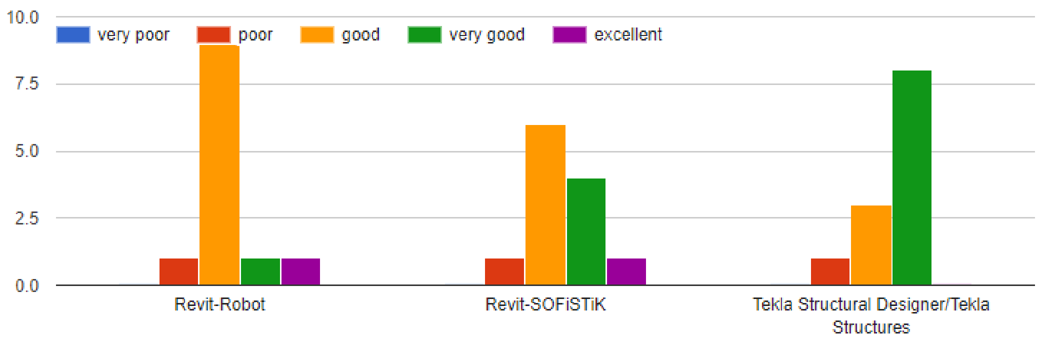


Table 18-Interoperability evaluation in the workflows.

Revit/Robot IFC quality is evaluated coherent, reliable, and very accurate. ProSap instead falls in the middle range with good quality and TSD/TS above average with good-very good quality.

To give a better idea of the results for each case, they are parametrized in a scale from 1 (very poor) to 5 (excellent), analysed through excel sheets and summarized in the following table.

Workflow / Survey Criteria (scale 1 to 5)	Revit /Robot 2021	Revit 2021/ SOFiSTiK	ProSap Professional v21	Tekla Structural Designer/Tekla Structures 2021
Structural modelling functionalities and capabilities in BIM workflows.	3	3.3	3.6	3.8
Analytical model	3.2	3.4	3.6	3.6
Physical model	3.5	3.6	3.5	3.7
Structural analysis and design	3.6	3.5	3.7	3.9
Detailing, Drawing Management & Documentation.	3.8	3.7	3.6	3.9
Quantity and Costs Estimation quality.	3.7	3.7	3.5	4
Automation of processes.	3.5	3.3	3.7	3.7
Interoperability quality in the workflows	3.2	3.4	n/a	3.6
Coherence of the model in the IFC import/export operations	3.5	3.5	3.3	3.5
Reliability of the IFC model in the import/export operations	3.2	3.2	3.2	3.6
Accuracy of the IFC model in the import/export operations	3.5	3.5	3	3.3

Table 19-Average Survey's results in a scale from 1 (very low) to 5 (excellent).

All given evaluations are in the range from 3.0 to 4.0, with average values around 3.5, which means that the software and workflows are evaluated between good and very good. TSD/TS comes with a higher appreciation following the other workflows at a similar situation.

The full Results of the Survey are presented in Appendix 7 - Survey's results.

4.5. BIM SDWAM (BIM Structural Design's Workflow Assessment Model).

Maturity assessment models as described in Chapter 2 (and further in Appendix 4 - BIM Maturity Assessment Models.), are generally applied to evaluate the level of BIM adoption for an Organization (OAM), Project (PAM), towards individual competencies (ICI), markets or industry. Very limited research was found for the software and workflows assessment models in the different specific disciplines.

Within this Section it is introduced a possible maturity model for the structural design's workflows, shortly named with BIM SDWAM ("*BIM Structural Design's Workflow Assessment Model*").

The configuration of the model follows the different discussed criteria and the analysis and discussion done during the Case Studies:

- ✓ Structural modelling functionalities and capabilities in BIM integrated workflows.
- ✓ Analytical model configuration, modification, and validation.
- ✓ Physical model configuration, reliability, and accuracy.
- ✓ Structural analysis & design functionalities and capabilities.
- ✓ Detailing, drawing management & documentation quality.
- ✓ Automation of processes.
- ✓ Interoperability quality within and outside the design workflows.
- ✓ IFC quality, coherence, reliability, and accuracy.
- ✓ Collaboration and communication within and outside the design workflows.
- ✓ Flexibility in the workflow's improvement towards full BIM adoption.
- ✓ Capacity in dealing with higher complexity in all stages of design.

An evaluation scale is proposed from 1 (*very low maturity*), 2 (low), 3 (good), 4 (very good) to 5 (excellent).

This model will be applied in the final Chapter for the general evaluations and conclusions.

5. DISCUSSION AND CONCLUSIONS.

The Thesis had as objective to analyze the BIM adoption processes in general, and with focus to the specific discipline of structural engineering design. For this purpose, BIM friendly processes were applied for the design and information modelling of cast in place concrete structures. Case Studies were analyzed applying openBIM software in integrated workflows.

The work was organized in five Chapters. The first starts with some introduction and historical information about BIM developments. In the second, it is formulated more clearly what involves BIM, its applications, processes and in general it is presented a theoretical background in BIM adoption. The third Chapter goes more into specific with the formulation, workflows detailing, and software in BIM for Structural Design. The fourth follows the Case Studies application, analysis, design, and results. The final Chapter concludes with discussions and results of the Thesis.

Chapter 1. It involves the introduction part, starting with the first developments in BIM, how it was born and how it evolved during time. Eastman is considered as one of pioneers, presenting structured databases for design and construction with the Building Description System (BDS). The Chapter continues with the introduction of the Thesis's general structure, objectives, methodology and expected results. It is quite interesting to see how BIM is developed from the integration of disciplines, from the enrichment of the drawing documentation with non-graphical information, organized in more structured and interoperable databases, software, and tools.

Chapter 2 continues with an exploration for the theoretical backgrounds in BIM adoption. Performance indicators and maturity assessment models, that have been proposed and used from many authors, are presented in the first pages. BIM had seen an exponential growth in the last decades. Trends, challenges, and benefits are discussed for the general picture and with focus to the specific structural discipline. The Bew and Richard's Maturity Model, like as well the Succar's stages and fields, show very clearly how you can evolve from a "Pre-BIM" situation towards a fully integrated one.

Adopting BIM is a continues improving of knowledge and processes. Maturity Assessment Models are applied to evaluate the current situation in BIM adoption for an organization, project, or an individual. Performance indicators are applied to check how well you are doing based on some specific criteria. "People", lack of knowledge, missing policies, technological fragmentation, and initial costs were some of the main identified challenges. BIM involves a new methodology, that requires the uses of interoperable software, applied in integrated and automated workflows, from people with the right expertise. At the end, most of the issues reduce in a required business strategy, with some surveys showing that the initial investment in BIM is justified from its future benefits.

Chapter 3 goes more into deep in BIM for structural engineering design. Research was analyzed for the specific topics and conclusions presented. Workflows were built for different scenario starting from the "*traditional design*", to "*IFC exchange*" and "*integrated modelling*". Four integrated workflows with openBIM software are chosen to investigate the modelling, analysis, design, and detailing processes for the concrete structures design. Revit - Robot 2021, Revit - SOFiSTiK 2021, ProSap Professional v21 and TSD-TS 2021 are applied for the analysis of three Case Studies. Interoperability within the workflows and between them, is continuously checked with results presented case by case.

Chapter 4 involves the application of the discussed workflows and software in the chosen case studies. It describes step by step the processes from the modelling of the concrete structures to analysis, design, detailing, quantity estimations and documentation reporting.

It is observed that modelling with BIM software may require more time, compared to the traditional design. This results because of the need to apply more parametrization with properties, user's preferences, references, including structured information to the model, to guarantee automation of processes, for obtaining reliable and accurate deliverables.

A Survey was conducted to share and analyze with other professionals in the field, some of the key issues of the study. Similar and comparable replies to the Thesis results are obtained. Some of the interviewed, have given higher appreciation for Revit/Robot, but when not applying 3D reinforcements detailing. TSD/TS designers, generally appreciate its applications, like as well the Revit/SOFiSTiK ones.

The workflows are evaluated during the presentation of the Case Studies based on the following Criteria:

- ✓ Structural modelling functionalities and capabilities in BIM integrated workflows.
- ✓ Analytical model configuration, modification, and validation.
- ✓ Physical model configuration, reliability, and accuracy.
- ✓ Structural analysis & design functionalities and capabilities.
- ✓ Detailing, drawing management & documentation quality.
- ✓ Automation of processes.
- ✓ Interoperability quality within and outside the design workflows.
- ✓ IFC quality, coherence, reliability, and accuracy.
- ✓ Collaboration and communication within and outside the design workflows.
- ✓ Flexibility in the workflow's improvement towards full BIM adoption.
- ✓ Capacity in dealing with higher complexity in all design's stages.

Interoperability.

Vendors apply different approaches to the structural design and information modelling. Revit-Robot's workflows divide the modelling stage from the analysis and design, in two different software. They are both produced from AutoDesk, but even though, a few issues with missing interoperability have been identified in the processes.

TSD-TS divides the modelling, analysis, and design from the detailing stages, leaving the first two activities involving the analytical model, to just one software. This can reduce errors in calculations and improve the accuracy in the information exchange. The "*changes recognition*" window in TSD/TS explains which elements have been modified, making easier for the software and the designer to check step by step the evolution of the model.

SOFiSTiK comes for its base commands integrated in Revit, making reliable its operation within the software. ProSap with its integrated tools, is installed and produced in one software, generating almost no issues in this direction.

Interoperability for the Case Studies was evaluated by applying IFC or the .cxl formats. TS resulted with a very good recognition and conversion of the IFC objects to native elements. The model could be exported both in TSD and Revit, automatically recognizing the analytical geometries. ProSap also does not present relevant issues in the automatic conversion of the imported IFC objects to native elements. Integrated command tools can be applied to correct and validate the model.

Modelling.

In all cases were identified good capabilities in modelling, respecting the physical and analytical geometries. Some limitations were identified when sending information from Revit to Robot, in the recognition of the boundary conditions, floor's slab and wall's foundation reinforcements. T foundation beams families are not provided in default in Revit and TSD. It is possible to model as foundation elements footings, mats, strips, and piles. In case of different configurations, other arrangements and workflows should be followed. The problem is not presented in ProSap, where all type of structural elements can be assigned with a "*foundation*" property, and soil-structure interaction calculated automatically, based on the lower area of the element, its section's dimensions, and the soil layers.

Revit and TSD allow to model arch's elements, by specific commands like "arch" lines, or "chord's height". ProSap does not provide a default function, so the elements for this case should be divided into smaller finite elements.

Accurate models can be designed in Revit and exported to the analysis software for the use as preliminary structural models. Revit allows to easily define the position of beams and columns respecting the different discipline's model. TSD permits to assign exact values for positioning and eccentricities. ProSap makes use of the "*Help for BIM*" and "*Alignments*", to configure the physical model respectively to the analytical one.

Once the model is finished, checking and validation functionalities are applied in all workflows. In Revit/Robot it can be done in both software, with notifications displaying if there are present any issues. TSD also includes a validation function, verifying the integrity of the analytical model, clashes of the physical elements, and the verification of the design's requirements. ProSap applies checking for each step of design, showing if there are any unresolved issues. Finally, it is included a separate checking functionality from Revit in SOFiSTiK, to guarantee the reliability of the analysis and design's processes.

Analysis.

Wide functionalities are available in all software. Robot is an advanced structural analysis software permitting linear, non-linear, static, dynamic, pushover, 1st order, 2nd order and buckling evaluations. After defining Code Checking you can run the analysis. Issues involving the model or loads configuration can be modified following the notifications. Analysis results can be checked for deformation, stresses, internal, and reaction forces. Some preliminary calculation and design can be done in Revit, or the full design process can continue in Robot. Loads can be modelled in advance in Revit, with load combinations generated after importation in Robot.

TSD together with ProSap provided fast calculations in all Case Studies. Automated wizards could evaluate and automatically apply wind and seismic actions to the structure. Results could be checked both graphically and analytically. Modifications and updates to the model could be made and applied case by case. In SOFiSTiK, before starting the design, you should follow the mapping of element's sections, materials, and loads. The software is automatically recognizing the Revit model, it is checking its analytical geometry and running the analysis based on that configuration.

Design.

The design's process is following the structural analysis, and it involves the checking and verification of the obtained results based on the Code Requirements. Robot provides different "*windows*" for the sections designing and the calculation of the "*required*" and "*provided*" reinforcements for the different structural elements. Preferences and Code Checking can be configured in advance and applied for the design of the elements. Robot, compared to the other workflows, requires a longer time for calculations.

SOFiSTiK has an integrated tool in Revit and comes with a separate Desktop application SSD, that can be used for more advanced analysis and design. Elements can be grouped, user's preferences and settings applied for each group of elements. The Revit integrated tool can follow the design for beams, columns, and slabs elements. SOFiSTiK requires stable operations without interferences from the other applications in Revit.

TSD and ProSap apply grouping of the elements, provide analysis, design and interactive results checking. Parametrical settings can automatically generate the reinforcements in the structural elements. Verification of elements is shown both graphically and analytically. This stage is faster and more automated within these two workflows compared to the other ones.

Calculation Reports are generated in all software with the respective passing and failing the check.

Detailing.

Robot and SOFiSTiK make calculations and provide detailing directly in 3D. The process of exporting for the reinforcement's bars from Robot to Revit, is a time-consuming process and not very efficient. Instead in SOFiSTiK, rebars are generated directly in Revit as native elements and can be further modified as required within the software. Detailing can be generated from the design's results, or manually modelled from the integrated command tools.

TSD generates initially 2D reinforcements and later in the exporting process to TS, recognizes and provides the reinforcement bars in 3D. ProSap details bars only in 2D. The processes are automatic in both cases. Detailing documentation are then generated through Drawing documentation in TSD, and with the support of the "PRO_CAD" integrated tools in ProSap, for beams, columns, slabs, walls, and the general plans. TSD/TS and ProSap processes result more automated compared to the other cases.

Drawing documentation and IFC.

For the first two workflows, the drawing documentation can be obtained following Revit's layout configurations. Calculation Reports can be generated respectively from Robot and SOFiSTiK. TSD includes a drawing management application with possibility of update directly to "*Trimble Connect*" CDE. If further modifications are done in TS, drawing documentation can be exported at the end, together with the final IFC model, including 3D rebars elements.

ProSap manages the drawing documentation in advance through the reinforcement parametrization and generation tools. The final model can be exported in 2D drawings and IFC format without including the steel reinforcements.

Quantity estimations.

The analysis conducted for the three Case Studies and four workflows provided that the quantity estimations and Reporting are semi-automated or automatically generated from the software.

Revit - Robot, Revit - SOFiSTiK and Tekla Structures calculate the quantities from the 3D model. "Schedule/Quantities" functionality in Revit, "Inquiry" and "Organizer" in TS, evaluate the quantities accurately based on specific parameters. The reliability of Revit's values depends on the accuracy of the elements modelling. Specific formula may be applied to produce more real values. Instead, ProSap gives initially only indicative quantities, and more accurate ones are obtained only subsequently, after the generation of the reinforcements within the integrated tools. A manual elaboration is required for the update of the final values. Further software and tools can be applied for a more accurate quantity estimation, based on the exported IFC model.

Collaboration and communication.

Reporting depends on the type of workflow being applied. For "*traditional design*" and "*IFC exchange*" you can follow the electronic communication by emails, sending photos, screenshots, doing directs comments, and following approval with the interested Parties. In case of a CDE use, all collaboration and communication should be done and formalized on a common structured platform. Documentations, communications, comments, approvals, and construction planning are shared with all involved Parties, informed in real time for every change and update during all the phases of a project.

Automation of processes.

BIM requires interoperable but also automated processes. This is necessary to improve workflows, reduce working time, reduce costs, and facilitate the planning, design, construction, and management operations. The role of the designer or the structural BIM specialist, is not substitutable. The automation is required to reduce the repeated work, create parametrized models, anticipate future problems, and increase collaboration and communication by reducing errors.

The BIM model requires more time to be build, but once is done, it guarantees a rich database for all future uses. The high accuracy of the physical model assures that the generated detailing and project's documentation are coherent, reliable, and accurate. All workflows were presented with a good automation between the processes, with the higher appreciation for ProSap and TSD/TS workflows.

Workflows comparison from "*traditional design*" to "*IFC exchange*" and "*integrated modelling*".

The Case Study nr.2 showed directly the improvements obtained improving from a "*traditional design*" to an "*IFC exchange*" workflow. Information is not shared within just .pdf or .dwg formats, but it includes IFC standards. Clash detection is not done manually by overlapping 2D designs and late detected on-site issues, but it is checked through BIM coordination tools in federated models. This allows for the different discipline models to have small incongruencies and be more reliable and accurate for the future uses of the model. Reinforcement's detailing is automatically obtained, saving time, and avoiding manual reworking for the Designing Team. Unnecessary additional costs are saved in time.

Project's complexity.

Case study nr.3 dealt with more complexity for the physical and analytical model, with curved shapes, requiring arched beams and rotated columns. The analytical geometries consequently generated eccentricities, automatically calculated from the software. After some time-consuming efforts in the modelling stage, there were no big differences identified for the rest of the design, in comparison to the previous case studies. BIM presents advantages with the increase of the project's size, dealing easily with higher quantity of data and model's complexity.

BIM SDWAM

Following literature research for Project's, Organization's, Individual's, or Market's Assessment Model, a similar one is introduced for the software/workflows involving the structural design. It is shortly named with **BIM SDWAM** ("*BIM Structural Design's Workflow Assessment Model"*) and it is defined with the criteria discussed during the Case Studies. An evaluation scale is applied from 1 (very low maturity), 2 (low), 3 (good), 4 (very good) to 5 (excellent).

The introduced *BIM SDWAM* model from the author, is applied following the summarized discussions from the Case Studies analyzed in the Thesis and the Survey. Comments and results are presented in the following table (see Table 20).

BIM SDWAM Workflow/ Evaluation Criteria (scale 1 to 5)	**Revit /Robot 2021**	**Revit 2021/ SOFiSTiK**	**ProSap Professional v21**	**Tekla Structural Designer/Tekla Structures 2021**
Structural modelling functionalities and capacities in integrated BIM workflows.	(3.5) Good to very good modelling. Limitations in some specific foundation's family modelling.	(3.5) Accurate mapping of materials, sections and loading to SOFiSTiK.	(4) Very good. Time consuming efforts in defining "Alignments"	(3.5) Good to very good. Some limitations in defining the T foundation beams in TSD.
Analytical model configuration.	(3) Good analytical model. Modifiable in separate view. Time consuming operation for checking.	(3.5) Good to very good. Separate tool in SOFiSTiK for the model validation with notifications.	(4) Very good. Easy configuration of the analytical model. Fast modification.	(4) Very good. Visualization of the analytical model and parametrical modification.
Physical model accuracy and reliability.	(4) Very good. Accurate and reliable physical model.	(4) Like Revit/Robot.	(3.5) Good to very good. Reliable. Lower accuracy compared to Revit and TSD.	(4) Very good. Reliable and accurate model.
Structural analysis & design functionalities and capabilities.	(4) Very good. Wide functionalities in Robot.	(3.5) Good to very good. Simple to wide functionalities from integrated tool to SSD	(4) Very good. Wide functionalities.	(4) Very good. Wide functionalities.

Detailing, Drawing Management & Documentation.	(4) Very good. Once configured, drawings are connected and automated.	(4) Like Revit/Robot.	(3.5) Good to very good. Automated drawings through parametrized integrated tools.	(4) Very good. Automated drawing management & documentation. Integration in Trimble CDE.
Quantity and Costs Estimation quality.	(3.5) Good to Very good.	(3.5) Like Revit/Robot.	(3) Good. Manual efforts required for accurate estimations.	(4) Very good. 3D reinforcement detailing. Accurate values in TS.
Automation of processes.	(3) Good. Time consuming processes.	(3.5) Good to very good. Semi-automated to automated processes.	(4) Very good. Mostly automated processes.	(4) Very good. Mostly automated processes.
Interoperability quality in the workflows	(3) Good interoperability. Limitations identified.	(4) Very good. Integrated tool in Revit.	(4.5) Very good to excellent. Add-in tools integrated in one software.	(4) Very good. Import/export operations through .cxl formats.
Coherence, Reliability and Accuracy of the IFC import/exported model.	(3.5) Good to very good. Reliable and accurate. Includes 3D reinforcements.	(3.5) Good to very good. Reliable and accurate. Includes 3D reinforcements.	(3.5) Good to very good. Accurate and reliable. Not including 3D reinforcements.	(4) Very good. Reliable and accurate. Includes 3D reinforcements.
Collaboration and Communication within and outside the workflow.	(4) Very good. Highly guaranteed through different apps and integrated tools, including direct CDE integration.	(4) Like Revit/Robot.	(3.5) Good to very good. Uses within one software. BCF and CDE not directly applicable. IFC friendly.	(4) Very good. "*Change's recognition*" for model's update. Directly updatable to Trimble CDE.
Workflow's improvements towards full BIM adoption	(4) Very good. openBIM software with recognition of native formats from different software and CDE. Tekla Integrator for .cxl exchange.	(4) Very good. Like Revit/Robot. Semi-automated to automated processes.	(3.5) Good to very good IFC import/update /export. Automated processes for detailing & drawing management.	(4) Very good. openBIM software with agreements for different vendors. IFC interoperable. High automation of processes.
Dealing with Project's complexity.	(3.5) Good to very good.	(3.5) Good to very good.	(3.5) Good to very good.	(4) Very good.
Average evaluation.	3.6 (3.58)	3.7 (3.71)	3.7 (3.71)	4 (3.96)

Table 20- Final Table for the Workflows evaluations based on the BIM SDWAM model. [1]

[1] It is advised to the check the Result's Tables for all Case Studies and the Survey for a more comprehensive understanding of the assessment.

The final average values give a parametrical evaluation of the uses for the analyzed Case Studies including the Survey’s results.

The BIM SDWAM presented in this Thesis, results quite interesting and opens new prospective to BIM maturity assessment models built for the specific design disciplines, like the structural one, and to more regulated and standardized maturity evaluations for the design’s and information modelling’s software and workflows.

6. APPENDICES.

Appendix 1 – Historical BIM.

In this appendix are presented some further information for the beginnings and developments in BIM.

The second Eastman's project in 1977, was named GLIDE ("*Graphical Language for Interactive Design"*) and it was developed at the Carnegie-Mellon University (ANDERSEN, 2016). It will state most of the today's modern BIM base features. The information databases are defined together with the design physical systems at a higher level of detail. GLIDE provided a digital representation with integrated information for the design & constructions phases of a building. It included graphical information (*with an unstructured set of planar or curved faces*), solid polyhedral bodies with volume containing surfaces and the model's information enriched with data such as materials, dimensions, rigidity, weight etc. (Eastman and Henrion, 1977)

In the 80′s, several systems like GDS, RUCAPS etc. were developed and started to be applied to real cases. RUCAPS was created in 1986, with special features of temporal phasing for the construction processes. It was first used in the realization of Heathrow Airport's Terminal 3. Later in 1988, was founded the Centre for Integrated Facility Engineering (CIFE) at Stanford by P. Teicholz. It focused more to the 4D aspects of building models. BIM, from this moment will follow two different trends, one in the development of specialized tools for the different disciplines involved and the other one in the testing of the digital models based on performance requirements. (Quirk, 2012)

Even the early development in the United States, it will be in the Soviet Block, where Gábor Bojár in 1982 and later Irwin Jungreis and Leonid Raiz, will first define the two BIM technologies: ArchiCAD and Revit. Initially, Bojàr will struggle with a not friendly business climate and limitations for computational resources but later ArchiCAD will exponentially grow with millions of worldwide project realizations. Instead, Irwin Jungreis and Leonid Raiz, after several releases, will develop the "*Revit*" program, meaning "revision & speed". It was written in C++, with a parametric object-oriented programming approach (Tammik, 2012). AutoDesk will purchase later Revit in 2002. It will become soon synonymous of BIM itself. With the use of parametric families, Revit will further enhance BIM applications with scheduling options & visual programming. Autodesk will buy later NavisWork in 2007, develop several mobile applications and very soon place itself as a leader of software products and services in the AEC industry. (AutoDesk, 2021)

The next important moment of growth in BIM and especially in the collaboration between the different disciplines, is when the architectural design of a building is going to be integrated to the engineering one. This is a shift from the traditional building design to the integrated project delivery, where different disciplines are integrated in central BIM models. All actors involved work collaboratively from the early stages of design, they have personalized accesses to a common data environment, check and make use of a building at the same time. Authorship can be guaranteed by acknowledging ownership and giving authorizations for modifications only to the respective discipline. (AIA, 2007)

Difficulties for interoperability came out when different software were used from the users. It will be necessary to develop a common bridge for information exchange with less manual intervention. The creation of the "*International Foundation Class*" (IFC) formats developed in 1995, will solve this crucial raising problem in collaboration. This will be possible from the buildingSMART[1], or as initially called the IAI – "*International Alliance for Interoperability*". IFCs are universally open formats, not controlled from any vendor, created to facilitate collaboration in the AEC industry. They are a registered format of the ISO – "*International Standard Organization*", with the ISO 16739-1:2018. The IFC/IFCXML format versions have been continuously updated from the first ones in 1996 v1.0 to the last v.4.2 (2019). (ANDERSEN, 2016) (buildingSMART, 2021)

BIM CDE allows (like BIM 360 in Revit) for architects, engineers, constructors & facility managers, to work contemporary in a project. They can create and coordinate the models they build, make orders, and proceed with construction works, making use of a common digital proprietary platform. This approach supports the early involvement for all participants from the planning & design phase and during the whole life cycle of a facility. In such way, it is possible to increase the productivity, efficiency and to reduce costs & time. (Fu, 2018)

Integration of programming and sectorial disciplines in the AEC industry have resulted a key factor for the BIM development. Eastman as one of the BIM pioneers, had an academic preparation in both fields of architecture and programming. Several BIM platforms have been developed from programmers in collaboration with the specific professionals from the different AEC disciplines. Parametrics and computational design are becoming a must if you want to compete in a contemporary avant-garde scene. The industry had started to realize only in the last decades the potentials from BIM. (Quirk, 2012)

Appendix 2 – Definitions and recent developments.

In this appendix are presented some detailed definitions and recent developments in BIM.

The British Standard Institute defines BIM as "*the process of design, construction and use of buildings or infrastructure*", making use of digital models for information processing. According to ISO 19650 - 1: 2018, BIM should provide better specifications and delivery with the right "*information concerning design, construction and management of buildings and infrastructure"*, making use of appropriate technologies. It goes through the whole life cycle, "*including construction, refurbishment, operation and dismantling*". (ISO, 2018)

An integrated production process for a building or an infrastructure, consist in the following steps: "*Design*" – "*Planning*" – "*Manage*" – "*Construction*" – "*Operation*" (Caputi and Ferrari, 2014). BIM includes *not only the 3D model, but also the management of the project*.

A BIM model includes the geometry, the spatial coordination and references with geolocations, dimensions and quantity of the elements, properties, costs, and scheduling of a project. A full model enriched with non-graphical information, can automatically generate all designs with data you need for

[1] buildingSMART is the world leader driving the digital transformation of the built assets. It is an open, neutral, and international non-profit organization. It has as focus delivering open and international standards for buildings and infrastructures. Started in 1994 as a consortium of 12 companies, was initially named as the "International Alliance for Interoperability" and later just buildingSMART. Today it is a worldwide organization, counting several chapters in the most industrialized countries of the world. (buildingSMART, 2021)

the construction and operation of a facility, like the construction drawings, plans, facades, sections, details, automatic reports, 4D timelines, 5D costs estimation, 6D sustainability evaluations and others related. (Azhar, 2011)

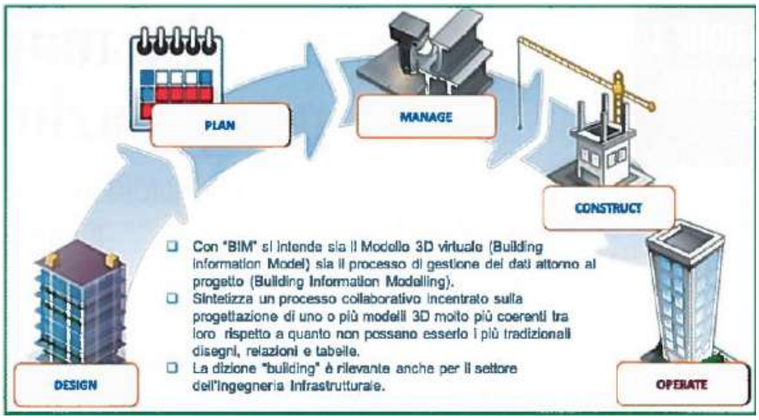


Fig. 119-Stages of the Integrated Process for the building or infrastructure production and management (Caputi and Ferrari, 2014)

BIM applications & research publications are shown to have increased during time, with higher technological developments with bigger focus in an integrated approach for design, construction, and facility management. Starting from 2012, it has been identified from (Wen et al., 2021) in a detailed bibliometrics analysis of "*Web of Science*" databases, a raise in *BIM-related publications*. Starting from 2012 with less than 100 publications, were identified in 2016 more than 140 publications in a year and around 300 in 2019. An exponential growth is readable in the graph's results with an increase of around 7859 % from 2010 to 2019 and 291% only from 2016 to 2019. (*see Fig. 120*)

The study continues by analyzing the countries with higher publications, co-citations and journals publishing BIM related works.

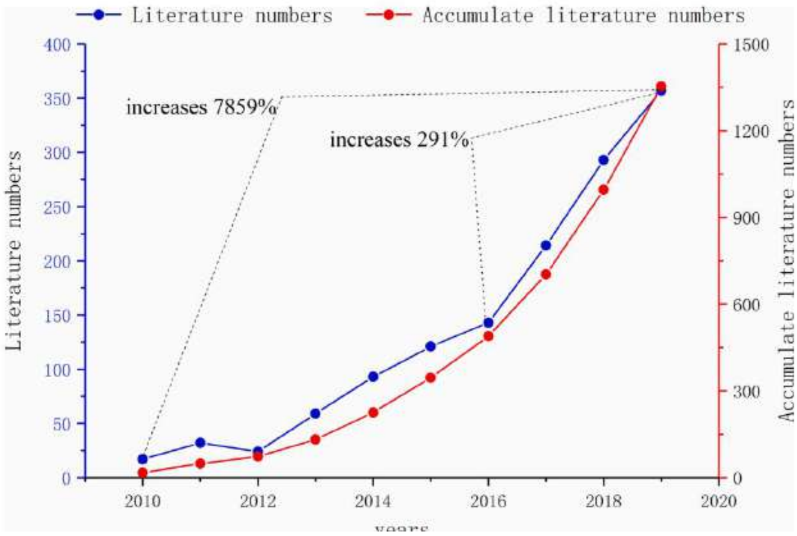


Fig. 120-Number of BIM-related publications from 2010 to 2019 (Wen et al., 2021)

Connecting the model’s designs with relational databases has been demonstrated to be a high value operation. Object based design and parametric manipulation generate lower redundancy of construction objects represented at several scales. Paper use is not supported in BIM, it can lose quality and does not produce models for facilitating renovations in the future. (Quirk, 2012)

BIM improves efficiency, reducing waste and enhances the quality of buildings. Applying traditional approaches there is a loss of information from one step to another, due to the process and technology applied. BIM allows to have a continuous flow of information. In a digital era, automation is higher, processes tend to be digitalized and all decisions driven from data. We are under a “*Fourth Industrial Revolution*” era. (Schwab, 2015)

IPD – “*Integrated Project Delivery*”, is a common practice supported in BIM. It consists in bringing together people, systems, and practices from the first phases of a project, optimizing resources, and raising collaboration through all phases of a project. (AIA, 2007)

MEP systems can be integrated in rich data BIM models. Operation and maintenance are facilitated by faster and well evaluated decision-making, allowing inclusive maintenance and renovations. BIM technologies are innovative, they optimize design management increasing productivity and design quality. All the graphical and non-graphical information that will be produced can be standardized in advance at the beginning of the project. (MagiCAD, 2019) The BIM modelling of MEP equipment and installations allows to have better prediction of installations during construction, to detect in time clashes with the structural and architectural model, and to have 3D visualizations of the federated model.

The integrated construction process simplifies the efficient transition from design to construction within the BIM model, and from construction to operation with the (COBie) – “*Construction for Operation Building information exchange*”. (COBie) is a standard to guarantee this phase of exchange management for the asset information model, for spaces, equipment, operation, and maintenance. Applying (COBie), you support the Owners or Contractors to have full information for the facilities, during the whole life cycle. (Caputi and Ferrari, 2014)

Applying BIM, you have higher productivity and better efficiency, more value and quality of the building, increased sustainability, facilitation to implementation, information sharing, construction and operation costs reduction, and faster processes. Several surveys have been identified that when BIM is not used during all phases of a project, you are losing some of its advantages. Design phase counts for higher use, following detailed design and procurement, construction, maintenance, and operation phases. (Doumbouya et al., 2016)

BIM allows to explore more design options at a shorter time, with more information for the evaluation. This permits to optimize design for all architectural and engineering designs. Information is included within a 3D model giving higher possibility of decision making based on accurate information. Engineering calculations for some building systems can be evaluated faster. Construction works scheduling and costs evaluations are automated from an accurate model. Procurement can be directly involved in the BIM workflows and connected to the model.

Appendix 3 - Real case studies.

The following applications have been casually selected from the research analysis (Azhar, 2011) (Czmoch and Pękala, 2014) (DODGE, 2016) (AutoDesk, 2017) *and reported in the identification of BIM adoption uses and potentials into some real case studies.*

- **Office Complex in Warsaw**, realized with BIM approach, consisted in 30.000 m^2 construction for office areas. The building was certified with BREAM certification. For the design have been working a few designers, with BIM experience only for the 3 Team Leaders. (Azhar, 2011)

  - Design resulted 10% faster and 80% more accurate.
  - Two Revit based models, one for the MEP and the other for the Architecture/Structure.
  - Navisworks for clash detections. No collisions identified during construction.
  - Collaboration based on a server-based model updatable from the local ones periodically.
  - During construction works, both uses in paper documentation (*required from Polish laws*) and BIM model (*good for MEP installations*).
  - A few re-designs were required. It paid back with savings in quantity estimations and material's ordering. Making use of BIM, it was possible to reduce more than 30% the required time in preparing designs and documentation reporting.

- **40-story "Morpheus Hotel" - Macau's City of Dreams Complex.** (Czmoch and Pękala, 2014)

The new building in Macau was designed from *Zaha Hadid* as a unique block, wrapped with a steel and glass lattice shell. *BuroHappold Engineering* was responsible for the structural design, detailing and delivering of the shop drawings for the building's exoskeleton. The structure had to resist to typhoons that are common in the region. The aluminum cladding limited the possibility to locate the connections.

BIM uses involved 3D visualizations, elements fabrication and installation. The Team could focus in finding the best engineering solution, instead of manually designing repetitive detailing. The project could be delivered at a high quality, with enhanced coordination between the construction Teams.

Fig. 121-40 story Morpheus Hotel – fifth tower, Macau's City of Dreams Complex (Google)

- **Aquarium Hilton Garden Inn.** (Azhar, 2011)

The *Aquarium Hilton Garden Inn* was a *46 million$* investment for *45.000 m^2* mixed uses. The BIM applications included: *designs coordination, clash detection and scheduling*.

The initial BIM investment was about *90.000$*, with *40.000$* paid from the Owner. There were identified more than *200.000$* of costs and *1.000 working hours* in savings. The different disciplines were modelled separately with clash detections applied from the General Contractor. The traditional approach was evaluated to identify 75% of clashes, and the BIM tools could fully explore the remaining ones. BIM facilitated the as-built model uses for the operation phases.

- **Savannah State University.** (Czmoch and Pękala, 2014)

BIM was applied in the design phase for the evaluation of the different design's options, with 3D visualizations and accurate costs estimations. Just a few investments for BIM adoption allowed to more than 2 million $ evaluated costs savings. The Owner could *make fast, informed, and definitive early decisions* about the project.

- **Mansion in Peachtree, Atlanta, Georgia.** (Czmoch and Pękala, 2014)

This project involved a cost of around 110 million $, with the BIM use mainly focused on the construction management. High costs savings were identified compared to the initial BIM investments.

Application involved construction design, better coordination between Consultants, problem solutions for Site and fast update following Owners changes. Shop drawings were automatically extracted from the BIM models. Clashes were identified through models and Scheduling prepared in advance.

- **The Guilin Liangjiang International Airport Terminal 2.** (AutoDesk, 2017)

The new terminal consisted in an area of 100.000 m^2, with 24 gates, three floors upper ground and one underground. Elements were fabricated off site and assembled according to detailed planning. Accurate design was required, to avoid errors, extra costs, and delays. AutoDesk Advance Steel was exploited and resulted to handle well curved elements design and detailing.

Advance Steel was applied with bidirectional information exchange with AutoDesk Revit. The 4D scheduling supported the construction team to have a clear view for works sequencing. Bill of quantities and estimations were automatically generated. This project comes as an example of how BIM software and workflows can deal with complex geometries, producing faster and more accurate design.

Fig. 122-Guiling Liangjiang International Airport Terminal 2 project (AutoDesk, 2017)

Appendix 4 - BIM Maturity Assessment Models.

In this appendix are presented some further descriptions in BIM Maturity Assessment Models.

The BIM Maturity Assessment Models are applied to better evaluate the BIM adoption maturity related to a Project, Organization, Individual or Market. They help to understand better the designs processes.

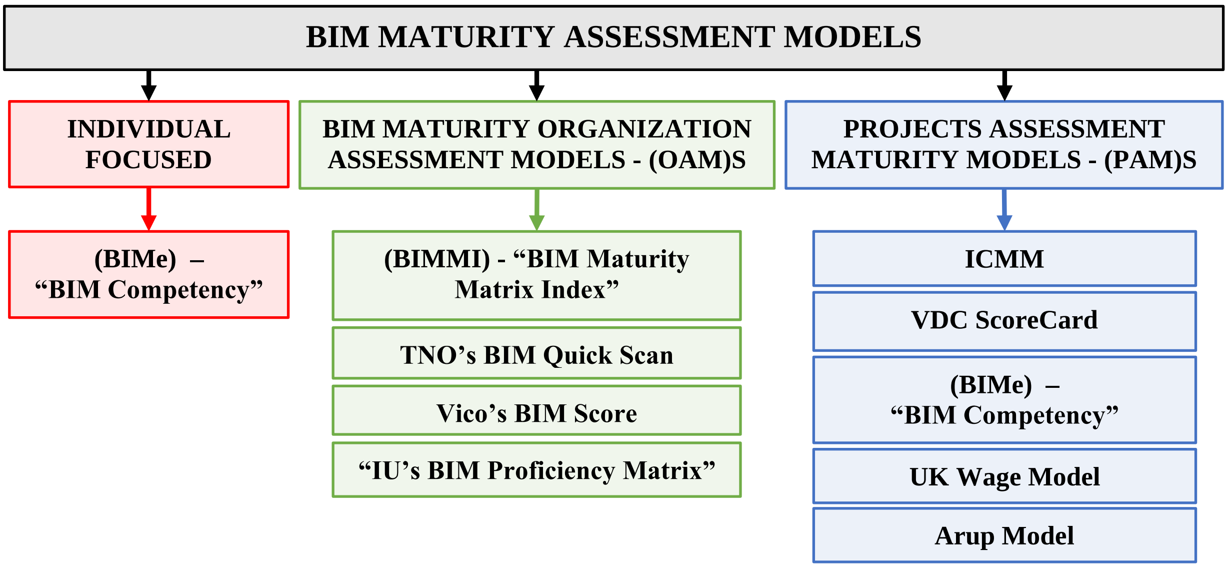


Table 21-BIM Maturity assessment models (Dakhil, 2017)

The BIM Maturity Index (BIMMI) developed from (Succar, 2010), defines the minimum BIM abilities and deliverables in companies. The evaluation is done on a five-level scale starting from "*initial*", "*defined*", "*managed*", "*integrated*", to "*optimized*". Based on the core framework for technologies, policies and processes, the Index defines the "*capability*" and "*maturity*" of Organizations in the implementation of BIM processes. "*Capability*" is defined as the ability to "*perform a task or deliver a BIM service*".

VICO's offers a BIM Scorecard, to evaluate BIM maturity for Organizations. It is mainly focused on clash detection identification, time's scheduling, quantity, and costs estimation. The evaluation is done based on the Organization's capability, best achievements, and processes integration. The VICO's Scorecard includes a four levels evaluation for Planning (Objective, Standards and Preparation), Adoption (Organization and Processes), Technology (Maturity, Coverage, and Integration) and Performance (Quantity and Quality).

The **TNO's BIM QuickScan** has been developed from the TNO's Netherlands Institution. It consists in some organization's management evaluations, divided into ten subcategories: *strategic issues, organization management and capacities, resources available, partners in collaboration, mentality of the firm, working culture, education level, information flow between the different actors, open processes, technologies, and applications*. The maturity assessment is done based on a "*graph*", where all the key elements are evaluated through some point scales. The *Maturity Assessment Evaluations* are done to distinguish the BIM adoption level between the different Organizations.

The **(IU)'s Indiana University's BIM Proficiency Assessment** developed in 2009, follows a matrix schema evaluation, based on eight categories crossing four maturity's areas. The columns or categories through which the evaluation is done consist in *a. Model's accuracy, b. Integrated Project Delivery Applications, c. Calculations, d. Location, e. Contents, f. Level of construction's information, g. Executive or As-built LOD 500 modelling and h. Facility Management Data.* The matrix rows include: *1.Modelling, 2.Design's Requirements, 3.Clash Detections, 4.Accuracy*.

Succar's Model.

Succar's model defines BIM, as previously explained, mainly as an integration of *technologies, processes, and policies*. "*BIM fields*" and "*BIM stages*" are part of the Succar's BIM Maturity Matrix Model in BIM adoption (Succar, 2010).

BIM technologies.

BIM adoption could not be possible without digitalization. In "*BIM technology*" can be considered all technological issues related to the uses of software, hardware, and networking services. Software includes a wide range of BIM authoring tools applied for the delivering of BIM products, like Revit, ArchiCAD Graphisoft, AllPlan, Tekla, ACCA, SOFiSTiK, ProSap Professional 2SI etc. Technologies involves all hardware used for the BIM implementation: computers, site survey equipment like laser scanning, terrestrial or aerial, site management tools, digital twins' developments [1] or Facility Management technologies (M. Caputi, 2021). The CDE platforms allow architects, engineers, owners, facility managers and constructors to work together and be always updated within a central BIM database. The CDE becomes "*the only single source of truth*", to collect, manage and distribute information for the whole team (BIMWiki, 2021). It is a combination of technical solutions and process workflows. Global providers for CDE are like Aconex-Oracle, Bexel Manager, Revit-BIM 360, Trimble Connect CDE etc.

BIM processes.

Processes are defined from Cambridge Dictionaries (Cambridge, 2021), as "*a series of actions that you take to achieve a result*". They are chronological sequential activities including people, materials, and technologies. The processes involve stakeholders starting from planning, procurement, design, constructing, facility management to dismantling and recycling. BIM Dictionary (BIMe, 2019b) [2], formulates the "*BIM process*" as a generic description including hierarchical workflows & repeatable procedures with clarified granularity steps, tools & techniques, with the main goal to achieve "*BIM deliverables*" [3].

By defining processes, we can state the "*AS-IS*" and "*TO-BE*" processes, to improve quality, efficiency, and in general the productivity, as defined from BPR – "*Business Process Re-engineering*". According

[1] "Digital Twins" have been identified with many definitions, and typically described "*as the virtual counterpart of a physical entity*", with the main goal to life-cycle management. They consist in a physical product, a virtual one and in bi-directional data exchange between them. (Jones et al., 2020)

[2] BIM Dictionary is a free and open-source database created from BIMe Initiative (https://bimexcellence.org/), based on voluntary contributors & sponsors.

[3] "BIM deliverables" include all type of deliverables expected from BIM based projects, processes & tools.

to *Sherwood-Smith*, BPR can be applied to re-design processes, to eliminate waste and improve efficiency, by exploring new ways in the organization of people and activities, with focus to digitalization (Chen, 2001). BPR is "*a business management strategy*", concepted 30 years ago, with the focus to re-think business processes, generating better workflows. The general goal is to improve the services and products offered from organizations, by reducing costs and making them more competitive in the market (GAO, 1997), (Wikipedia, 2020).

BIM policies.

Policies include all the "*principles and rules*", which have as focus to regulate the AEC market and the relations between the different stakeholders. Policies may be supportive, advisory, or obligatory depending on the institutions defining them. They are written from Educational Centers, Public Entities, Research Institutions, or other specialized bodies. For example, in UK, the "*Government Construction Strategy (July 2012)*" defined that starting from 2016, it is mandatory, to apply a "*fully 3D collaborative BIM*" for all central government funded projects. (Cherkaoui, 2017)(CabinetOffice, 2012)

BIM stages.

In "*BIM Stages*", the *pre-BIM* situation is the first stage, where standard conventional design with no BIM is applied, design & construction follows a traditional approach with 2D designs, separate reporting, low collaboration, missing of interoperability, laborious modifications re-works, no clash detections and so on. The next stages follow with the "*object-based modelling*", "*model-based collaboration*", "*network-based integration*" and finally with the "*Integrated Project Delivery (IPD)*".

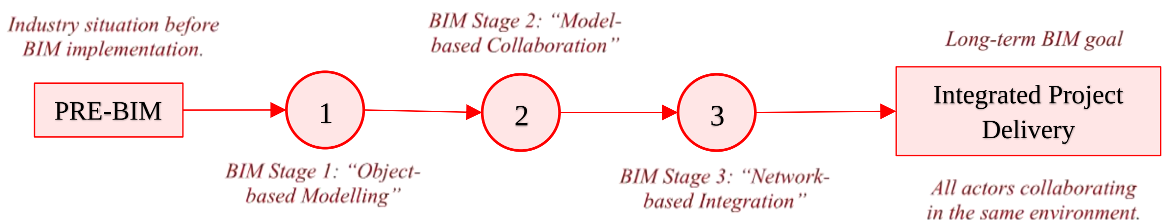


Fig. 123-Linear "BIM stages" (Succar, 2009)

(Succar, 2009) presents a structured view of the different scenarios where we can see the transition of organizations, projects, or industry through BIM adoption. The moment for which a "*jump*" is identified in the BIM adoption towards capability stage nr.1 ("*object-based modelling*"), is called "*Point of Adoption*" (*PoA*) (Succar and Kassem, 2016).

From this moment, you must apply BIM software for modelling, staff's training, make use of new technologies and BIM friendly processes. There is still no collaboration and integration between the different disciplines, and the maturity level is identified at an "*initial level*".

Implementing further technologies and improved workflows, the next (*PoA*)s will be reached in the capability stages of "*collaboration*" and "*integration*".

Appendix 5 - BIM adoption potentials.

In this appendix are given some further descriptions in BIM adoption potentials and benefits.

BIM's dimensions are some structured views to distinguish the different scales of BIM adoption. Starting from **BIM 3D** you have a 3D parametric model enriched with data. Continuing with **4D BIM**, it includes the time's scheduling. Dividing the project into different phases, creates simulations for work's scheduling and accurate planning for the material's ordering and construction works. **BIM 5D** is the costs estimation, with labor's evaluation and delivery. It allows to compare costs interventions between the different design's options. **BIM 6D** involves sustainability issues in the evaluation of environmental impact and energy consumption (.gbxml formats). Models can be used to make LEED's standard evaluation. **BIM 7D** is the facility management application, with enriched database for every building element. All specifications are relevant to maintenances or renovations, allowing fast interventions. (BIMA+, 2021)

BIM results **in higher efficacity** for a facility, during its whole life cycle. It produces an exhaustive database and data rich models, facilitating **early decisions for all the stakeholders** involved in the process. The digital model includes all the **physical and functional information** of design for simulations, supporting collaboration. "***Day to day"*** **real data** supports the Facility Managers to make better decisions for the operation and maintenance of the building or the infrastructure. (Caputi and Ferrari, 2014)

BIM skeptics can say that you can do great works just with Excel, and indeed BIM is not made to replace it, but to **automate the "*collection of information from a model*"**. BIM automates the material quantities with information like typology; quantities like volume, area, weights, or lengths; manufacturer data, Classification Standards, and specified property data from User. The amount of reinforcing for concrete is automatically updated when you make changes to the model. Cost's estimations are more accurate, based on precise modeling, construction joint solutions, additional information like man-hours working, list prices etc. Scheduling and sequence of planned tasks can be done automatically from the model based on "*relational logics*" given at the beginning from the Designer (BIMCorner, 2019) (BIMA+, 2021). BIM helps to reduce or eliminate not necessary rework in case of design changes or updates. (DODGE, 2016)

Traditional 2D design may seem to be faster than BIM, but with the raising of complexity, it becomes a time-consuming process to make modifications to the drawing documentation, compared to processes involving a BIM model. Parametric design allows rapid changes to the building elements with faster shop drawing generations and updates. (SOTHAM, 2018)

Costs are maintained under control during all the life-cycle phases of a building, including materials ordering, construction works, energy analysis, maintenance and renovation works. **BIM reduces unpredicted works to happen** during the whole life cycle of a building. The BIM model reliability and accuracy are tested several times during the design and construction phases. (HMC, 2020)

BIM creates **facilitations for the construction works**. Communication is enhanced from the first stages making easy to implement activities through digital 3D models. All actors are informed on time through digital mobile applications. Material's ordering is automated, and all work's activities are continuously monitored. Most of activities are planned in the design phases, **so delays and errors are reduced** during the construction works. (BIM360, 2017) (Azhar, 2011)

Clash detection between the different disciplines **can automatically** verify collisions and generate reports. Design may need to be modified, producing changes also to material's ordering and construction scheduling. BIM Coordination tools (like Bexel Managers, NavisWork etc.), allow to identify these issues with efficiency and efficacy. (Bryde et al., 2013)

BIM is evaluated with **savings for the (FM) facility managements**. The benefits are high compared to the initial costs that the BIM adoption may require (Smith and Tardiff, 2009). Storing graphical and non-graphical information data, during all the stages of a project allows to have **an exhaustive virtual model** for the operation phases. (BIMCorner, 2019).

The CAFM Systems – "*Computer Aided Facility Management*" allow operators to direct management and planned maintenance. The CAFM Systems should be built in integration with BIM models, to guarantee efficiency in the decisional processes. The integrated approach allows better planning with digital databases for the real estate and data rich reports for the operation of the facility. (Caputi and Ferrari, 2014)

Communication and collaboration are enhanced. A good cooperation between the Team's participants is relevant to the project's success. Integrated BIM is concepted to assure collaboration within a central model, with owners, designers, construction managers and facility management collaborators working together in a cloud based CDE. Personalized accesses give authorizations to visualize, modify, update, coordinate, and approve the documentation of the central BIM model during the different phases of the project. (M. Caputi, 2021)

Intelligent buildings. Digital models offer integrated information for the uses of a buildings. Applying sensors can be detected issues for the MEP systems, moisture, and in general building's real time data. This is possible by connecting the (BMS) *Building Management Systems* with the BIM models. Better relationships are created between Owners, Contractors and Maintenance in the problem's analysis and solution during the operation phases. (MagiCAD, 2019)

Rendering and virtual building experience. Virtual walks in the model and 3D visualizations allow to create a better idea of the future facility. Owners are not used to understand detailed designs. 3D views are easier for everyone to better understand a project. A good rendering helps to win a project or a contract. (BIMCorner, 2019)

Sustainability. Making use of BIM, it is possible to make more accurate calculations and to better define materials, processes and reduce materials waste. This creates lower **environmental impacts**, reduces carbon emissions, and allows sustainability certification such as LEED. (BIMA+, 2021)

Prefabrication is facilitated applying the BIM methodology. **Parametrization** supports a dynamic and standardized modelling with higher quality. (SOTHAM, 2018) Productivity is raised by generating faster shop drawings and creating databases for manufacturing. Offsite processes allow to respect the environment, with less waste and higher efficiency.

The Construction Industry has been always slow and behind the other Sectors in adopting new technologies. Offering a better product, you are **more competitive** in the market. Sometime the cheaper price for a design can be a winning approach for a contract, but this is not always the case. For a developed or regulated market, the "**Best Value**" can result as a better choice for Contractors to guarantee the *overall cheaper solution*. In assigning the Winner of a Procurement Contract, in some countries are being more applied combined criteria including the added value, risk assessment, staff's competences and at the end the lower economic value (25% of total points evaluation). (BIMCorner, 2019) (Doumbouya et al., 2016)

Onsite coordination for **materials ordering**, **installation** and in general **construction works** are better managed with the BIM methodology. General Contractors (GC) and Construction Manager (CM) based on the (DODGE, 2016)'s survey, agreed that BIM produces a higher benefit for *Site Management*. Waste and reworks are reduced with higher productivity.

(Franz and Messner, 2019) following data from 200 projects have analyzed the questions raised in BIM adoption for project's performance, costs, scheduling, quality, and the role of (BEP) – BIM Execution Plan. Applying some regression analysis, were concluded some positive feedbacks in faster delivery, better quality, and higher collaboration. Preparing the (BEP) – BIM Execution Plan, it was identified to generate positive impacts for a better BIM adoption in a project.

Appendix 6 - Business process re-engineering.

BPR - "*Business Process Re-engineering*" can be applied to improve workflows from a "*traditional design*" to "*IFC exchange*", towards "*integrated modelling*". A simple schema in the application of the BPR is given in the Fig. 124.

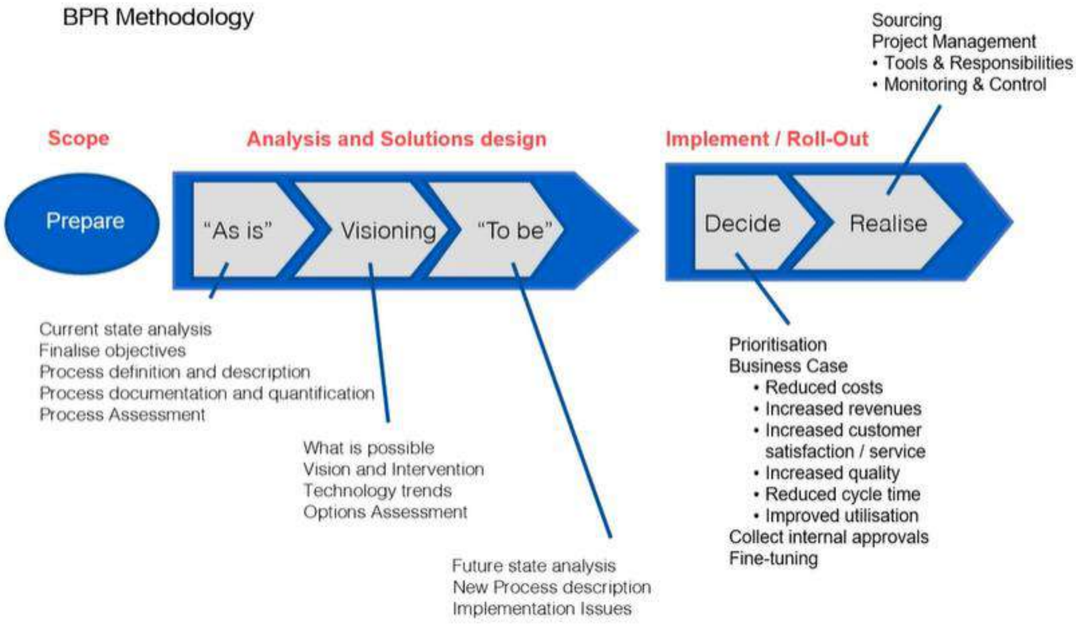


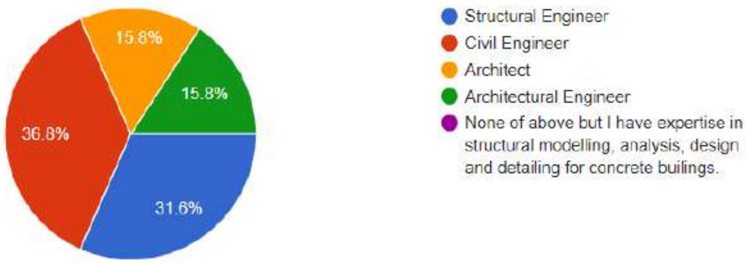
Fig. 124-Business Process Re-engineering (Caputi, 2021)

The visioning of the BIM adoption processes involves the application of improvements in the projects or organization workflows, starting from the "*AS-IS*" situation towards the "*TO-BE*" one. Some activities involving the re-engineering processes are presented below and generally detailed in *Section 3.3-Workflows.*

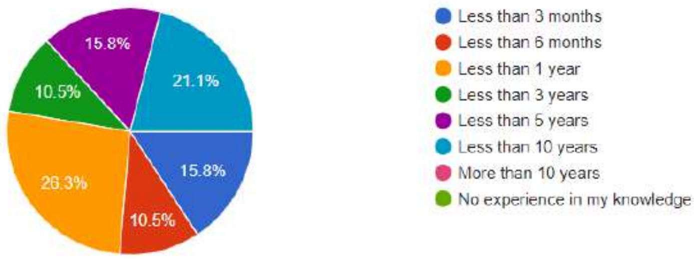
- *Owners* or *General Contractors* decide to make use of BIM in their projects. *Design Teams,* from *architects*, start to use BIM for creating 3D models. *Engineer*s explore *different solutions* and *evaluate different designs options*.
- *The communication and collaboration* are analyzed to be improved by making use of digital technologies with record keeping of documentation, versioning, approvals etc.
- Instead of applying just 2D drawings for information exchange *an IFC interoperable format will be used*, and different discipline models will be integrated into federated models.
- Structural BIM modelers (other disciplines too) will make use of *openBIM software and workflows* for the modelling and designing phases of the project.
- *Incremental LOD definition models are produced* for the structural design, starting from preliminary LOD 200, to detailed, ready for construction LOD 400 and final as-built LOD 500 models.
- The structural model is *designed from the Design Teams*, then later coordinated with the other disciplines from the *BIM Coordinator* (assigned from General Contractor) and approved from the *BIM Manager* (assigned from Client and Supervisor).
- Interoperable model formats, drawing documentation, calculation reporting, quantity and costs estimations are *produced and shared between the Parties.*
- The use of BIM friendly software *allows automation of detailing* with quantity estimations. *Project's costs can be evaluated at the early phases of design,* facilitating the choice of an optimal design. The Client is provided with accurate predictions, allowing to keep under control the costs of the project, without having unforeseen changes during construction.
- *Clash detection* is applied with the support of BIM Coordination tools after the federation of the different discipline models.
- The improvement of the workflow towards BIM adoption follows in a *reduction of paper use* for the project's communications.
- In the final workflow of "*integrated modelling*", all information will be produced and shared within a *CDE*. Design Teams, Owners, Constructors, General Contractor, Supervisors, BIM Coordinator and Managers *will access a cloud-based software*, following different discipline authorizations.
- *Contractors and Construction firms* can build following the built BIM models, with the possibility of applying fast project's updates and adjustments if necessary.
- After construction, will be *possible to handover the models* to the *owners or the facility managers*, for the *operation and maintenance phases*. Mechanical systems can be *handled easily,* and *possible renovations* applied making use of the *data rich models*.

Appendix 7 - Survey's results.

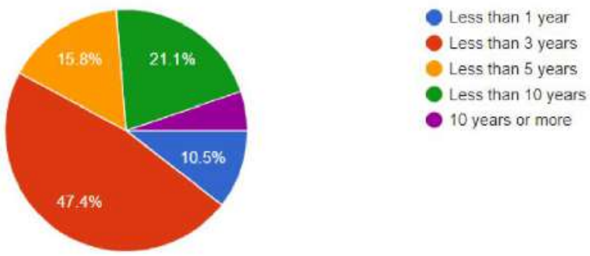
Profession



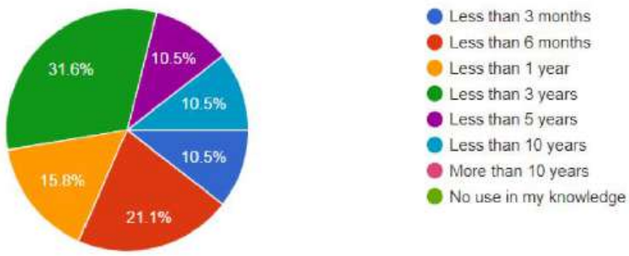
I have followed academic programs, frequented professional postgraduate courses or have practical experience in BIM methodology and applications . The accumulated experience in time is:



I have the following years of experience or expertise in practicing structural modelling, analysis, design and detailing for concrete buildings:

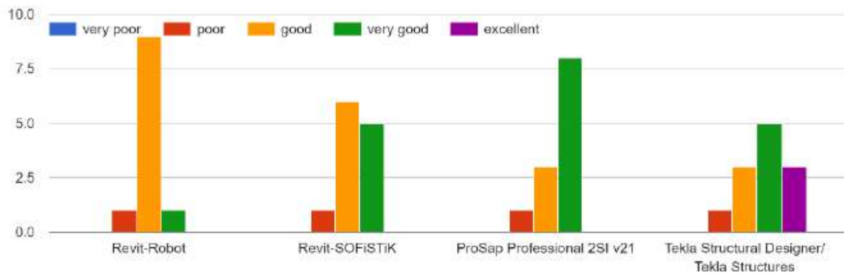


I have been making use of BIM workflows or openBIM software for the structural design for the following time:

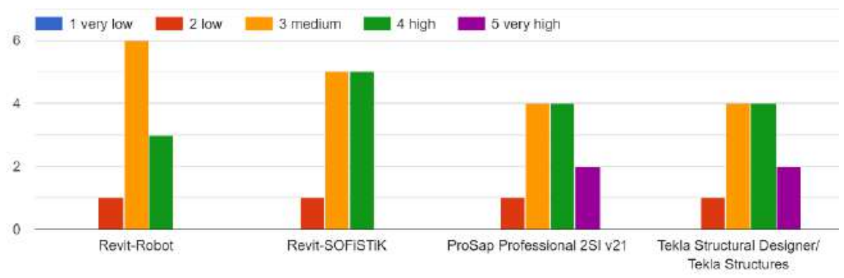


I have expertise in being part of the following workflow/ software

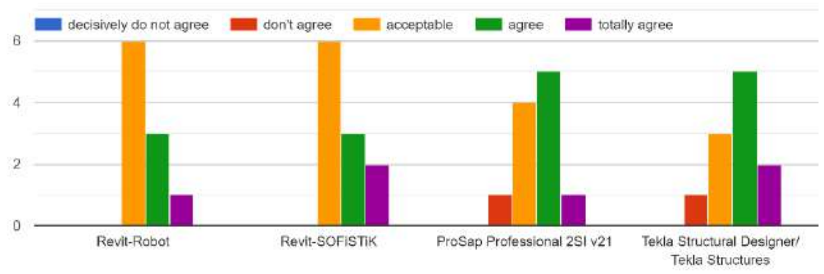
I give the following evaluation for the high potential in being well integrated in BIM workflows and offering advanced functionalities and wide capacities for structural modelling.



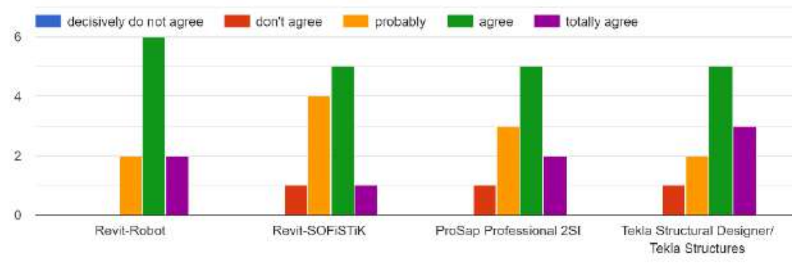
My evaluation in a scale from 1 (low) to 5 (max), for the structural analytical model configuration, necessity of modification and automation in the following workflow/software, is:



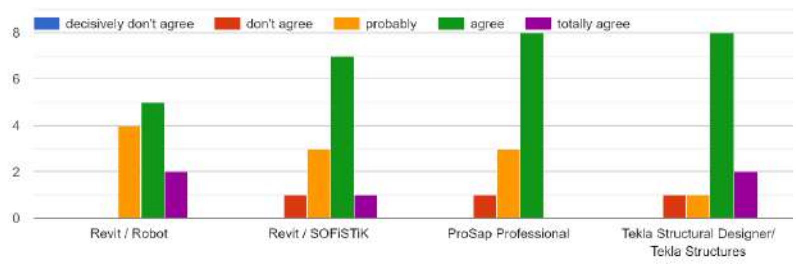
My evaluation in a scale from 1 (low) to 5 (max) for the structural physical modelling reliability and accuracy, in the following workflow/software, is:



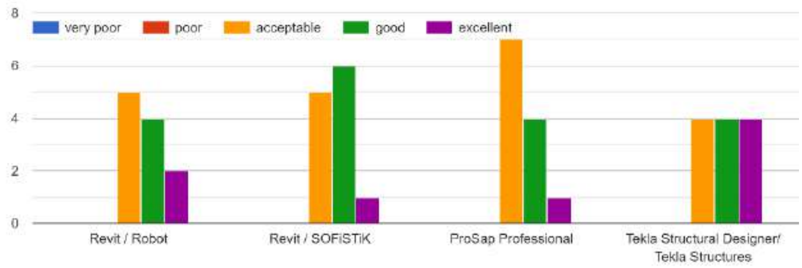
The following workflow/software have advanced functionalities and capabilities for the analysis & design process.



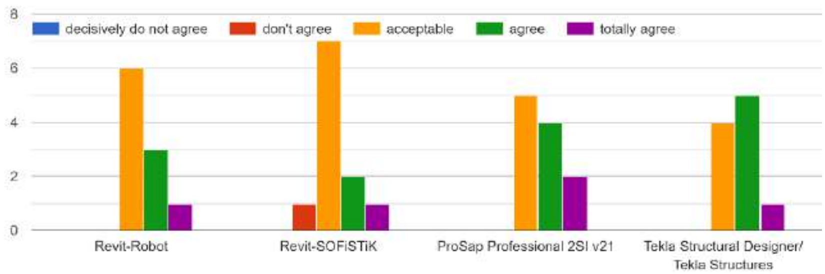
In my experience the following workflow/software have high potentials and capabilities in the automation of general drawing documentation and reinforcement detailing:



In my experience the following workflow/software has this level of information quality in the generation of quantity estimations and construction time scheduling:

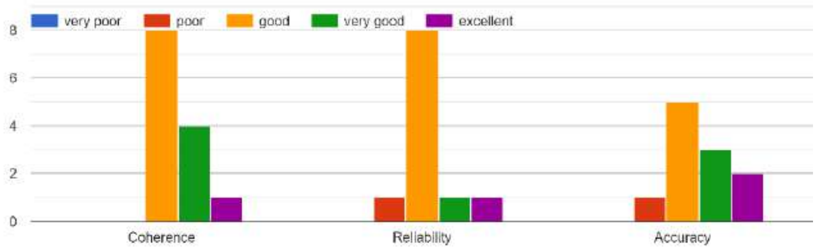


I think, in general most of the processes in the mentioned software/workflow are highly automatized with small manual efforts for intervention between the different steps.

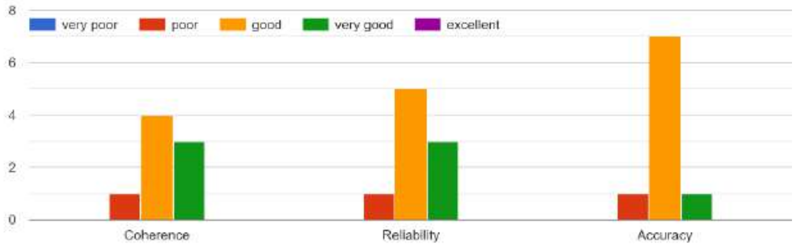


I think the interoperability between the software for each workflow is:

Revit/Robot IFC(Industry Foundation Classes) import/export structural model coherence, reliability and accuracy is:



ProSap Professional 2SI , IFC(Industry Foundation Classes) import/export structural model coherence, reliability and accuracy is:



Tekla Structural Designer/Tekla Structures , IFC(Industry Foundation Classes) import/export structural model coherence, reliability and accuracy is:

7. LIST OF ACRONYMS AND ABBREVIATIONS.

They are to be listed transparently, logically separated, in column (tabular) form. Acronyms / abbreviations / translations that are not in the public domain should be indicated. Acronyms / abbreviations / translations in the list are to be listed in alphabetical order. Acronyms and abbreviations are to be indicated in the List of Acronyms and Abbreviations.

AECO	Architecture, Engineering, Construction and Operation Industry
AIA	American Institute of Architects
AIR	Asset Information Requirement
BEP	BIM Execution Plan
BCF	BIM Collaboration Format
BDS	Building Description System
BIM	Building Information Modelling
BIM SDWAM	BIM Structural Design's Workflow Assessment Model
BMS	Building Management Systems
BPR	Business Process Re-engineering
CAFM	Computer Aided Facility Management
COBie	Construction Operations Building information exchange
CDE	Common Data Environment
FEA	Finite Element Analysis
FEM	Finite Element Method
FM	Facility Management
EIR	Exchange Information Requirement
IAI	International Alliance for Interoperability
ICI	Individual Competency Index.
IFC	Industry Foundation Class
IPD	Integrated Project Delivery
ISO	International Standard Organization
LEED	Leadership in Energy and Environmental Design
MEP	Mechanical, Electrical and Plumbing
OICE	Associazione delle organizzazioni di ingegneria, di architettura, e di consulenza tecnico-economica
OAM	BIM Maturity Organization Assessment Model.
OIR	Organization Information Requirement
PAM	BIM Maturity Project Assessment Model
PoA	Point of Adoption
PIR	Project Information Requirement
RSA	Robot Structural Analysis
TSD	Tekla Structural Designer
TS	Tekla Structures

8. REFERENCES.

AGACAD, 2014. Replace IFC elements with native Revit® families - YouTube [WWW Document]. URL https://www.youtube.com/watch?v=RSxGOF_ePfY (accessed 7.29.21).

AIA, 2007. Integrated Project Delivery: A Guide California Council National.

ALLPlan, N.C., 2020. BIM Study – Benefits And Relevance Of BIM For Civil Engineers [WWW Document]. URL https://blog.allplan.com/en/bim-study-benefits-and-relevance-of-bim-for-civil-engineers (accessed 5.11.21).

ANDERSEN, 2016. Evolution of BIM and BIM Adoption [WWW Document]. URL https://www.andersenwindows.com/for-professionals/pro-views/bim-evolution/ (accessed 5.8.21).

AppStore, A., 2021. Autodesk App Store : Plugins, Add-ons, Extensions for Autodesk software, AutoCAD, Revit, Inventor, 3ds Max, Maya... [WWW Document]. URL https://apps.autodesk.com/en (accessed 5.21.21).

AutoDesk, 2021. Autodesk | 3D Design, Engineering & Construction Software [WWW Document]. URL https://www.autodesk.com/ (accessed 5.8.21).

AutoDesk, 2017. The Guilin Liangjiang International Airport Terminal 2 project.

Azhar, S., 2011. Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. Leadership and Management in Engineering 11, 241–252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127

Beckwith, L., 2015. 3 Approaches to Business Strategy [WWW Document]. ThoughtHub Blog Video and Knowledge. URL https://www.sagu.edu/thoughthub/3-approaches-to-strategy (accessed 5.9.21).

Bew, M., Richards M., 2008. Bew-Richards BIM maturity model, in: BuildingSMART Construct IT Autumn Members Meeting (Ed.), BuildingSMART Construct IT Autumn Members Meeting. Brighton.

BIM360, A., 2017. Top 10 Benefits of BIM in Construction [WWW Document]. URL https://bim360resources.autodesk.com/connect-construct/top-10-benefits-of-bim-in-construction (accessed 5.9.21).

BIMA+, 2021. Lessons of the BIM A+ Modules - BIM A+ Master. BIM A+ EMJMD Master Program.

BIMCorner, 2019. Top 12 benefits of BIM technology - Why should I use BIM? [WWW Document]. URL https://bimcorner.com/benefits-of-using-bim-technology/ (accessed 5.9.21).

BIMe, I., 2019a. BIM Workflow - BIM Dictionary [WWW Document]. URL https://bimdictionary.com/en/bim-workflow/1 (accessed 5.9.21).

BIMe, I., 2019b. BIM Process - BIM Dictionary [WWW Document]. URL https://bimdictionary.com/en/bim-process/1 (accessed 5.9.21).

BIMserver.center, 2020. CYPE-Revit Interoperability Guide [WWW Document]. URL https://blog.bimserver.center/en/new-cype-revit-interoperability-guide/ (accessed 7.29.21).

BIMWiki, D.B.W., 2021. Common data environment CDE [WWW Document]. URL https://www.designingbuildings.co.uk/wiki/Common_data_environment_CDE (accessed 5.9.21).

Bryde, D., Broquetas, M., Volm, J.M., 2013. The project benefits of building information modelling (BIM). International Journal of Project Management 31, 971–980. https://doi.org/10.1016/j.ijproman.2012.12.001

buildingSMART, 2021. buildingSMART - The International Home of BIM [WWW Document]. URL https://www.buildingsmart.org/ (accessed 5.8.21).

buildingSMART, 2020. Building Room 6: Structural Engineering [WWW Document]. buildingSMART Conference 2020. URL https://vimeo.com/420738862 (accessed 5.17.21).

CabinetOffice, U., 2012. Government Construction Strategy, London, UK. London, UK.

CAD, T., 2018. Revit Robot Structural Analysis Tutorial [WWW Document]. URL https://www.youtube.com/watch?v=2v9CQHYqmMY (accessed 5.20.21).

Cambridge, D., 2021. PROCESS | meaning in the Cambridge English Dictionary [WWW Document]. URL https://dictionary.cambridge.org/dictionary/english/process (accessed 5.9.21).

Caputi, 2021. BIM A+5: Recordings- Day 2: 12/02/2021 - Business Process Management [WWW Document]. URL https://elearning.bimaplus.org/mod/page/view.php?id=314 (accessed 5.22.21).

Caputi, M., 2021. BIM Value in Business Process Management.

Caputi, M., Ferrari, L., 2014. Il BIM e il Facility Management - Come garantire il valore dell’asset per tutta la sua vita economica. Mantuenzione, Tecnica e Management 12–13.

Chen, Y.-C., 2001. Empirical modelling for participative business process reengineering. Coventry, United Kingdom.

Cherkaoui, H., 2017. UK follows through on BIM level 2 mandate - LetsBuild [WWW Document]. URL https://www.letsbuild.com/blog/uk-government-follows-bim-level-2-mandate (accessed 5.12.21).

Chien, K.F., Wu, Z.H., Huang, S.C., 2014. Identifying and assessing critical risk factors for BIM projects: Empirical study. Automation in Construction 45, 1–15. https://doi.org/10.1016/j.autcon.2014.04.012

CIFE, 2007. CIFE Technical Reports. Stanford University.

Czmoch, I., Pękala, A., 2014. Traditional design versus BIM based design. Procedia Engineering 91, 210–215. https://doi.org/10.1016/j.proeng.2014.12.048

Dakhil, A., 2017. Building Information Modelling (BIM) maturity-benefits assessment relationship framework for UK construction clients. Manchester, UK.

Dakhil, A., al Shawi, M., Underwood, J., 2015. BIM Client Maturity: Literature Review, in: 12th International Post-Graduate Research Conference. MediCityUK - University of Salford, Manchester.

DODGE, D.& A., 2016. Leading the Future of Building - Connecting Design and Construction - SmartMarket Brief.

Doumbouya, L., Gao, G., Guan, C., 2016. Adoption of the Building Information Modeling (BIM) for Construction Project Effectiveness: The Review of BIM Benefits. American Journal of Civil Engineering and Architecture 4, 74–79. https://doi.org/10.12691/ajcea-4-3-1

Eastman, C., 1976. General purpose building description systems. Computer-Aided Design 8, 17–26. https://doi.org/10.1016/0010-4485(76)90005-1

Eastman, C., Henrion, M., 1977. Glide: A language for design information systems, in: Proceedings of the 4th Annual Conference on Computer Graphics and Interactive Techniques, SIGGRAPH 1977. Association for Computing Machinery, Inc, pp. 24–33. https://doi.org/10.1145/563858.563863

Fernando, J., 2021. Return on Investment (ROI) Definition [WWW Document]. URL https://www.investopedia.com/terms/r/returnoninvestment.asp (accessed 5.9.21).

Franz, B., Messner, J., 2019. Evaluating the Impact of Building Information Modeling on Project Performance. Journal of Computing in Civil Engineering 33, 04019015. https://doi.org/10.1061/(asce)cp.1943-5487.0000832

Fu, F., 2018. Design and Analysis of Tall and Complex Structures, Design and Analysis of Tall and Complex Structures. Elsevier. https://doi.org/10.1016/c2015-0-06071-3

GAO, G.-10. 1. 15, 1997. Business Process Reengineering Assessment Guide.

GSA, 2007. GSA BIM Guide Series 01 GSA BIM Guide Overview. Washington.

Hamidavi, T., Abrishami, S., Hosseini, M.R., 2020. Towards intelligent structural design of buildings: A BIM-based solution. Journal of Building Engineering 32, 101685. https://doi.org/10.1016/j.jobe.2020.101685

HMC, A., 2020. Top 5 Benefits of BIM Construction [WWW Document]. Thought Leadership. URL https://hmcarchitects.com/news/top-5-benefits-of-bim-construction-2020-05-13/ (accessed 5.9.21).

Hosseini, M.R., Maghrebi, M., Akbarnezhad, A., Martek, I., Arashpour, M., 2018. Analysis of Citation Networks in Building Information Modeling Research. Journal of Construction Engineering and Management 144, 04018064. https://doi.org/10.1061/(asce)co.1943-7862.0001492

Ibrahim5aad, 2020. GitHub - IFCtoREVIT [WWW Document]. URL https://github.com/Ibrahim5aad/IFCtoREVIT (accessed 7.29.21).

ISO, T.C.I. /TC59/SC13, 2018. ISO - ISO 19650-1:2018 - Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 1: Concepts and principles, International Standard Organization.

ISO19650-0, 2019. EN ISO 19650-0:2019 Transition guidance to BS EN ISO 19650.

Jones, D., Snider, C., Nassehi, A., Yon, J., Hicks, B., 2020. Characterising the Digital Twin: A systematic literature review. CIRP Journal of Manufacturing Science and Technology 29, 36–52. https://doi.org/10.1016/j.cirpj.2020.02.002

Kaner, I., Sacks, R., Kassian, W., Quitt, T., 2008. Case studies of BIM adoption for precast concrete design by mid-sized structural engineering firms [2008-21]. ITcon 13, 303–323.

Kassem, M., Succar, B., 2017. Macro BIM adoption: Comparative market analysis. Automation in Construction 81, 286–299. https://doi.org/10.1016/j.autcon.2017.04.005

Lee, G., Borrmann, A., 2020. BIM policy and management. Construction Management and Economics 3, 413–419. https://doi.org/10.1080/01446193.2020.1726979

Lee, S. il, Bae, J.S., Cho, Y.S., 2012. Efficiency analysis of Set-based Design with structural building information modeling (S-BIM) on high-rise building structures. Automation in Construction 23, 20–32. https://doi.org/10.1016/j.autcon.2011.12.008

Liu, Y., Li, M., Wong, B.C.L., Chan, C.M., Cheng, J.C.P., Gan, V.J.L., 2021. BIM-BVBS integration with openBIM standards for automatic prefabrication of steel reinforcement. Automation in Construction 125, 103654. https://doi.org/10.1016/j.autcon.2021.103654

Maciel, A.R., Fabiano R, 2016. Interoperability with IFC in the automated rebar fabrication, in: 33rd International Symposium on Automation and Robotics in Construction (ISARC 2016).

MagiCAD, 2019. BIM - Building Information Modelling in the construction industry [WWW Document]. URL https://www.magicad.com/en/bim/ (accessed 5.9.21).

McGraw-Hill, Bernstein, H.M., Jones, S.A., 2008. Modeling (BIM) Building Information Transforming Design and Construction to Achieve Greater Industry Productivity. New York.

NBS, 2016. What is BIM? | NBS [WWW Document]. URL https://www.thenbs.com/knowledge/what-is-building-information-modelling-bim (accessed 5.8.21).

NBS, 2014. BIM Levels explained | NBS [WWW Document]. URL https://www.thenbs.com/knowledge/bim-levels-explained (accessed 5.9.21).

O'Brien, P., Lindh, M., Goldsworthy, B., 2021. Introduction to Tekla Tedds: Engineering Calculation Automation [WWW Document]. Tekla. URL https://www.tekla.com/about/webinars/video/introduction-tekla-tedds-engineering-calculation-automation (accessed 6.22.21).

OICE, 2021. Report Oice: l'86% delle imprese di ingegneria italiane ha effettuato investimenti in BIM - BIM Portale [WWW Document]. URL https://www.bimportale.com/report-oice-l86-delle-imprese-ingegneria-italiane-effettuato-investimenti-bim/?utm_source=newsletter&utm_medium=email&utm_campaign=BIMportale (accessed 8.5.21).

Olawumi, T.O., Chan, D.W.M., Wong, J.K.W., Chan, A.P.C., 2018. Barriers to the integration of BIM and sustainability practices in construction projects: A Delphi survey of international experts. Journal of Building Engineering 20, 60–71. https://doi.org/10.1016/j.jobe.2018.06.017

Oracle, 2021. Exploring CDE and BIM in Construction [WWW Document]. URL https://www.oracle.com/industries/construction-engineering/what-is-cde-and-bim/ (accessed 8.23.21).

Poirier, Erik, Staub-French, S., Forgues, D., 2015. Embedded contexts of innovation: BIM adoption and implementation for a specialty contracting SME. Construction Innovation 15, 42–65. https://doi.org/10.1108/CI-01-2014-0013

Poirier, E., Staub-French, Sh., Forgues, D., 2015. Assessing the performance of the building information modeling (BIM) implementation process within a small specialty contracting enterprise. Canadian Journal of Civil Engineering 42, 766–778. https://doi.org/10.1139/cjce-2014-0484

Porter, M.E., 1980. Competitive Strategy: Techniques for Analyzing Industries and Competitors, 1st edition. ed. Free Press, New York.

Quirk, V., 2012. A Brief History of BIM | ArchDaily [WWW Document]. URL https://www.archdaily.com/302490/a-brief-history-of-bim (accessed 5.8.21).

Rogers, E.M., 1983. DIFFUSION OF INNOVATIONS Third Edition, 3rd edition 1983. ed. The Free Press - A Division of Macmimillan Publishing Co., Inc., USA.

Sacks R., Eastman Ch., Lee G., Teicholz P., 2018. BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers, 3rd Edition | Wiley, 3rd Edition. ed. Wiley & Sons.

Sampaio, A.Z., Azevedo, V., 2018. Structural Design Developed in a BIM Environment: Benefits and Limitations. International Journal of Civil Infrastructure (IJCI) 1, 30–41.

Schwab, K., 2015. The Fourth Industrial Revolution: what it means and how to respond | World Economic Forum [WWW Document]. URL https://www.weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond/ (accessed 5.9.21).

Sinopoli, J., 2010. Design, Construction, and Renovations, in: Smart Building Systems for Architects, Owners and Builders. Elsevier, pp. 139–158. https://doi.org/10.1016/b978-1-85617-653-8.00013-2

Smith, D.K., Tardiff, M., 2009. Building Information Modeling: A Strategic Implementation Guide for Architects, Engineers, Constructors, and Real Estate Asset Managers, Building Information Modeling: A Strategic Implementation Guide for Architects, Engineers, Constructors, and Real Estate Asset Managers. John Wiley and Sons. https://doi.org/10.1002/9780470432846

SOFiSTiK, 2019. Webinar: SOFiSTiK Analysis + Design [WWW Document]. URL https://info.sofistik.de/en/analysis-design-webinar-aufzeichnung-typ?submissionGuid=f0283485-e999-46ec-9592-dcec4a16c474 (accessed 7.13.21).

SOTHAM, E., 2018. Advantages and disadvantages of BIM in the construction industry [WWW Document]. URL https://www.sotham.co.uk/advantages-and-disadvantages-of-bim/ (accessed 5.9.21).

Succar, B., 2010. Building Information Modelling Maturity Matrix. Concepts and Technologies 65–103.

Succar, B., 2009. Building information modelling framework: A research and delivery foundation for industry stakeholders. Automation in Construction 18, 357–375. https://doi.org/10.1016/j.autcon.2008.10.003

Succar, B., Kassem, M., 2016. Building Information Modelling: Point of Adoption, in: CIB World Congress. Tampere, Finland.

Succar, B., Sher, W., Williams, A., 2013. An integrated approach to BIM competency assessment, acquisition and application. Automation in Construction 35, 174–189. https://doi.org/10.1016/j.autcon.2013.05.016

Suermann, P.C., 2009. EVALUATING THE IMPACT OF BUILDING INFORMATION MODELING (BIM) ON CONSTRUCTION.

Talamo, C., Bonanomi, M.M., 2020. The Impact of Digitalization on Processes and Organizational Structures of Architecture and Engineering Firms, in: Daniotti, B., Gianinetto, M., Della, S., Editors, T. (Eds.), Digital Transformation of the Design, Construction and Management Processes of the Built Environment, Research for Development. Springer International Publishing, Cham, pp. 175–185. https://doi.org/10.1007/978-3-030-33570-0

Tammik, J., 2012. The Building Coder: The Genesis of Revit and its API [WWW Document]. URL https://thebuildingcoder.typepad.com/blog/2012/01/the-genesis-of-revit-and-its-api.html (accessed 5.8.21).

Tang, L., Chen, C., Tang, S., Wu, Z., Trofimova, P., 2017. Building Information Modeling and Building Performance Optimization, in: Encyclopedia of Sustainable Technologies. Elsevier, pp. 311–320. https://doi.org/10.1016/B978-0-12-409548-9.10200-3

Tekla, 2021. Tekla Structural Designer - Design and Analysis Software [WWW Document]. URL https://www.tekla.com/products/tekla-structural-designer (accessed 7.18.21).

Tekla Structures, 2021. Tekla Structures Interoperability and Partners | Tekla [WWW Document]. URL https://www.tekla.com/products/tekla-structures/partners (accessed 7.18.21).

Trivedi, G., 2017. BIM Today - There are 3 P's of BIM: people, processes and policies [WWW Document]. URL https://www.pbctoday.co.uk/news/bim-news/3-ps-of-bim/33019/ (accessed 5.9.21).

Turk, Ž., 2020. Interoperability in construction – Mission impossible? Developments in the Built Environment 4, 100018. https://doi.org/10.1016/j.dibe.2020.100018

Vilutiene, T., Kalibatiene, D., Hosseini, M.R., Pellicer, E., Zavadskas, E.K., 2019. Building information modeling (BIM) for structural engineering: A bibliometric analysis of the literature. Advances in Civil Engineering 2019. https://doi.org/10.1155/2019/5290690

Wen, Q.J., Ren, Z.J., Lu, H., Wu, J.F., 2021. The progress and trend of BIM research: A bibliometrics-based visualization analysis. Automation in Construction 124, 103558. https://doi.org/10.1016/j.autcon.2021.103558

Wikipedia, 2020. Business Process Re-engineering [WWW Document]. URL https://en.wikipedia.org/wiki/Business_process_re-engineering (accessed 5.9.21).

Winch, G., 1998. Zephyrs of creative destruction: Understanding the management of innovation in construction. Building Research and Information 26, 268–279. https://doi.org/10.1080/096132198369751