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**BIM Interoperability in the Structural
Engineer Workflow: State-of-the-art
from a Literature Review**

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Abstract – Italiano

Il metodo del Building Information Modeling si è affermato come approccio principale nel processo di digitalizzazione nell'industria dell'architettura, dell'ingegneria, e delle costruzioni. Nel corso degli ultimi cinque/sei anni, l'introduzione di nuovi standard ha reso obbligatorio in un numero crescente di progetti l'uso del BIM richiedendo grandi sforzi in termini di formazione di professionisti, certificazione, etc. L'ingegnere strutturale non è escluso dal gruppo dei professionisti che ha dovuto cambiare il proprio flusso di lavoro, spostandosi dall'uso del CAD all'ambiente BIM. Le possibilità offerte da questa metodologia hanno permesso di ottimizzare i processi, ridurre i tempi, i costi e gli errori. Un ruolo importante in questo processo è giocato dallo scambio dei modelli tra gli ambienti BIM e FEM. Infatti, un ingegnere dovrebbe essere in grado di scambiare questi modelli senza perdere informazioni, in modo da avere una base affidabile su cui lavorare. L'obiettivo di questa tesi è quello di investigare le metodologie e i risultati legati a questo tema presenti nella letteratura, considerando gli scambi BIM-to-BIM, BIM-to-FEM e FEM-to-FEM. Partendo da un corposo campione della letteratura è stato possibile analizzare l'interoperabilità sotto il punto di vista degli approcci, della struttura e dei risultati. Da questi studi è stato inoltre possibile concludere che diversi problemi possono emergere durante lo scambio di dati tra diversi software. È inoltre emerso che questi problemi sono attribuibili sia a una non eccellente implementazione nei software, sia ad una mancanza di conoscenza degli strumenti di import/export da parte degli autori

Abstract – English

Building Information Modeling method has become established as the leading process in the complete digitalization of the modern architecture, engineering, and construction industry. Through the last five/six years, the introduction of new standards mandates the use of BIM methodology in an increasing number of projects requiring a huge effort in terms of training of professionals, certification, etc. The structural engineer is not excluded from the group of professionals that have to change their design workflow, shifting from the use of CAD systems to the BIM environment. Many new possibilities are now given to optimize the processes, experiencing reduction of time, costs, and errors. The necessity of exchanging models into, and between, BIM and FEM environments plays a crucial role. Indeed, an engineer should be able to trade models without information loss in order to always have a reliable basis to work with. The Aim of this MSc thesis is to investigate the methodologies and the results found in the literature regarding the theme of the BIM workflow for the structural engineer, considering the BIM-to-BIM, BIM-to-FEM, and FEM-to-FEM model exchanges. From a hefty sample of papers and thesis present in the literature it was possible to analyze the subject interoperability from the point of view of the procedures, structure, and results. From these studies it was possible to state that many drawbacks arise during the exchange of data between different software. It emerged that these problems are ascribable both to a not proper implementation in the software and to a lack of knowledge from the authors of the import/export tools.

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General layout

This MSc thesis analyzes the literature regarding the theme of interoperability between BIM and FEM software from the point of view of a structural engineer. It is divided into four chapters.

Chapter 1: in this chapter it is presented the introduction of the BIM fundamentals and the concept of interoperability, in order to provide a solid base for the next chapters.

Chapter 2: in this chapter it is presented the sample of the literature considered in this thesis. These works are analyzed and classified taking into consideration the aims, software, type of data exchange, methodology, and material. The information omitted by the authors are then described to state if these works are repeatable or not.

Chapter 3: in this chapter are presented and analyzed the result of the works. These are then compared in order to detect possible differences. A set of questions and answers is proposed in order to describe the main drawbacks and the dependency on the type of exchange, the software, and materials.

Chapter 4: in this chapter are described the conclusions, resuming all the drawbacks and the problems detected in the approach of the authors. Furthermore, a methodology for future works similar to the one analyzed in this thesis is presented. At the end the limitations and suggested future works are indicated.

List of acronyms

BIM: Building Information Modeling

FEM: Finite Element Method

AEC: Architecture Engineering, and construction

CAD: Computer Aided Drafting

PAS: Publicly Available Specification

ISO: International Organization for Standardization

UNI: Ente Nazionale Italiano di Unificazione

EUPPD: European Union Public Procurement Directive

bSI: buildingSMART International

IFC: Industry Foundation Classes

MVD: Model View Definition

API: Application Programming Interface

CIS: CIMsteel Integration Standards

GUID: Globally Unique Identifier

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Chapter 1. BIM: introduction and interoperability

1.1 BIM: a technology and a process

Through the past years, Building Information Model(ing) (BIM) has become established as the leading process in the complete digitalization of the modern architecture, engineering, and construction (AEC) industry. The main difference with respect to the CAD methodology lies in the use of digital parametric objects and the inclusion of non-graphical data related to the object such as material properties or maintenance schedule.

The semantics of the acronym BIM is not univocal but has a dual acceptance. As a matter of fact, it is possible to talk about BIM as a technology or BIM as a process. In the first case the acronym refers to Building Information Model, consisting in the creation of one or more accurate virtual models of a building, which support all the phases of design, allowing better analysis and control than manual processes. When completed, these computer models contain precise geometry and data needed to support the construction, fabrication, and procurement activities through which the building is realized, operated, and maintained [1]. The model could be 7-dimensional, where the first three dimensions are devoted to spatial representation, the fourth to time and scheduling, the fifth to the cost evaluation. Instead, for the last two dimensions there is not a common definition around the world; from a survey [2], Sustainability for the 6D is declared by the most, and Facility Management activities for the 7D. However, it is important to report that these results are in opposition with the Italian standard [3], indeed, in the definition of the 6th and the 7th dimensions, the meanings are swapped with respect to the international conventions. In particular 6D is specified as “Phase of management of the work (use, maintenance and disposal)”; instead, the 7D is related to “Assessment of sustainability (social, economic and environmental)”. The model could also be developed according to predefined Levels Of Development (LOD) depending on the quantity of data/information included from the users and its consistency. Even if the starting concepts are the same, their definition and implementation is not unique all around the world. As a matter of fact several countries produced standards incorporating different concepts of LOD.

Internationally the most authoritative are the US and UK ones, these are at the base of the latest international and national standards such the ISO and the Italian ones. In this context a crucial importance is given to the development of commercial software, and Common Data Environments in which the model “lives”.

Instead, in the acceptance of BIM as a process, the letter M stands for modelling placing the emphasis on the methodology that could be developed. In fact, one of the major benefits of BIM is the possibility of using a single shared model, through which all the stakeholders involved in the design, construction and management of a building could work and communicate, even if all belong to different disciplines. So when adopted well, BIM facilitates a more integrated design and construction process that results in better-quality buildings at lower cost and reduced project duration [1].

In this chapter the basic information of BIM as a technology and as a process are presented. The themes of: BIM history, BIM maturity levels, and international BIM adoption and standard are analyzed, providing a brief but organic description that could contextualize the topics presented in the further discussions.

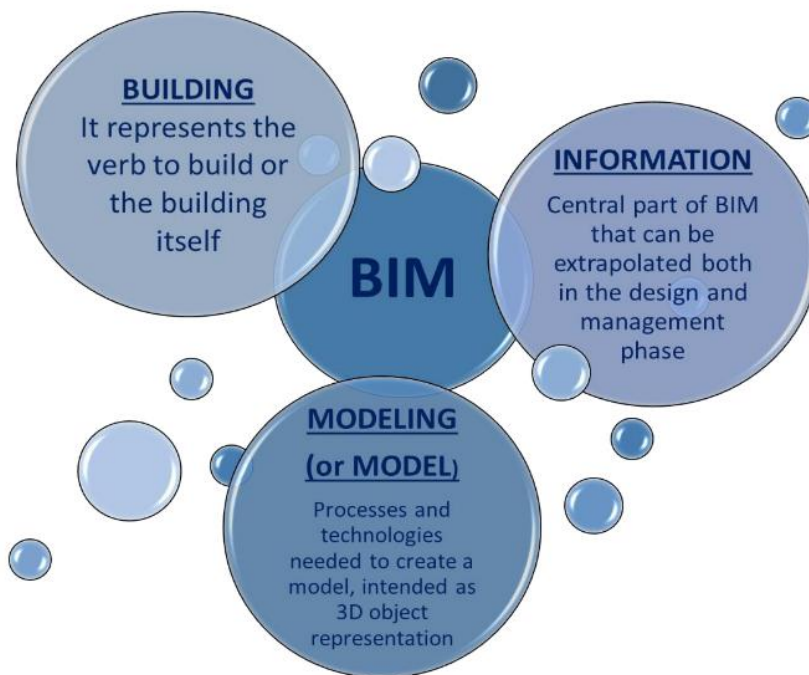


Figure 1 - Analysis of BIM acronym meaning, taken from [12]

History of CAD and BIM

BIM represents the natural evolution of Computer Aided Design (CAD), the standard of digital representation of a building through the past decades.

The very first attempt of developing a software similar to CAD is performed by Patrick J. Hanratty in 1957 by means of PRONTO (Program for Numerical Tooling Operations).

Successively in 1963 Ivan Sutherland develops a new software called Sketchpad that nowadays is considered the precursor of modern CAD programs. In sketchpad is introduced the concept of “objects” or “instances” opening the way for object-oriented programming.

During the 60s and 70s the automotive, naval, and aerospace industries grab the advantages that could derive from the use of CAD, in terms of greater speed of processing and rework of projects, reduction of errors, and advancement of automation in the factory. Instead, the AEC industry do not immediately seize the opportunities offered by the new tools, and begin to adopt CAD systems only in the late 70s [4].

The idea of a digital model on which some non-graphical data could be included is born with the work of Eastman in 1975, where a primitive version of the modern concept of BIM called Building Description System (BDS) is conceived. The idea behind BDS is to combine the positive aspects from 2D drawings and physical models, including element’s properties, and eliminate the intrinsic weaknesses of the two approaches. The potentialities of BSD are to design 3D digital models, in which with only one changing all the views could be automatically updated and automatic spatial conflict detection is possible. Moreover, a “single integrated database for visual and quantitative analyses” could be created in parallel, enhancing the possibility of using the model for analysis purposes. Is important to notice that in those years the commercial distribution of computer is at its origins and only 7 years later the first personal computer is born [5].

In the ‘80s several systems are developed everywhere. They quite gained popularity within the industry, and some are even applied to construction projects. In 1982 one of the most used nowadays and the first one designed for PC commercial CAD software called AutoCAD see the light of the day.

Some years later in 1984, RUCAPS (Really Universal Computer-Aided Production System) is created. It is described as a 2½ dimensional interactive system, closer to the philosophy of 2D but concentrated on the rapid production of 2D drawings (plans,

elevations, and sections). It is considered as a forerunner of BIM and the inspiration behind the development of Revit.

In 1987 the Hungarian company Graphisoft release Archicad, by the most considered the first BIM implementation on PC and MAC. In those years it is considered "revolutionary" for the ability to store large amounts of information within the 3D model. But it is not able to exploit parametric modeling. This gap is filled by Parametric Technology Corporation (PTC) with Pro/ENGINEER, considered the first ever marketed parametric modelling design software in BIM history.

In the 1990s the simplification in the use of the computer due to the spread of graphical user interfaces and the lowering of hardware costs let CAD systems to be widespread among all professional firms. In this decade the use of 3D design become more relevant, pushed from the new tools given by the software.

One important milestone in the BIM history is 2000, where a group of PTC's formers implemented Revit, an innovative software based upon object-oriented programming able to revolutionize the BIM industry. Just 2 years later the US company Autodesk buys it for US\$ 133 million and continues investing in its development. Through the 00s Revit is subdivided in several applications related to the professionals to which it is intended to be used, such as: Revit Structure, Revit MEP, etc. Lately this partitioning between the different disciplines is removed and up to nowadays just one universal version is available.

In these years several companies develop many BIM programs, it is possible to cite the most important one: Revit, Archicad, Allplan, and Vectorworks. The application of BIM constantly rises, aiming for an increase of research and standards on this topic.

From the 20s, a new paradigm for BIM is created. Thanks to advances in AI and automation, integration with technologies such as 3D printing, prefabrication, AR, and VR, continues to push the boundaries and potential of BIM to a new level.

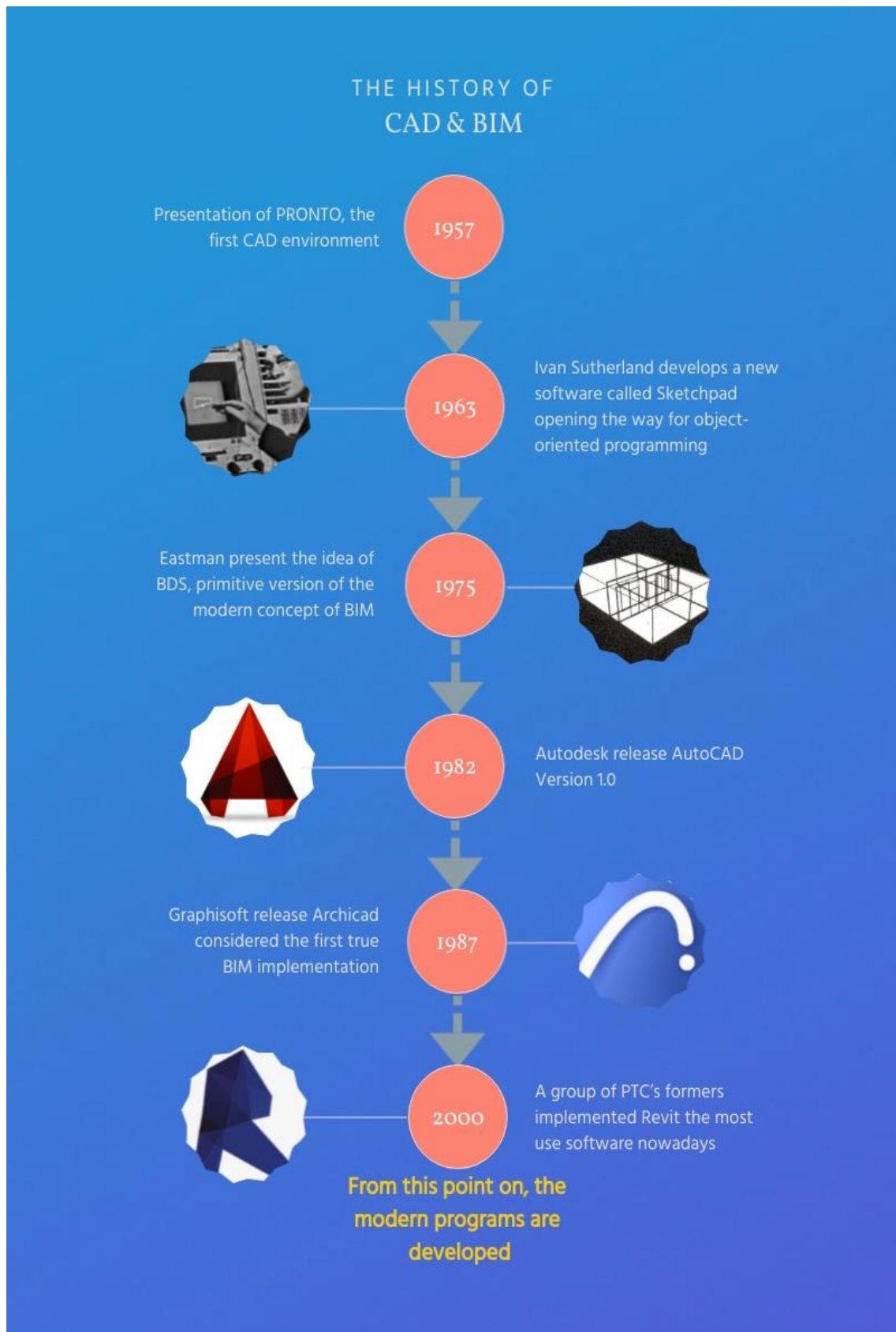


Figure 2 - History of CAD & BIM

1.1.1 BIM maturity levels

In order to support the BIM adoption at its higher level, particularly with respect to interoperability, in May 2011, the UK government releases a futuristic construction strategy, presenting a scalable subset of possible stages in which a firm which implements BIM in its design, construction and facility management projects can be. These levels take the name of BIM maturity levels and are defined as: level 0, level 1, level 2, and level 3. In the future it is not excluded that further levels may be added, but for now Level 3 is the highest level attainable. The definitions of the BIM levels of maturity are based on the content of UK regulations (PAS1192-2 and strategic plans on the application of BIM technology in the AEC industry). With these references the UK government mandates construction vendors, applying for government tenders, to achieve BIM Level 2 by 2016, giving start to a sudden race to upgrade and specialize the tools and the processes not only in the major firms of the country, but to all the components in the AEC market. To graphically represent these steps and integrate what is reported in the norms, a proper diagram, called Bew-Richards wedge, is developed in those years [6].

These levels are nowadays used all around the world to define the level of interoperability of a firm. These are not mandatory outside the UK borders but represent a gold standard to look at. Based on them, a company is able to schedule BIM implementation, allowing a better organization, and improving their consciousness on the steps to be followed for a complete BIM application.

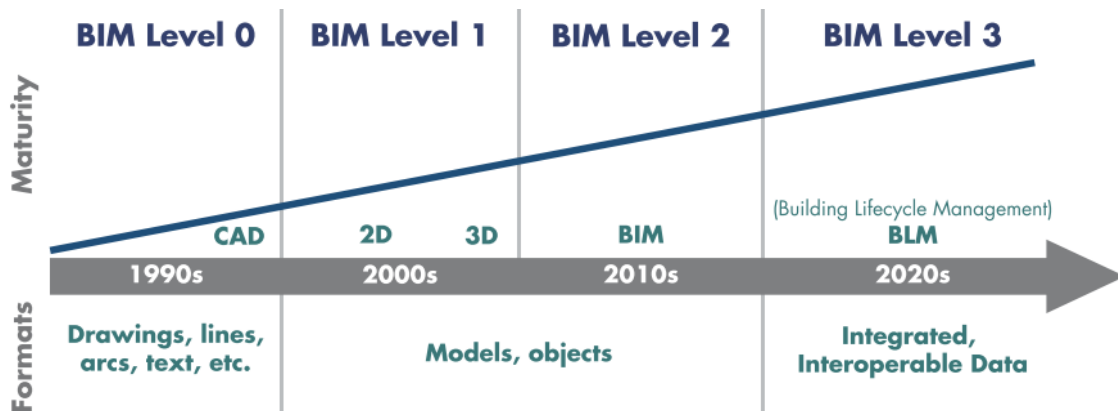


Figure 3 - Bew-Richards's wedge for BIM maturity levels, taken from [1]

Level 0 means that the project promotes zero collaboration and makes use of paper-based 2D CAD drafting techniques. The main goal is to generate Production Information in the form of paper or electronic prints, leading to the probable use of obsolete information which implies errors, misunderstandings, and losses.

Level 1 BIM involves using both 3D CAD and 2D drafting. While 3D CAD is used for conceptual works, 2D is used for the generation of statutory approval documentation and Production Information. At this level, data sharing happens electronically using a Common Data Environment (CDE) managed by the contractor, but the information are not distributed between stakeholders. At this level, there is zero or low collaboration between the different stakeholders as everyone creates and manages their own data, drawings, and schemes. To achieve level 1 BIM, the followings should be taken care of:

- Roles and responsibilities of all stakeholders should be outlined;
- Standardized naming convention should be adopted;
- Creation and maintenance of project-specific codes and spatial coordination;
- Adoption of Common Data Environment of Electronic Document Management System for information sharing between all teams;
- Setting up an appropriate information hierarchy that supports CDE and document repository.

Level 2 BIM is prescribed by the UK Government for public sector projects. This level promotes collaborative working by giving each of the stakeholders its own 3D model on which also 4D and 5D data are included. Collaborative working is the distinguishing aspect of this Level, so it requires streamlined information exchange related to a project and seamless coordination between all the systems and the stakeholders. All the parties work on their local 3D models and information are exchanged through a common file format. Such a system allows organizations to combine external data with their own model in order to create a federated BIM Model. For achieving level 2, it is essential for an organization to:

- Achieve all the guidelines outlined in Level 1;
- Install software that supports common file formats such as IFC or COBie;
- Use further dimensions than the spatial ones;
- Work in a fully interoperable way with all the parties involved in the project.

Level 3 is often termed as “iBIM” whose scope is not completely defined. It promises deeper collaboration between all stakeholders through a single shared model stored in a central repository. Level 3 concept enables all the participants to work on the same model simultaneously, which eliminates the chance of conflicting information. Level 3 proposes the use of an integrated solution built around open standards, where a single server stores all the project data. Proper implementation and adoption of Level 3 require:

- Development of a fresh ‘Open Data’ standard that facilitates the sharing of project data around the globe;
- Creation of new frameworks for BIM-based projects for promoting collaboration and ensuring consistency;
- Training clients in the public sector to use BIM techniques.

Many aspects can be implemented in BIM Level 3: increased focus on lifecycle management, use of real time, cost, and carbon data during the whole lifecycle management, connection of built assets into the Internet of Things, Smart Cities, and Smart Grids.

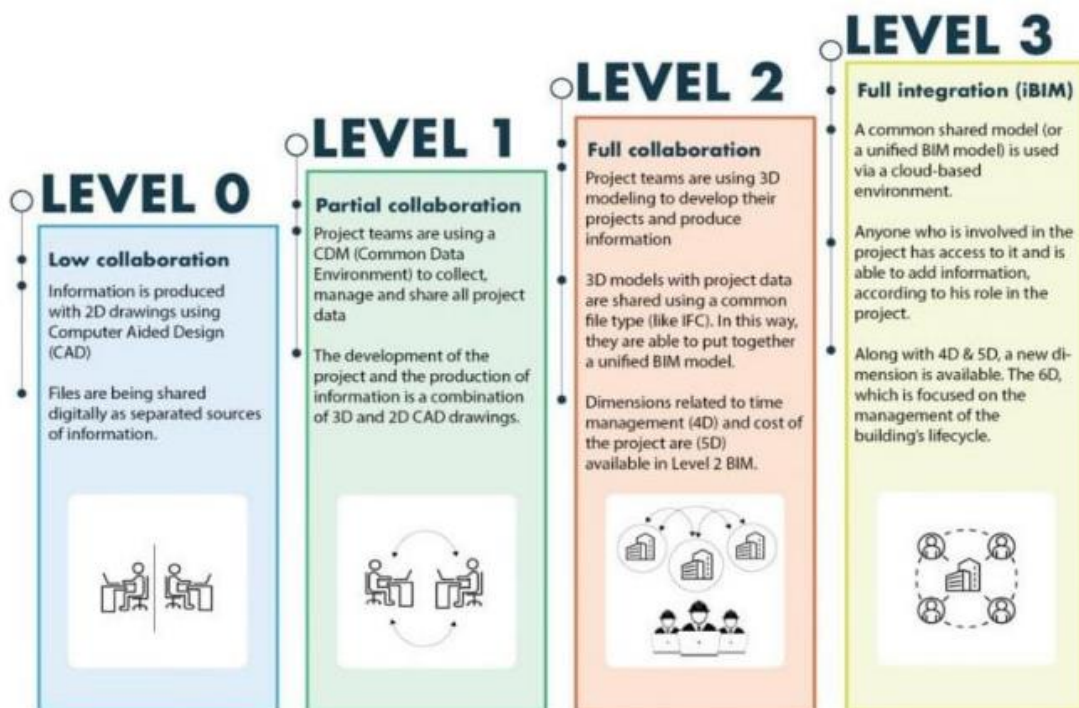


Figure 4 - BIM maturity levels characteristics, taken from [12]

1.1.2 BIM adoption in the world: use and standards

BIM use is currently spreading worldwide. On every continent are present thousands of firms that are investing in recruiting and training of specialized workers in BIM technology, as well as governments in producing new standards. A Zion Market research [7] states that the global Building Information Modeling market accounted for USD 5.41 Billion in 2020 and it is expected to reach USD 22.87 Billion by 2028, growing at a compound annual growth rate of around 19.7% between 2020 and 2028. It highlights also that the global Building Information Modeling market has witnessed a slight decline in the growth for the short term due to the lockdown enforcement place by governments to contain COVID spreading. However, the global markets are slowly opening to their full potential and there is a surge in demand for Building Information Modeling as the construction industry returns to normality. The report suggests that the factors behind the expected growth could be: the increasing population across the world and rapid urbanization, continuously increasing constructions of commercial, government and residential buildings, the smart city projects across developing countries, mandates of governments for BIM.

In this framework the leading nations in BIM adoption are: UK, US, Nordic countries and Singapore, however other countries like China, India, France, Germany and UAE are rapidly accelerating their digitalization process in AEC sector [8]. In particular the situation in Europe is analyzed.

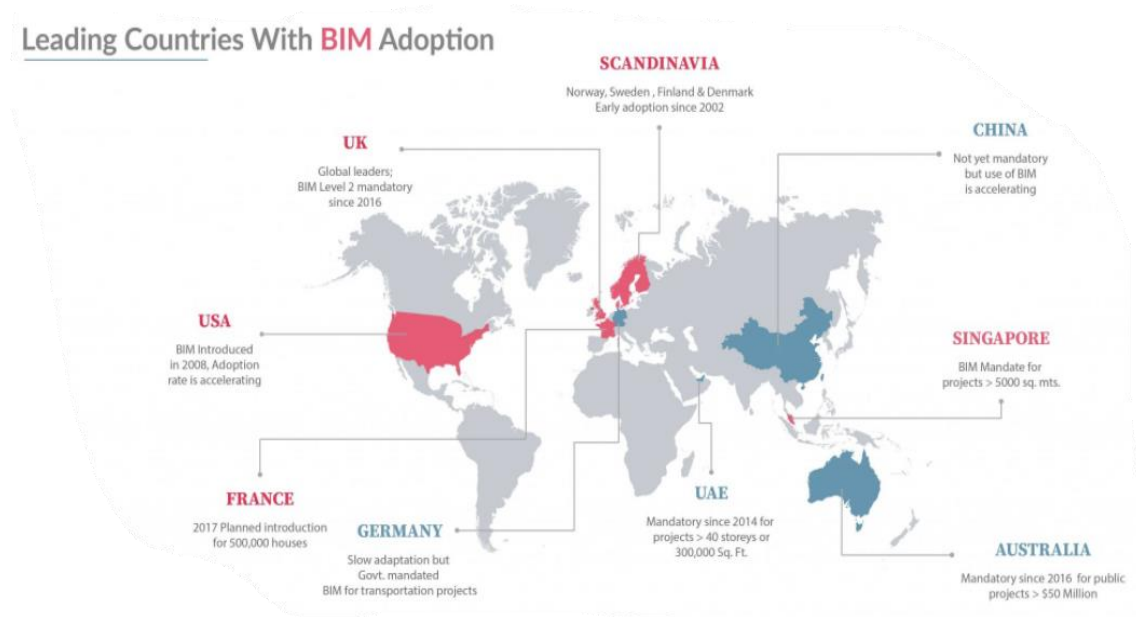


Figure 5 - Leading countries in BIM adoption, in magenta are represented the top 5 with the higher BIM adoption, in blue the other major countries with BIM adoption, taken from [7]

United Kingdom

Currently, the UK has the most striving and radical BIM strategy in the world. If you are not BIM Level 2 compliant, you cannot participate in any government project in the UK. The UK government mandates BIM from April 2016 in every construction project, which requires that all projects funded by the central government be delivered with “fully collaborative 3D BIM”. As the mandate has come into force, there is a rise in levels of BIM adoption demonstrating how the implementation of new standards could drastically push BIM adoption worldwide [9].

The reference standards in the UK are the series of PAS 1192 norms. These are intended to provide the information for a proper transition to the BIM maturity level 2. The importance of this set of standards is increased in recent years due to the decision of the International Organization for Standardization (ISO) to use them as the basis of the ISO 19650, the international standards for BIM implementation. The UK standards are the most authoritative in Europe and are an important reference for the European Union

European Union

The digitalization of building construction processes becomes one of the most important goals for European countries. The starting point of this evolution in Europe can be detected in the European Union Public Procurement Directive (EUPPD) 2014/24 of

February 2014 [\[10\]](#), pushing EU member to set dedicated legislative provisions related to BIM adoption in their countries as a reference standard for all funded projects and public works [\[11\]](#).

However, this decision has created an inhomogeneous situation. Some countries are early adopters such as Finland, Norway, and Denmark, while other countries such as Bulgaria, Greece and Malta currently do not yet have any specification about the use of the BIM process. This leads to an evident BIM divergence in the definitions and practices, and the problem of giving a response for the current non-standardized approach highlights the presence of a fragmented market. The European Commission is still working to smooth out the discrepancy in the application process of BIM, but until now a clear picture of the stage of BIM adoption in the EU to foster a narrowing of the gap is still missing [\[12\]](#).

Italy

For what concerns the situation in Italy, a Politecnico di Milano MSc thesis [\[12\]](#), shows some important information about the market tendencies. It underlines that BIM projects in the public sector have seen a big evolution in the number of procedures that provide the use of BIM methodologies in the tender documents through the years; going from only 4 BIM calls in 2015, to 302 calls in 2018. Additionally, it states that in Italy the BIM maturity varies a lot also across regions. In particular it identified northern regions cities, such as Milano, Bergamo, and Brescia, in which some firms are already operating at a BIM maturity level similar to advanced BIM countries. Again, in the research a complete Italian legislation review is developed, highlighting that to implement the EUPPD, the first legislative steps of Italy are performed by Law n.11 of 28 January 2016 and Legislative Decree of 18 April 2016, n.50. These efforts lead to the New Public Procurement Code which pushes the progressive introduction of BIM as a mandatory electronic modelling tool for building and infrastructure, and giving birth to the Ministerial Decree no. 50/2017, which defines the deadlines of the mandatory introduction of BIM in public tenders based on the procurement's value.

In the thesis also the Italian Organization for Standardization (UNI) standard creation is analyzed. It explains that to go more into details and ensure a real applicability of BIM tools to the Italian building process, the (UNI) releases a new complete standard set called UNI 11337 “Digital Management of Building Information Processes”. Those standards aim to remove part of the risks and uncertainties deriving from sharing information in a virtual construction environment, and to create favorable market conditions for the Italian construction sector. The UNI 11337 standard deals with the digital management of building information processes and specifically with the evolution and development of information models, elaborations, objects and information flows for digitized products and processes [12].

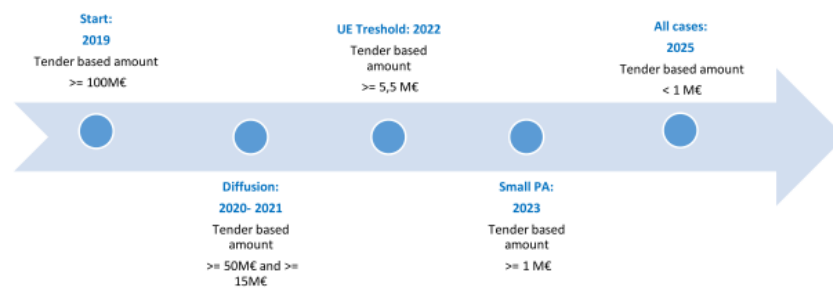


Figure 6 - Time line of the multi-year Italian government plan related to BIM adoption in public projects, take from [12]

1.2 BIM Interoperability

The AEC industry commonly presents some individualities, which may lead to distinct needs in communication between stakeholders and companies. In addition, the elaboration of a construction project is highly collaborative, and besides the fact that they usually comprise several areas, these professionals are spread in offices that use different software and platforms. These specific characteristics lead to a pronounced necessity for efficient interoperability [1].

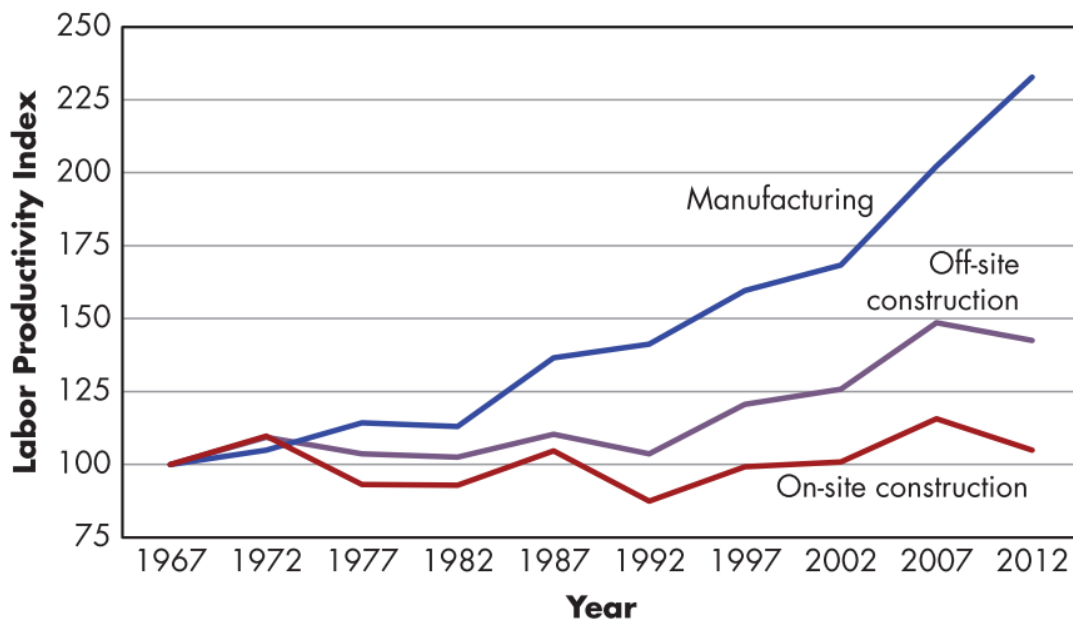
It is possible to give a proper definition of Interoperability: “Interoperability means the ability of information, communication technology systems, and of the business processes they support to exchange data and to enable the sharing of information and knowledge” [13]. This definition by the European Interoperability Framework is readily applicable in the AEC domain. It is clear that to completely exploit the vast number of benefits regarding BIM implementation it is necessary first to provide a complete and proficient interoperability level.

In this chapter the BIM interoperability is analyzed, revealing the most authoritative research on the importance of the topic; in particular regarding the data exchange in the structural engineer workflow. The topics related to interoperability between BIM to Finite Element Method (FEM) software are presented, showing all the possible ways to share data between them. The related buildingSMART International (bSI) standards, the IFCs and the MVDs, used for this scope are described and examined in order to provide all the information necessary for the contextualization of the interoperability tests presented in Chapter 2.

1.2.1 Importance of interoperability

Historically, the AEC industry is the most influential and impacting in every culture and on every country worldwide. For centuries its productivity level grows almost in parallel with respect to the manufacturing industry. However, from the beginning of digitalization in the 70s, the productivity of the manufacturing industries has more than doubled. Meanwhile, the productivity of construction work performed on-site is relatively unchanged. An American report [14] shows that the trend of increasingly weaker

construction productivity when compared with manufacturing continues, but it also showed the gap between off-site and on-site construction activities. It is clear that fabrication off-site is more productive than construction on-site. In this framework the BIM application, and its ability to enhance pre-fabrication could play an important role in the pursuit of productivity increasing. In particular, the necessity of creating a common environment and a seamless information exchange workflow for all the stakeholders involved in the construction of a building, pushes the industry to develop tools and



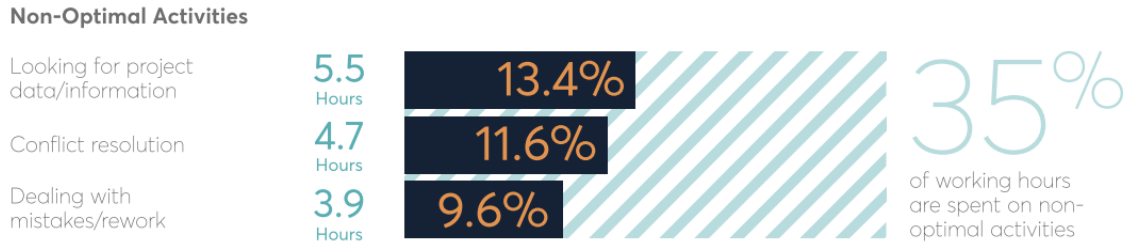
processes to increase the level of interoperability.

Figure 7 - Productivity trend in manufacturing and construction industries, taken from [1]

With the aim of highlighting the importance of a fully digital information exchange process, a report commissioned by the US National Institute of Standards and Technology is presented. Based on interviews and survey responses, they estimated a \$15.8 billion in annual non optimal interoperability costs in the AEC industry in 2002 in the US market. In addition to the costs quantified, respondents indicated that there are also additional significant inefficiency and lost opportunity costs associated with interoperability problems over the ones considered in the report. Thus, the \$15.8 billion cost estimate developed in this study is likely to be a conservative figure [15].

Another report [16], presented almost two decades after, confirms this trend. In the work based on 500+ worldwide firms, in the work is shown that in the US 35% of time

is wasted in non-optimal workflows, corresponding to \$177.5 Billion in 2018 alone. The causes of this time waste are brought back to looking for project data and conflict resolution dealing with mistakes and rework. The same scenario is encountered also in



the other countries included in the report: UK, Australia and New Zealand.

Figure 8 - Hour lost in non-optimal activities during a week, taken from [16]

Some sectors are much more afflicted to interoperability problems than others. In particular, among all the possible data exchanges, the one of our interests is between BIM software and structural analysis software. The boosting of interoperability for a structural engineer must represent a very important step in the BIM seamless workflow. According to a McGraw Hill Construction report [6], the value/difficulty ratio for engineering analysis using BIM is very low. This ratio for structural analysis is even negative, which means a structural engineer is better off creating a structural analysis model from scratch rather than reusing the BIM model generated from the corresponding architectural design process. It is clear that the amount of rework would drastically reduce productivity, increase the time demand, and consequently let the costs grow.

Structural engineer workflow and data exchange

Any AEC project needs the presence in the design team of one or more structural engineers involved in the concept, analysis and design of the structural skeleton which supports the whole construction. With its work the structural engineer must work in strict contact with all the parties engaged in the design process such as: architects, MEP engineers, cost managers, etc. Working with CAD tools, the structural engineer consolidates its workflow, bringing some advantages with respect hand drawing, which represents a very time demanding activity. With the introduction of BIM and its collaborative potentialities, many of the shortcomings related to non-updated drawings, non-automated clash detection, etc. could be overcome.

A work [17], based on literature and industrial best practices, presents a comparison between two possible concrete structures workflows for a structural engineer: one using CAD only and one introducing BIM. According to the authors the process without BIM, requires many stages of clash checking, verification, and file transferring. These files transfers are often not in the same format, so users need to export files to different formats and sometimes even re-enter data in different systems. Instead, the BIM process map represents an improvement on the process, since many tasks and file transfers could be simplified or even excluded, minimizing errors, and saving time. In this map, BIM is shown as a repository to aggregate all the information that are needed. In particular they highlight that with the use of a BIM model as a repository, these processes become much more automatized, and designers may insert their data directly in the model repository, minimizing or automating clash and error detection. These workflow maps can be seen in Figure 9-10.

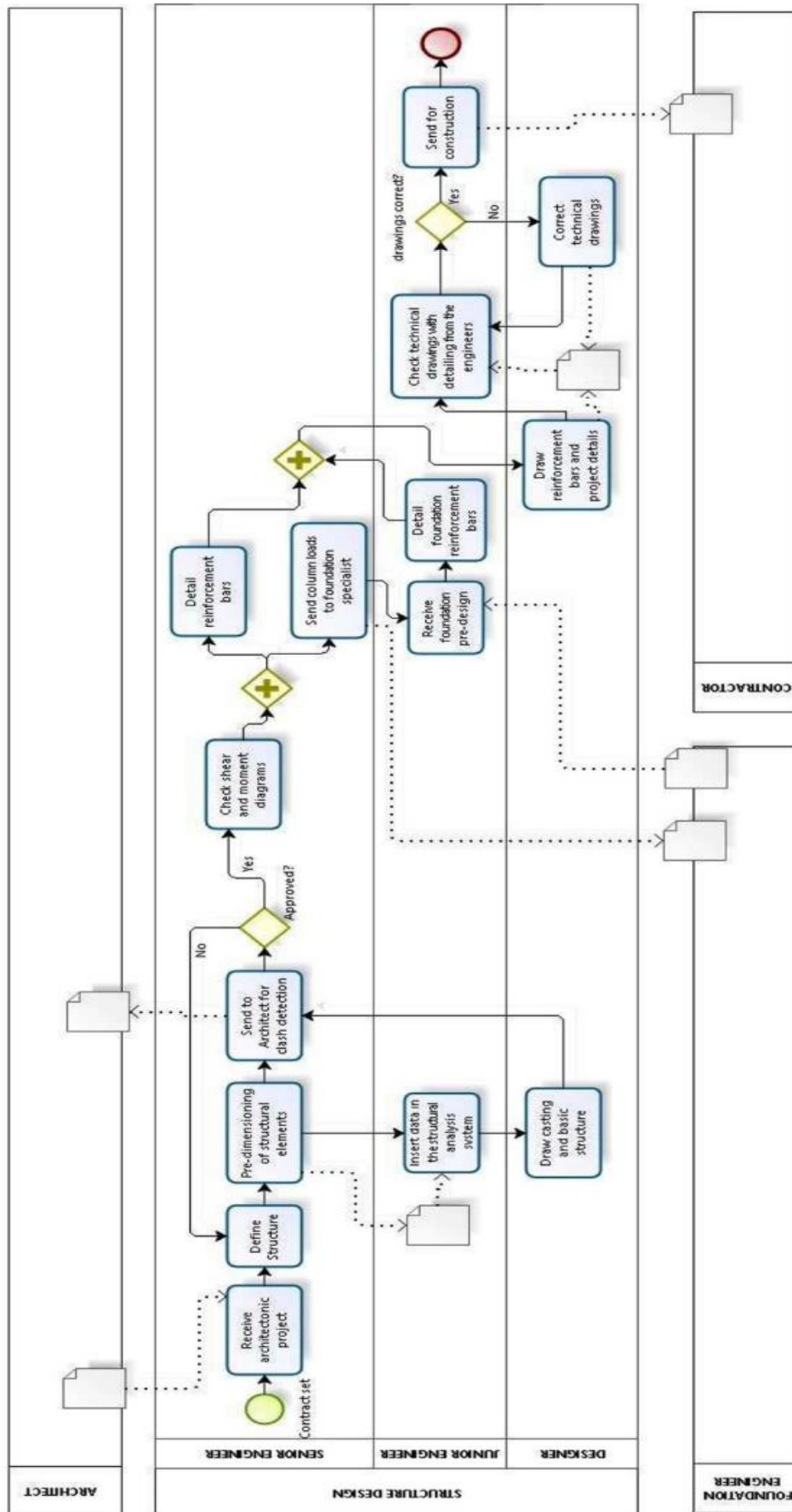


Figure 9 - Process map of a structural design company using CAD, taken from [17]

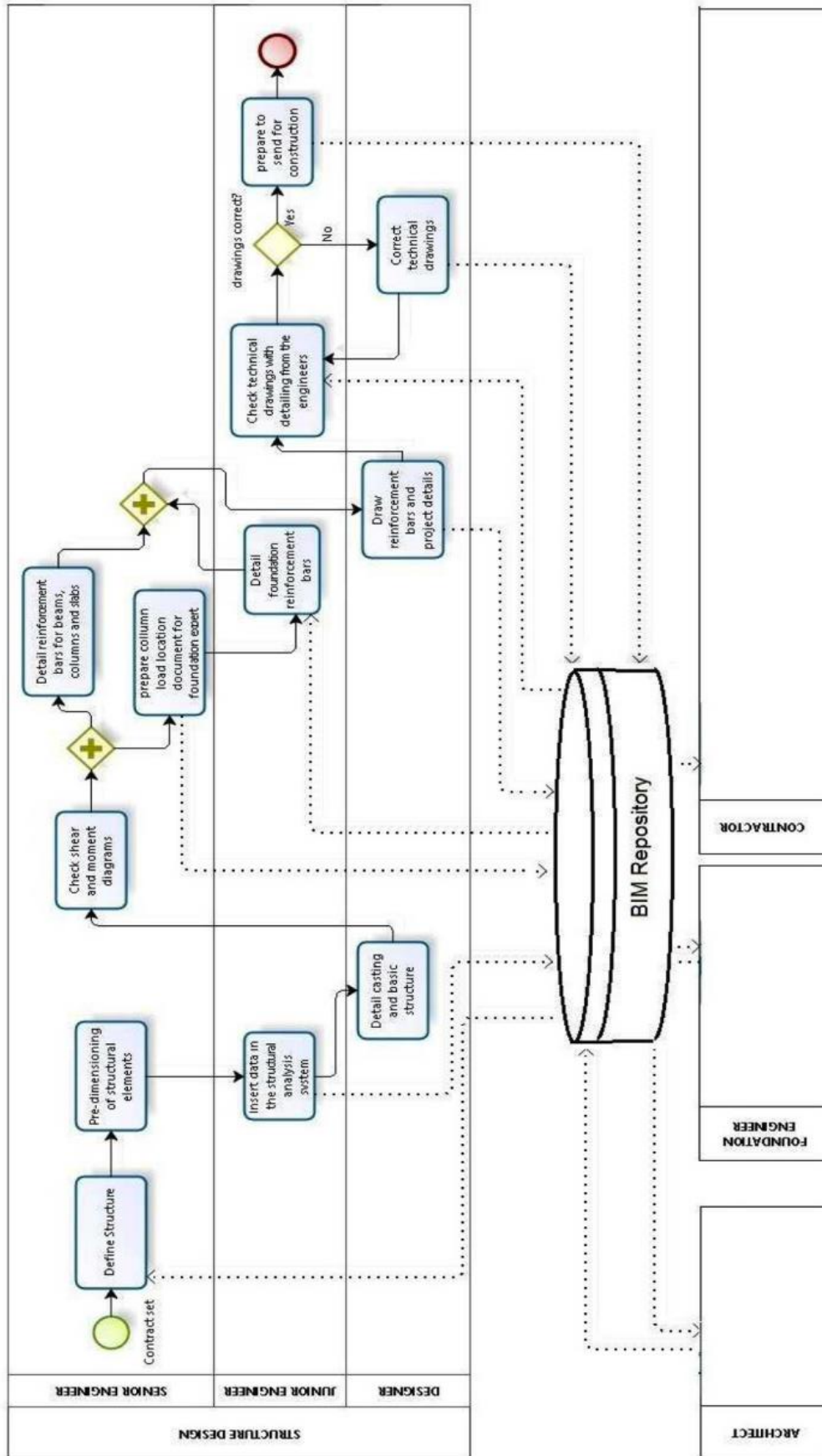


Figure 10 - Process map of a structural design company using BIM, taken from [17]

It is now clear that it is necessary to comprehend how these data exchanges can take form considering the technologies available at this time. A paper [18] presents a complete classification on the possible types and formats of data exchange taking reference to the literature, stating that several approaches to data exchange between the two domains exist. In the work three possible ways to create a structural analysis model are identified, based on the primary role of the software tool that generates the structural analysis model: architectural tool, structural analysis tool, or a third-party data exchange tool. The possibilities are:

- The structural analysis model is created in a native software tool;
- The structural analysis model can be created from a native model by a structural analysis tool;
- An additional software tool (or a plug-in) is used to generate the structural analysis model.

Another classification is then presented in the paper, in this case the emphasis is put on the parties involved in the data exchange. It is possible to have: a single software provider, two interoperating software providers, or an additional provider that is not part of the interoperating software tools. In practice is possible to exchange data using:

- A direct link using a native file
- A direct link using Application Programming Interface (API);
- An indirect link through a third-party channel

In conclusion, two BIM-based exchange approaches are recognized: open and closed BIM. Where the term closed BIM refers to a workflow where software tools from only one software producer (or several cooperating producers) are used and the data exchange takes place via software-to-software interfaces. On the other hand, an open, non-proprietary format is used for data exchange purposes.

The software companies provide tools to the AEC industry that can support both open data exchange and closed software-to-software exchange. As is possible to see in Chapter 2, even if the academic community focuses on improving open exchange approaches, some studies analyzed also close BIM data exchanges. For what concerns open exchange, the most authoritative and widely distributed standard is the IFC developed by buildingSMART in the OpenBIM approach. Moreover, in some papers also CIMSteel

Integration Standards (CIS/2), by means of .STP extension, is used by the authors to cover the gaps of programs not providing IFC import/export tools.

1.2.2 BuildingSMART Standards

At the moment, IFC is the most frequently implemented standard for BIM-based data exchange, with over 150 software tools claiming to support the schema. Leading market software applications in the fields of architectural design and structural analysis claim to support either import or export or both of IFC data models. The IFC standard is one of the five standards developed by buildingSMART and implemented in the OpenBIM approach. Before discussing the IFC standard, buildingSMART and OpenBIM are presented in order to give a contextualization.

BuildingSmart and OpenBIM

BuildingSMART is an open, neutral, and international not-for-profit organization constituted by a global community of chapters, members, partners, and sponsors led by the parent body, buildingSMART International. The buildingSMART community is committed to creating and developing open digital ways of working for built asset environment. Its standards help asset owners and the entire supply chain work more efficiently and collaboratively through the entire project and asset lifecycle. It is considered the worldwide authority driving the digital transformation of the built asset environment, through creation and adoption of open, international standards for infrastructure and buildings. International open digital data-sharing standards are critical to this transformation, helping businesses owners, architects, engineers, contractors and operators become global industry leaders, while also mitigating risks, saving time, and reducing costs [\[19\]](#).

In order to extend the benefits of BIM by improving the accessibility, usability, management, and sustainability of digital data in the built asset industry buildingSMART develops the openBIM approach. At its core, openBIM is a collaborative process that is vendor neutral. The intents of openBIM are several and can be summed up in:

- Define a shareable project information that supports seamless collaboration for all project participants;

- Empower stakeholders to develop new ways of working by transforming traditional peer-to-peer work processes.;
- Improve project delivery and asset performance. Firms that adopt an openBIM approach develop cross-party collaboration, enhanced communication, and industry standard exchange methodologies. This delivers better project outcomes, greater predictability, improved performance, and increased safety with reduced risk.
- Help connecting people throughout the whole lifecycle of an asset, processes, and data to achieve asset delivery, operation, and maintenance goals;
- If applied in a seamless digital workflow, make critical project information accessible to participants on a timely basis to support decision-making through various phases of the project from inception to hand-over to refurbishment and even demolition.
- Remove the problem of BIM data that is typically constrained by proprietary vendor data formats, by discipline or by the phase of a project.
- Extend the breadth and depth of the use of BIM by creating common alignment and language.
- Enable an accessible digital twin which provides the core foundation to a long-term data strategy for built assets. This provides better sustainability for projects and for more efficient management of the built environment.

Summing up, openBIM is based on: interoperability, open and neutral standards, reliable data exchanges, collaborating workflows, flexibility of choice, sustainability [\[20\]](#).

OpenBIM standards

In the development of the present thesis only IFC and MVD standards are analyzed, however these are not the only one developed by buildingSMART, altogether the standard developed in the openBIM approach are:

- Information Delivery Manual (IDM): it describes a methodology for defining and documenting business processes, data requirements, and answers to the questions related to what and when information are shared;

- Industry Foundation Classes (IFC): it describes an industry-specific data model schema, and answers to the questions related to how to share the model data;
- Model View Definitions (MVD): it describes data model exchange specifications defining which information is to be shared in a specific exchange scenario, and answers to the questions related to what specific information is shared;
- BIM Collaboration Format (BCF): it describes software-independent communication protocols that allow the addition of textual comments to the model, and answers to the questions related to how to share comments on the model;
- International Framework of Dictionaries (IFD): it describes a standard library of general definitions of BIM objects and their attributes, and answers to the questions related to which terms have to be considered and what their meaning is.

IFC standard

In conclusion, IFC is a particular data format that aims the interchange of an information model without loss or distortion of data or information. It is an open, neutral file format, not controlled by individual software manufacturers and it is created to facilitate interoperability between the various operators. Furthermore it allows processing of all the information of the building, throughout its entire life cycle, from the feasibility analysis to its construction and maintenance, passing through the various phases of design and planning, and for the aim of this thesis in interoperability for structural analysis [\[21\]](#).

Implementation process of an IFC model consists of two parts: IFC file parser, and IFC model schema. The IFC file parser is developed to import/export the physical file of an IFC model, and then the IFC model schema is developed to generate all corresponding objects defined in the physical file of the IFC model. The architecture of the IFC model schema is organized in four conceptual layers: resource layer, core layer, interoperability layer, and domain layer. Within each conceptual layer, a set of model schemata are defined and illustrated.

1.2.3 IFC standard: history and latest format

The Industry Foundation Classes is the flagship standard of buildingSMART. It is the most mature standard that has a long history and many implementations in software. IFC

is always defined using STEP technology from its creation. The STEP standard (ISO 10303) represents the result of a work of ISO on the development of a comprehensive standard for the electronic exchange of product data between computer-based product life-cycle systems very efficiently [22].

After the initial founding of Industry Alliance for Interoperability, former name of buildingSMART, in 1995, the first generation of IFC appears in 1997, starting with IFC version 1.0. The next step is the IFC2x release published in Nov 2000. It introduces the concept of a core model and domain extensions. It is the first IFC release that gets a broader implementation base, and its implementations are certified using an earlier certification program. In Nov 2001 issues with the initial IFC2x release are fixed within the IFC2x Addendum 1 release.

The initial IFC2x2 release is published in May 2003 as the first successor of the new IFC platform IFC2x. It introduces many extensions to better support the building service and structural domain, e.g., it contains the first IFC sub model for structural analysis, and many other extensions. Also the inclusion of 2D content within the model space of a BIM model (line, text, symbols) and presentation information (color, hatching, surface properties, like shading and rendering) are new in IFC2x2. Issues with the initial IFC2x2 release are fixed within the IFC2x2 Addendum 1 release, published in July 2004.

The IFC2x3 release is published in Feb 2006 as a successor of IFC2x2. It soon is established as the common ground of IFC implementations, combining previous IFC2x and IFC2x2 implementation threads. IFC2x3 is mainly a quality improvement release, not adding scope, but it is a refinement on top of IFC2x2. Since July 2007 the IFC2x release (as all previous releases of IFC) is superseded by the IFC2x3 Technical Corrigendum 1. The purpose of technical corrigendum is to correct several known minor technical problems. In this case it solves the troubles of the release IFC2x Edition 3 specification, and to improve the documentation generally. Technical corrections include the deletion, modification, or addition of several where rules in the EXPRESS schema, which is the programming language of STEP standard. As well, several functions in the EXPRESS schema are modified and a new one is added due to many ambiguities that could not be resolved satisfactorily.

In February 2013 the IFC4 is published enhancing some improvements. In detail, it:

- Is a Full ISO standard and not only PAS;

- Enhances capability of the IFC specification in its main architectural, building service and structural elements with new geometric, parametric, and other features;
- Enables numerous new BIM workflows – including 4D and 5D model exchanges, manufacturer, product libraries, BIM to GIS interoperability, enhanced thermal simulations and sustainability assessments;
- Links all IFC property definitions to the buildingSMART data dictionary;
- Improves readability and ease of access to the documentation with numerous implementation concepts and fully linked examples;
- Allows containment of ifcXML4 schema, fully integrated into the IFC specification in addition to the EXPRESS schema;
- Allows full integration with new mvdXML technology and allows easy definition of data validation services for IFC4 data submissions;
- Corrects technical problems found since the release of the IFC2x3;
- Enables the extension of IFC to infrastructure and other parts of the built environment;
- Implements multilingual translations of the schema;

Some months later, in July a minor update for IFC4 is published taking into account the experiences and feedback from the pilot implementations. Furthermore, in the next two years two updates are developed: the IFC4 Addendum 2 and the IFC4 Addendum 2 Technical Corrigendum 1.

In June 2018 IFC4.1 is born with the main purpose to provide a basis for the various infrastructure domain extensions currently being developed. IFC 4.1 is withdrawn in April 2019 by IFC4.2 which extends the IFC schema to include the description of bridge constructions.

At this time the newest IFC format is the IFC4.3 which is published in July 2021 but still under voting. Its purpose is to extend the IFC schema to cover the description of infrastructure constructions within the domains of Railways, Roads, Ports and Waterways including the elements that are common across those domains [\[23\]](#).

1.2.4 MVD

In general, a MVD, is a selection of entities of the overall IFC schema used to describe and facilitate a specific use or workflow. MVDs can be as broad as nearly the entire schema (e.g. for archiving a project) or as specific as a couple object types and associated data (e.g. for pricing a curtain wall system). It is born to support BIM interoperability, as a matter of fact across hundreds of software applications, industry domains, and regions worldwide, not every domain expert of a project needs all the same information to be delivered or received. So, it could be possible to develop as many MVDs as disciplines, allowing to export lighter files consistent with the real necessities of the specialist. In conclusion the MVD can be seen as a filter that gives the possibility of exporting only the information of an IFC file that are necessary for a specific task.

Software companies develop programs that support the export of BIM data via IFC, and they have to choose which MVDs their products could support. In general, a BIM-authoring tool has a list of MVDs options in their IFC export user interfaces, giving to the consumer the ability to choose the proper MVD according to the needs of the final IFC receiver.

All the known MVDs can be found in buildingSMART database consultable on its online technical resources. In the following an adaptation of this database is reported.

Chapter 1. BIM: Introduction and Interoperability

IFC Schema	MVD Name	Status	Summary
IFC4.2	Bridge Construction View	Draft	Build and maintain bridges.
IFC4 ADD2 TC1	Reference View	Final	Simplified geometric and relational representation of spatial and physical components to reference model information for design coordination between architectural, structural, and building services (MEP) domains
IFC4 ADD2 TC1	Design Transfer View	Draft	Advanced geometric and relational representation of spatial and physical components to enable the transfer of model information from one tool to another. Not a "round-trip" transfer, but a higher fidelity one-way transfer of data and responsibility.
IFC4 ADD2 TC1	Quantity Takeoff View	Draft	Estimate and track construction materials and costs.
IFC4 ADD2 TC1	IFC4Precast	Draft	Precast MVD
IFC4 ADD2 TC1	Energy Analysis View	Draft	Estimate and track energy usage and costs.
IFC4 ADD2 TC1	Product Library View	Draft	Manufacturer product information and configurations.
IFC4	LandXML view		Basic buildingSMART MVD for LandXML v1.2.
IFC2x3 TC1	Coordination View	Final	Spatial and physical components for design coordination between architectural, structural, and building services (MEP) domains
IFC2x3 TC1	Space Boundary Addon View	Final	Identification and export of additional Space Boundaries (polygons which define the extents of a space's contact with directly adjacent surfaces [e.g. walls, floors, ceilings] and openings). Can be used for building energy analysis and quantity take-off.
IFC2x3 TC1	Basic FM Handover View	Final	Handover of model information from planning and design applications to CAFM and CMMS applications, as well as the handover of model information from construction and commissioning software to CAFM and CMMS applications
IFC2x3 TC1	Structural Analysis View	Final	The structural analysis model, created in a structural design application by a structural engineer to one or many structural analysis applications.
IFC 2x3	Architectural Design to Building Energy Analysis	Candidate	This is not a formal bSI MVD
IFC 2x3	Architectural Design to Circulation/Security Analysis	Proposal	This is not a formal bSI MVD
IFC 2x3	Architectural Design to Quantity Takeoff for Cost Estimating	Candidate	This is not a formal bSI MVD
IFC 2x3	Architectural Design to Spatial Program Validation	Candidate	This is not a formal bSI MVD
IFC 2x3	Concept Design BIM 2010	Official	This is not a formal bSI MVD
IFC 2x3	Design to Code Compliance Checking (ICC 2006)	Proposal	This is not a formal bSI MVD
IFC 2x3	Nordic Energy Analysis (subset of CDB-2010)	Candidate	This is not a formal bSI MVD
IFC 2x3	Architectural design to structural design	Draft	This is not a formal bSI MVD
IFC 2x3	Architectural design to thermal simulation	Proposal	This is not a formal bSI MVD
IFC 2x3	Architectural Programming to Architectural Design	Draft	This is not a formal bSI MVD
IFC 2x3	Curtain Wall Design to Energy Analysis	Draft	This is not a formal bSI MVD
IFC 2x3	Extended coordination view	Idea	This is not a formal bSI MVD
IFC 2x3	Extensibility	Idea	This is not a formal bSI MVD
IFC 2x3	Indoor climate simulation to HVAC design	Proposal	This is not a formal bSI MVD
IFC 2x3	Landscape design to road design	Idea	This is not a formal bSI MVD
IFC 2x3	Masonry Structural Design to Structural Analysis	Draft	This is not a formal bSI MVD

IFC 2x3	Modular Bldgs-Arch.Design to Struc.Design	Draft	This is not a formal bSI MVD
IFC 2x3	Precast Concrete Exchanges	Candidate	This is not a formal bSI MVD
IFC 2x3	Road design to landscape design	Idea	This is not a formal bSI MVD
IFC 2x3	Space Requirements and Targets to Thermal Simulation	Draft	This is not a formal bSI MVD
IFC 2x3	Structural design to structural analysis	Proposal	This is not a formal bSI MVD
IFC 2x3	Structural Design to Structural Detailing (ATC-75)	Draft	This is not a formal bSI MVD
IFC 2x3	Wood Structural Design to Structural Analysis	Draft	This is not a formal bSI MVD
IFC 2x3	Architectural design to quantity take-off - level 1	Idea	This is not a formal bSI MVD
IFC 2x3	Architectural design to quantity take-off - level 2	Draft	This is not a formal bSI MVD
IFC 2x3	Architectural design to quantity take-off - level 3	Idea	This is not a formal bSI MVD

Table 1 - MVD Database table, last update on 19 November 2021

According to buildingSMART, Coordination View Version 2.0 developed for IFC2x3, is the most commonly implemented MVD in the BIM authoring tools, until today. But the distribution of the updated version for IFC4: Reference View Version is rapidly taking pace. These are optimized for the coordinated exchange of BIM models between the main disciplines in the building industry. However, these formats are not suitable for analysis tools. Considering structural analysis needs, the Virtual Building Laboratory research group of Tampere University of Technology, in 2008, develops a structural analysis view to support information exchange from building information models to structural analysis models. Unfortunately, this model view is not maintained after release, therefore a few of its concepts are not consistent with IFC4 schema [\[24\]](#).

Chapter 2. Literature review

2.1 Introduction

The aim of this thesis is to link all the information regarding the topic of interoperability problems that a structural engineer faces during the BIM workflow by providing a complete review on the literature from the point of view of the approaches, methodologies, type of structure, results, and evolution in time. The motivation of this work is born during an internship as structural engineer in 2021. Indeed, the principal task that I was aimed to accomplish was the creation the structural BIM model for two cast in place concrete structures of hundreds of thousands of volume. Due to lack of proper direct link between the programs, these models had to be exported using IFC format into the structural analysis software used in the firm, with the necessity to design and check the reinforcement. However, during the exchange many problems arose, in particular the geometry was not properly exported, providing a model that had to be modified. Also the loads and boundary conditions were lacking. Instead, the section properties, after a time demanding mapping between the section catalog of the two programs, were correctly exchanged. This procedure required dozens of hours, and consequently became also expensive from the point of view of the costs. I ask myself if the problem was the lack of experience in the field or if it was a common problem of every structural engineer. I found controversial answers in the literature and on the internet, for this reason at that point I realized the necessity of an in-depth study of the theme, that would bring me to an answer for my question. During the literature review also arose the problem of structural model exchange between BIM software, for this reason the aim of the thesis was extended to the interoperability problems of the whole BIM workflow of a structural engineer.

In order to provide a work as exhaustive as possible, in this chapter a total of twenty-one works is analyzed, ranging from 2008 to 2021. The literature presents experimental tests in which one model from the BIM software (or structural analysis software) is exchanged to the structural analysis software (or BIM software) and the drawbacks of this interchange are highlighted. The motivation behind the decision of this timeframe is due to the will of analyze the research starting from the official release of the IFC2x3 TC1

format in July 2007, because for many years this has represented the most complete IFC version and is still the most used in hundreds of software. The list of the works analyzed in this thesis is chronologically proposed in Table 2.

In the following chapters some questions are formulated in order to piece together all the studies on the subject, analyze the applied methods, show the possible variation in time of the interoperability drawbacks, and provide all the necessary information about the current state of the data exchange in structural engineer BIM workflow.

Title	Authors	Year	Type	Tag
Interoperability in practice: Geometric data exchange using the IFC standard	Pazlar et al.	2008	Article	[25]
Benchmark tests for BIM data exchanges of precast concrete	Jeong et al.	2009	Article	[26]
The Rosewood experiment - Building information modeling and interoperability for architectural precast facades	Sacks et al.	2010	Article	[27]
BIM model analysis on a structural design perspective	Silveira Azevedo	2014	Article	[28]
Current State of Information Exchange between the two most popular BIM software: Revit and Tekla	Nizam et al.	2015	Article	[29]
From BIM to FEM: the analysis of an historical masonry building	Crespi et al.	2015	Article	[30]
The effect of interoperability between BIM and FEM tools on structural modeling and analysis.	Drávai et al.	2016	MSc thesis	[31]
BIM Software Capability and Interoperability Analysis	Taher	2016	MSc thesis	[32]
View of Data interoperability assessment though IFC for BIM in structural design – a five-year gap analysis	Muller et al.	2017	Article	[17]
Building information modeling (BIM) collaboration from the structural engineering perspective	Shin	2017	Article	[33]
Interoperability analysis of ifc-based data exchange between heterogeneous BIM software	Lai et al.	2018	Article	[34]
BIM Interoperability for Structure Analysis	Ren et al.	2018	Article	[35]
From Architectural Design to Structural Analysis: A Data- Driven Approach to Study Building Information Modeling (BIM) Interoperability	Aldegeily et al.	2018	MSc thesis	[36]
Evaluation of Interoperability in Construction Programs Using the IFC 4 State of The Art	Quintero	2018	MSc thesis	[37]
Analysis of the interoperability from BIM to FEM	Beirmaert et al.	2018	MSc thesis	[38]
Improvements for the workflow interoperability between bim and fem tools	Birkemo et al.	2019	Article	[39]
Aspetti di interoperabilità nella digitalizzazione di infrastrutture esistenti con metodologia BIM: il caso studio del ponte Balbis di Torino	Maddaluno	2020	MSc thesis	[40]
Assessment of model-based data exchange between architectural design and structural analysis	Sibenik et al.	2020	Article	[18]
Investigation of data sharing in the Structural Engineering domain	Rafeequl	2020	MSc thesis	[41]
Web-Based Tool for Interoperability among Structural Analysis Applications	Shoieb et al.	2020	Article	[42]
BIM interoperability in structural analysis	Atia	2021	MSc thesis	[43]

Table 2 - Table of the works present in the sample of literature

Before discussing the results present in the sample of the literature analyzed, it is necessary to analyze, classify, and then describe their peculiarities. In the next chapter the software, the type of link, the aims of data exchange, the methodology, the structural materials or construction technologies, and the clear definition of the necessary information are analyzed. This helps in the analysis of the results performed in the next chapters, and to state if different combination of the above-mentioned factors lead to the different outcomes.

2.2 Software and type of data exchange

From Chapter 1, it is clear that an important role in the interoperability workflow of a structural engineer, who intends to apply the BIM approach, is played both by the software that implements BIM and structural analysis, and by the possible data exchange formats. It is then necessary to show the computer programs and type of interoperability that are used in the papers analyzed in this thesis.

Assessment of the used software

From the first attempts to develop rudimental CAD software many commercial software houses are founded and grown in importance in the AEC market. Nowadays the BIM market is living a flourishing age by providing dozens of different tools, including architectural, structural, and MEP modeler, IFC model viewer¹, parametric design applications, and additional authoring tools (e.g. one-to-one interoperability tools).

The same evolution path is happened to structural analysis software. These programs are used in most of the cases to create, analyze and design structural models implementing the finite element approach. As well as BIM software, FEM programs need to incorporate non-graphical data in order to perform any kind of analysis, so it is required to properly receive and process all the necessary data contained in the BIM model.

Regarding the experimental tests performed in the literature, many software are used. These are separated in two categories, one for BIM and one for structural analysis and are reported in Tables 3-4.

¹IFC Model Viewer are tool tools designed to import, analyze, and export the openBIM standard e.g. Solibri Model Viewer

Authors	Revit	Archicad	Tekla Structures	AECOSim Building Designer	Digital Project	StructureWorks	ProSteel	Vectorworks	MagiCAD	Allplan
Pazlar et al.	YES	YES	-	-	-	-	-	-	-	YES
Jeong et al.	YES (Revit building)	YES	YES	YES (Beniley Architecture)	YES	Yes	-	-	-	-
Sacks et al.	YES (Revit building)	-	YES	-	-	-	-	-	-	-
Silveira Azevedo et al.	YES	-	-	-	-	-	-	-	-	-
Nizam et al.	YES	-	YES	-	-	-	-	-	-	-
Crespi et al.	YES	-	-	-	-	-	-	-	-	-
Drávai et al.	YES	-	YES	YES	-	-	YES	-	-	-
Taher	YES	-	YES	-	-	-	-	-	-	-
Muller et al.	YES	-	-	-	-	-	-	-	-	-
Shin	YES	-	YES	-	-	-	-	-	-	-
Lai et al.	-	YES	YES	-	-	-	-	-	YES	-
Ren et al.	YES	-	-	-	-	-	-	-	-	-
Aldegeily et al.	YES	-	YES	-	-	-	-	-	-	-
Quintero	YES	-	-	-	-	-	-	-	-	YES
Beimaert et al.	YES	YES	YES	YES	-	-	-	YES	-	-
Birkemo et al.	YES	-	-	-	-	-	-	-	-	-
Maddaluno	YES	-	-	-	-	-	-	-	-	-
Sibenik et al.	YES	YES	-	-	-	-	-	-	-	YES
Rafcequl	YES	-	-	-	-	-	-	-	-	-
Shoteb et al.	-	-	-	-	-	-	-	-	-	-
Atria	YES	-	-	-	-	-	-	-	-	-

Table 3 - List of BIM software used in each work, YES mean that the software is present

Authors	Midas Gen	Midas FEA	SAP 2000	Robot SA Pro	ETABS	TQS	STAAD PRO	SAFE	RISA 3-D	SCIA	FEM-Design	Focus Konstruksjon	SOFiSTiK	Abaqus/CAE	RFEM
Pazlar et al.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Jeong et al.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sacks et al.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Silveira Azevedo et al.	-	-	YES	YES	-	-	-	-	-	-	-	-	-	-	-
Nizam et al.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Crespi et al.	-	YES	-	-	-	-	-	-	-	-	-	-	-	-	-
Drávai et al.	-	-	-	YES	-	-	YES	-	-	-	YES	-	-	YES	YES
Taher	-	-	-	YES	-	-	YES	-	-	-	-	-	-	-	-
Muller et al.	-	-	-	-	-	YES	-	-	-	-	-	-	-	-	-
Shin	YES	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lai et al.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ren et al.	-	-	YES	YES	YES	-	-	-	-	-	-	-	-	-	-
Aldegeily et al.	-	-	YES	YES	YES	-	YES	YES	YES	-	-	-	-	-	-
Quintero	-	-	YES	-	-	-	-	-	-	-	-	-	-	-	-
Beirmaert et al.	-	-	-	YES	YES	-	YES	-	-	YES	YES	-	-	-	YES
Birkemo et al.	-	-	-	YES	-	-	-	-	-	-	-	YES	YES	-	-
Maddaluno	-	-	YES	-	-	-	-	-	-	-	-	-	-	-	-
Sibenik et al.	-	-	-	-	-	-	-	-	-	YES	-	-	-	-	YES
Rafaequl	-	-	-	-	-	-	-	-	-	YES	-	-	-	-	-
Shoieb et al.	-	-	YES	YES	YES	-	YES	-	-	-	-	-	-	-	YES
Atia	YES	-	YES	YES	YES	-	-	-	-	-	-	-	-	-	-

Table 4 - List of FEM software used in each work, YES mean that the software is present

It has emerged that different approaches are followed. The cases are divided in four categories independently from the aim: one-to-one approach, in which the information goes from one software to another one, e.g. in the work of Pazlar et al. [25], where the BIM model is exchanged between Allplan and Archicad; one-to-many approach, where the information is transferred from one program to many others, e.g. in the thesis of Atia [43], where the model is shared from Revit to Midas Gen, Sap2000, etc.; many-to-one approach, in which the information is driven from many software to a single one, e.g. in the paper of Lai [34], where the models coming from several BIM software are sent to a unique IFC model viewer; and many-to-many approach, where the data is shared from some programs to others software, e.g. in Beirnaert et al. thesis, in which the BIM models created in Revit, Tekla Structure, Vectorworks, etc. are exported into many FEM programs like SCIA, FEM-Design, RFEM, etc. From the analysis of the use of the software, the most used BIM program is Revit, which it is present in the 86% of the cases, followed by Tekla structures with 45%, instead all the other software: Archicad, AECOsim Building Designer, Digital Project, StructureWorks Precast, ProSteel, and Vectorworks are included in less than 25% of the papers. These results represent well the real distribution of the market, as a matter of fact Revit is the most used BIM authoring tool in the world. This drives the extensive use of this software inside research groups, generating a vast number of essays.

In the case of structural analysis applications, it can be noticed that the market is wider, and this is reflected with the high number of possible software that are used in the research, indeed a more homogeneous distribution is present in the sample that is considered for this thesis. The most used are Sap2000 and Robot Structural Analysis Pro with almost 40% of presence in the works. The first is one of the most used structural analysis software worldwide, instead Robot Structural Analysis Pro is designed by Autodesk, and it must be noticed that this software is not available as a standalone, but can be used only by purchasing the Autodesk's suite "AEC Collection".

The sample of works is sufficiently wide to provide a solid base for the analysis of the interoperability in the structural engineer's workflow, however due to a not homogeneous distribution of the software's use, some situations are privileged with respect to others in which the tests are present in a lower number.

Types of data exchange

The next step is represented by the analysis of the types of data exchange studied in the works. Three assessments are performed: one related to the use of direct link between BIM and structural analysis software belonging to the same software house, that allows the use of native files; another, considering the application of direct link via API; and a last one concerning the use of open formats, in particular the IFC standard.

- **Direct link and native files:** this kind of data exchange is present when a software house provides both BIM and structural analysis applications and allows to interchange data using a native file format. The data are automatically transferred, and it is expected that no data should be lost during this process.
- **Use of direct link using API:** this kind of data exchange is present when one software house develops an API and gives the possibility to other software houses to develop interfaces able to let communicate programs of the two parts. In this case the BIM software developers provide to the structural analysis developers an API in order to design a direct link between the two applications.
- **Use of indirect link:** in this case data are exchanged between BIM and structural programs using platform independent formats, in particular the open IFC standard developed by buildingSMART in the openBIM approach. Summarizing what is stated in Chapter 1, in order to appropriately apply the openBIM approach it is first necessary that the software are able to import and export the format. Then it is necessary to choose the IFC format between the available ones as well as for the MVD. It is important to remember that the combination of IFC and MVD strongly influences the data contained in the file, and in this case may give as an output a completely wrong structural model. This kind of interchange is called indirect, neutral, and open because is independent from the software that are used, it does not promote any of them, and allows communication between two software with completely different semantics.

The results of the assessments are reported in Table 5, where are indicated the types of interoperability and possibly the data format that are used.

Authors	Direct link native	Direct link API	Indirect link					Other
			IFC2x	IFC2x2	IFC2x3	IFC4	MVD	
Pazlar et al.	-	-	YES	-	-	-	-	-
Jeong et al.	-	-	-	-	YES	-	-	MVD version is not specified YES (CIS/2, DWG)
Sacks et al.	-	-	-	YES	-	-	-	-
Silveira Azevedo et al.	YES	YES	-	-	-	-	-	-
Nizam et al.	-	-	-	-	YES	-	-	Coordination View 2.0
Crespi et al.	Not specified							-
Drávai et al.	YES	YES	-	-	YES	-	-	Coordination View 2.0
Taher	YES	YES	-	-	YES	-	-	Coordination View 2.0 YES (CIS/2, DWG)
Muller et al.	-	YES	-	YES (but not specified)	-	-	-	MVD version is not specified
Shin	-	YES	-	YES (but not specified)	-	-	-	MVD version is not specified
Lai et al.	-	-	-	YES (but not specified)	-	-	-	MVD version is not specified
Ren et al.	-	-	-	YES (but not specified)	-	-	-	MVD version is not specified
Aldegejly et al.	YES	YES	-	YES (but not specified)	-	-	-	MVD version is not specified
Quintero	-	-	-	-	-	YES	-	Design Transfer View, Reference View, Structural Analysis View, and Architectural Coordination View
Beirmaert et al.	YES	YES	-	-	YES	YES	-	Coordination View 2.0, and Reference View are used however is not clear if any other MVD is used
Birkemo et al.	YES	YES	-	-	-	-	-	-
Maddaluno	-	YES	-	-	YES	YES	-	Coordination View 2.0, and Reference View
Sibenik et al.	-	-	-	-	YES	-	-	Coordination View 2.0
Rafeequl	-	-	-	-	-	YES	-	Reference View
Shoieb et al.	-	-	-	-	YES	YES	-	Structural Analysis View, and Architectural Coordination View YES (CIS/2, STD)
Atia	YES	YES	-	-	-	-	-	-

Table 5 - Type of link used in the work, versions of IFC and MVD, YES mean that the link is present

Most of the works include the use of IFC format. Many versions are analyzed: IFC2x, IFC2x2, but in particular IFC2x3 and IFC4 are the most used. In some cases, it is clear (or stated) the use of the IFC data exchange, but the version that is used is not defined. The same observation can be made for the MVDs, the most frequent is the Coordination View 2.0, however also the Reference View is pretty much used. Some non-certified MVD are present such as Design transfer view (currently it is a draft), or Structural Analysis, and Architectural Coordination. The last two are MVDs provided in Sap2000 for both IFC2x3 and IFC4, but it is not clear what these MVD includes, it is assumed that these corresponds to Structural Analysis View and Coordination View 2.0 in IFC2x3, and the structural and architectural subsets of Reference view for IFC4. These gaps reduce the consistency of the results because a full contextualization is not possible, as already stated the version of the IFC file or the MVD strongly influences the outputs obtained in the interchange. Also the use of direct links is very widespread, in particular the case of exchange via APIs. Software like Revit and Tekla pushed the use of this approach thanks to the open distribution of their relative API increasing the interest on the topic. In some cases, due to the lack of proper tools for IFC exporting, the authors use different formats like CIS/2, STD, or DWG.

2.3 Analysis on the methodology, type of structure and materials

Not all the authors try to achieve the same interoperability aims nor follow the same approach, however it is important to clearly define how they proceed and if they state all the necessary information in order to reproduce their experiments. Furthermore, the material and the construction technologies need to be presented in order to spot possible voids to be filled with future research, and to have a base for the comparison of the results.

Interoperability aims

The sentence “interoperability aims” means to evaluate which programs are involved in the exchange. In this case three possible situations are recognized:

- The first in which the exchange of the structural model is between two BIM authoring tools (BIM-to-BIM). This situation may happen for example when there is the need to send the structural BIM model to a BIM manager who needs a complete model and consistent attached data without any losses for coordination purposes;
- A second case where the need is to have a bidirectional data exchange between the BIM modeler and the structural analysis code (BIM-to-FEM), crucial for the specialist that has need an analytical model with all the material and sectional parameters as well as the loads and boundary conditions;
- The last case in which the data exchange is necessary between two structural codes, for example between when a public administration or a third party needs to control the model and the results obtained by a firm involved in a public procurement.

In Table 6 the reports are classified on the basis of their interoperability aims.

Authors	BIM to BIM	BIM to FEM	FEM to FEM
Pazlar et al.	YES	-	-
Jeong et al.	YES	-	-
Sacks et al.	YES	-	-
Silveira Azevedo et al.	-	YES	-
Nizam et al.	YES	-	-
Crespi et al.	-	YES	-
Drávai et al.	-	YES	-
Taher	-YES	YES	-
Muller et al.	YES	YES	-
Shin	YES	YES	-
Lai et al.	YES	-	-
Ren et al.	-	YES	-
Aldegeily et al.	-	YES	-
Quintero	YES	YES	-
Beirmaert et al.	-	YES	-
Birkemo et al.	-	YES	-
Maddaluno	-	YES	-
Sibenik et al.	-	YES	-
Rafeequl	-	YES	-
Shoieb et al.	-	-	YES
Atia	-	YES	-

Table 6 - BIM aims pursued from the authors, YES means that the aim is pursued in the work

It can be noticed that the vast majority of the reports focuses on the connection between BIM to BIM and BIM to FEM, highlighting the high level of interest in the themes due to the practical exigence of the final users that encounter this problem repetitively in every project. On the other hand, the data exchange between FEM programs it is not so common, the most probable situation in which this kind of exchange may arise is when there is the necessity to submit the analytical model to a third-party consultant, for external controls on the results. However, in most of the cases the consultant prefers to develop his own model or to start from the BIM model, overpassing the necessity of FEM-to-FEM exchange. For these reasons the BIM to BIM and the BIM to FEM cases are analyzed much deeper in the following.

Procedure followed by the authors

In this part the origin and the interoperability roadmap of the model is analyzed in order to show all the possible methodology that the authors follow. First of all, the model can be originated both in the BIM software or in the structural analysis program, it can be enriched directly by all the non-graphical data useful in the structural analysis context such as material properties, loads, and constraints, otherwise these information are added after the exchange. This depends on the software, as a matter of fact not in every application it is possible to insert these information, and this is particularly true in the older versions of the software.

Analyzing the works, the vast majority of the authors decide to design the model in the BIM environment due to the higher flexibility and better modeling tools present in the software with respect to the ones in the structural analysis modeler. In fact, the geometry design of the model is not so comfortable in FEM software, where in general it is necessary to manually define the nodes to which the elements are connected, followed by the definition of the elements, the assignment to each element of the relative section, material, etc. Furthermore, in case the geometry changes it is necessary to delete both the nodes and the elements and to redefine them from the principle, resulting in a time consuming and error-prone procedure. However, as it can be seen in Table 7 in some cases, in order to provide a complete analysis, the model is designed in the FEM application.

It is important to cite that in some BIM programs (e.g. Revit) it is present the possibility of modifying the analytical model before exporting it. Furthermore, it is possible to apply the boundary conditions and load definitions that are necessary for the analysis directly in the analytical model. In this way the model exported by using direct links, that in most of the cases consists in the analytical one, could be much better, at least from the geometrical point of view.

Authors	Model in BIM environment	Model in FEM environment
Pazlar et al.	YES	-
Jeong et al.	YES	-
Sacks et al.	YES	-
Silveira Azevedo et al.	YES	-
Nizam et al.	YES	-
Crespi et al.	YES	-
Drávai et al.	YES	-
Taher	YES	YES
Muller et al.	YES	YES
Shin	YES	YES
Lai et al.	YES	-
Ren et al.	YES	-
Aldegeily et al.	YES	-
Quintero	YES	YES
Beirnaert et al.	YES	-
Birkemo et al.	YES	-
Maddaluno	YES	-
Sibenik et al.	YES	-
Rafeequl	YES	-
Shoieb et al.	-	YES
Atia	YES	-

Table 7 - Modelling environment, YES means that the native model is developed in this environment

Once that the link to be used, either direct or indirect, is defined by the researcher as well as the interoperability aim, the way in which the model is exchanged have to be defined. Many decisions are taken by the authors, but three of them are particularly frequent:

- One way trip: in this case the model follows a linear process passing from one software to another and possibly re-exported to another different program. This approach is used to detect the problems related to the model interoperability and it is mainly effective in the assessment of the trustworthiness of the link between two distinct programs.
- Two-way roundtrip: in this case the model is firstly exported to a second software and then it is taken back to the initial one forming a circular circuit. It is very useful to follow this method when the intention is to investigate the level of efficiency of the direct link between software that gives the possibility of bi-directional information transfer.

- Self-roundtrip: when IFC format is used, it is possible to export and immediately re import in the same application the IFC file. In this way it is possible to directly observe if the process filters out some important information attached to the model. This is not a situation that could find place in the workflow of a structural engineer but helps in the evaluation of the efficiency of interoperability using IFC standard.

In addition, in the case of use of IFC format it may be chosen to perform a preliminary test using a third-party IFC model viewer. In particular these are software able to graphically show the 3D imported model, turn on/off and possibly cancel objects, and in general present IFC files checking tools, all this with the aim to detect possible errors, missing, and imperfections that would reduce the quality of the exported file in order to provide the best possible model. These applications are widely used in the reports in order to visually check the geometrical representation of the exported IFC models detecting earlier errors. In Table 8 the approaches followed by the authors are reported also showing the possible use of a third-party model viewer.

Authors	One way trip	Two-way roundtrip	Self-roundtrip	Use of IFC viewer
Pazlar et al.	YES	-	YES	YES (IFC Engine Viewer, IFCViewer, DDSIFCViewer)
Jeong et al.	YES	-	YES	YES (Solibri Model Viewer)
Sacks et al.	YES	-	-	-
Silveira Azevedo et al.	YES	-	-	-
Nizam et al.	YES	-	-	YES (Solibri Model Viewer)
Crespi et al.	YES	-	-	-
Drávai et al.	YES	-	-	YES (Solibri Model Viewer)
Taher	YES	YES	-	-
Muller et al.	YES	-	YES	YES
Shin	YES	YES	-	YES(Navisworks)
Lai et al.	YES	-	-	YES (Solibri Model Viewer)
Ren et al.	YES	-	YES	-
Aldegeily et al.	YES	YES	-	YES (Solibri Model Viewer)
Quintero	YES	YES	-	-
Beirmaert et al.	YES	-	-	YES (Solibri Model Viewer)
Birkemo et al.	YES	-	-	-
Maddaluno	YES	-	-	YES (BIMVision)-
Sibenik et al.	YES	-	-	-
Rafeequl	YES	-	YES	YES (FZKViewer)
Shoieb et al.	YES	-	-	-
Atia	YES	-	-	-

Table 8 - Procedure followed by the authors, YES means that this kind of procedure is followed

Analyzing the data, the one-way trip is the most followed approach since it is used in all the cases. This information shows that even if this is the simplest procedure a lot of interest is put into understanding if a sufficient level of data exchange is possible between one software to another. However, the most interesting method is the two-way roundtrip due to the fact that is the most complete one, indeed a structural engineer have to update its model many times during the design of a project, and this in the optic of the BIM implementation, involves dozens of exchanges between the BIM model and the structural one and the possibility to have a seamless interoperability in a roundtrip way would be an important result. This aspect is crucial, it is what the end user really needs in its workflow, and only when the bidirectional conversion of the model is enhanced it is possible to talk about true interoperability. This aspect is examined only in a few works even if it would represent the core of the problem and the real purpose of BIM methodology.

Another aspect is that IFC model viewers are used in a high number, this reflects the necessity of visually checking the model before the import. In this way it is possible to check if the information present in the IFC file are lost during the import phase due to a software bad interpretation of the file or during the export phase.

Types of structure and materials used in the models

The dimension and the complexity strongly influence the interoperability, then it is indeed easy to understand that a complex model of a steel structure comprehensive of connections needs a higher amount of information rather than a simply supported beam. Higher amount of data unavoidably implies higher possible errors, misrepresentations or shortcomings.

Another aspect to be taken into account is the dependency of the results on the material, the type of the structure, or the construction technology that are used to build in the real word the BIM model. Regarding the material, masonry, concrete both cast-in-place or precast, steel, and wood are the most used in the AEC industry. All of them are able to provide high structural and durability performances necessary for all the buildings around the world. In new buildings and bridges, concrete and steel structures are preferred, instead, masonry is more present in old buildings, whereas wood is used for roofs or small to medium buildings.

In Table 9 is highlighted the use of single elements or composed structure, where with single element intended a single beam, column, wall, or slab. Instead, in Table 10 the material, as well as the type of building used in the papers are shown.

Authors	Single element	Articulate structure	Type
Pazlar et al.	YES	YES	Article
Jeong et al.	-	YES	Article
Sacks et al.	-	YES	Article
Silveira Azevedo et al.	-	YES	Article
Nizam et al.	-	YES	Article
Crespi et al.	-	YES	Article
Drávai et al.	YES	YES	MSc thesis
Taher	YES	YES	MSc thesis
Muller et al.	YES	YES	Article
Shin	-	YES	Article
Lai et al.	YES	-	Article
Ren et al.	YES	-	Article
Aldegeily et al.	-	YES	MSc thesis
Quintero	-	YES	MSc thesis
Beirnaert et al.	YES	-	MSc thesis
Birkemo et al.	-	YES	Article
Maddaluno	-	YES	MSc thesis
Sibenik et al.	-	YES	Article
Rafeequl	-	YES	MSc thesis
Shoieb et al.	-	YES	Article
Atia	YES	YES	MSc thesis

Table 9 - Types of the structure used in the tests, YES means that this type of structure is used

In some cases simple structures are analyzed, this is done in order to comprehend better how, even in a simple situation, there might be or not loss of information such as loads, material properties, or restraints. Much more relevant is the use of articulate models, in this case it is possible to determine how the element's joints, and more complex load situations are exported.

The use of BIM in very easy situations is not so necessary also considering the fact that the collaborative work is drastically reduced. Differently in a highly collaborative project involving dozens of professionals the use of BIM becomes necessary. In the real-world applications, this second situation is obviously more frequent, indeed even in the simplest project, the use of a single element is not so common. For this reason the analysis

of complex structures is so extensively present in the works. However, an important aspect to be taken into account is the real need that such experiments have to fulfill, the level of interoperability. So, it is questionable the decision that is taken by many authors to investigate only articulated structures, when tests on single elements already present a low level of interoperability, in particular in the case of indirect link via IFC. A much more relevant contribution is provided from those works which investigate firstly the case of single elements, analyzing in depth the problems, and possibly only in a second moment consider the case of articulated structures. This type of approach is particularly present in the thesis rather than in peer-reviewed articles as it can be appreciated in the previous table.

Authors	Material / type of building
Pazlar et al.	Medium size buildings but not specified material
Jeong et al.	Cast in place concrete, steel, and precast façade of a portion of a building
Sacks et al.	Precast Facades of an existing building
Silveira Azevedo et al.	Cast in place concrete small frame
Nizam et al.	One- and two-story wall structure but of not specifies material
Crespi et al.	Masonry existent old building
Drávai et al.	Steel, cast in place concrete and timber beams; steel and cast in place concrete frame; steel platform structure; steel conveyor bridge
Taher	Steel and timber beams; steel building
Muller et al.	Cast in place concrete frame structure and portions of it
Shin	Cast in place concrete and steel structure
Lai et al.	Cast in place concrete frame structure
Ren et al.	Steel single beam, column, and plate
Aldegeily et al.	Cast in place concrete building and steel building
Quintero	Cast in place concrete frame and single beam
Beirmaert et al.	Steel and cast in place concrete beam
Birkemo et al.	Precast and cast in place concrete, and steel structure
Maddaluno	Cast in place concrete bridge
Sibenik et al.	Masonry and cast in place concrete structure
Rafeequl	Cast in place concrete structure
Shoieb et al.	Steel or cast in place concrete structure
Atia	Steel and concrete simple elements and frame buildings

Table 10 - Material and type of building

Concerning the results of the material analysis, it has emerged that the most considered situation is the concrete cast in place one, that is indeed the most adopted structural material in every country. Also the case of steel structures is analyzed, these structures

are treated in almost half of the cases. A minor role is attributed for masonry, wood, and precast structures. However, it would be a wise decision in the future works, to consider much more the cases of precast concrete and wood structure. Indeed one of the principal benefits of BIM technology is the enhancement of prefabrication, due to the fact that the design of such elements is developed earlier and in a much more collaborative way with the contractor, providing the possibility to fix in an earlier stage size and position of structural and architectural elements.

Furthermore, the use of one material rather than another one also influences the shape of the section used to take advantage of the material's peculiar properties. This difference influences the interoperability, due to the fact that steel beam sections are represented and exported differently rather than rectangular concrete sections.

Simple beams, columns, or slabs are considered, but much more consideration is attributed to frame structure, since they are the most adopted building technique in the construction market. However also other types of structures are considered in the articles, such as bridges, wall structures, and precast facades. These structures represent very complex situations, however, as previously stated, even in single elements many problems arise, highlighting that tests that consider these kinds of very articulated situations do not make any sense. The analysis of much more simple structures, such as a simple beam supported by two columns, or a slab on four columns, would be much more proficient because it would be able to check the essential problems related to interoperability using a very simple model.

Analysis on the clearness of the information regarding the methodology, the IFCs, the MVDs, and the repeatability of the tests

An extremely important aspect to be accounted for is the quality of the information reported in the works, anyone who reads the publication with the aim of promoting its validity should be able to replicate the experiments taking as a reference the information included in the paper or the thesis.

Assuming to have all the geometrical information of the structures, an investigation on the necessary information that have to be present in the sample analyzed in this thesis is performed. The information are related to the aim of the work, indeed in a work which examines only the geometric aspects of the model, it is not necessary to include details

regarding loads or material properties. However it is believed that in tests on the interoperability from the structural engineer point of view it is strictly necessary to include the following aspects and to investigate their exchange:

- Geometry;
- Section properties;
- Material properties;
- Loads;
- Restraints;
- Reinforcement in case of concrete structures;

In order to analyze the repeatability of the tests performed in the sample present in this thesis, the data regarding: the procedure, the version of IFCs, and the MVDs are analyzed, and the repeatability is specified and described. The results are reported in Table 11.

It can be concluded that in almost half of the cases it is not possible to completely perform the same test that is conducted by the authors, due to one or many omissions. The most important problem that is experienced, is the absence of information on the IFC and MVD versions that are used in the works. Indeed, these are frequently omitted or not properly indicated.

This bad way to proceed induces a high level of confusion in the readers, in particular it is difficult to interpret the results and correlate each other. Indeed, due to the omission of such information, it is not easy to understand if bad results are related to a low level of knowledge on the software tools, or to an intrinsic low level of interoperability in the software. The case of MVDs is very relevant, indeed, due to their “filtering” action, they can exclude elements or properties essentials in the structural analysis procedure, that may bring the author to state wrong conclusion on the software, when instead, the problem can be reconducted to its own lack of knowledge on the tool.

This tendency to exclude information increases the complexity of the analysis of the literature. Indeed, in order to have a precise view of the problem, it is necessary to analyze several works and spend much more time.

Authors	Procedure	IFC	MVD	Replicable?	Comments
Pazlar et al.	Clearly defined	Clearly defined	MVD not present because in IFC2x no MVD are present	YES	-
Jeong et al.	Clearly defined	IFC2x3 is presented but it is not clearly stated that it is used	MVD version is not specified	NO	The MVD version influences a lot the information included in the IFC. The absence of such information does not allow replicability
Sacks et al.	Clearly defined	Clearly defined	MVD not present because in IFC2x2 no MVD are present	YES	-
Silveira Azevedo et al.	Clearly defined	-	-	YES	-
Nizam et al.	Clearly defined	Clearly defined	Clearly defined	YES	-
Crespi et al.	Type of exchange format not specified	-	-	NO	It is not possible to perform the test because it is not possible to know the type of exchange
Drávai et al.	Clearly defined	Clearly defined	Clearly defined	YES	-
Taher	Clearly defined	IFC2x3 is clearly cited in a picture but it is not stated its use	MVD Coordination View 2.0 is clearly cited in a picture, but it is not stated its use	YES	-
Muller et al.	The procedure is not clearly specified, also model viewer are not specified	IFC version is not specified	MVD version is not specified	NO	The IFC and MVD version influences the information included in the IFC. Also the type of exchange influences the results. Replicability is not possible
Shin	Clearly defined	IFC version is not specified	MVD version is not specified	NO	The IFC and MVD version influences a lot the information included in the IFC. The absence of such information does not allow replicability
Lai et al.	Clearly defined	IFC2x3 is cited but it is not stated that if it is used	MVD coordination view 2.0 is cited but it is not stated that it is used	NO	The IFC and MVD version influences a lot the information included in the IFC. The absence of such information does not allow replicability
Ren et al.	Clearly defined	IFC version is not specified	MVD version is not specified	NO	The IFC and MVD version influences a lot the information included in the IFC. The absence of such information does not allow replicability
Aldegeyly et al.	Clearly defined	IFC version is not specified	MVD version is not specified	NO	The IFC and MVD version influences a lot the information included in the IFC. The absence of such information does not allow replicability
Quintero	Clearly defined	Clearly defined	It is stated that both IFC2x3 and IFC4 can import and export structural analysis and architectural coordination view, but these are present in buildingSMART list	YES	-
Beirmaert et al.	Clearly defined	IFC2x3 and IFC4 are used but it is not clear in which data exchange are used	It is stated that both IFC2x3 and IFC4 can import and export structural analysis and architectural coordination view, but these are present in buildingSMART list	NO	It is not possible to repeat the test without the information of the IFC and MVD versions used in each test
Birkemo et al.	Clearly defined	-	-	YES	-
Maddaluno	Clearly defined	Clearly defined	Clearly defined	YES	-
Sibenik et al.	Clearly defined	IFC version is not specified, but it is specified the use of an MVD present only for IFC2x3, so its use is assumed	Clearly defined	YES	-
Rafeequl	Clearly defined	Clearly defined	Clearly defined	YES	-
Shoieb et al.	Clearly defined	Clearly defined	It is stated that both IFC2x3 and IFC4 can import and export structural analysis view and architectural coordination view but is not clear how these MVDs work.	NO	It is not possible to repeat the test without the information of the IFC and MVD versions used in each test
Atia	Clearly defined	-	-	YES	-

Table 11 - Analysis on the misinformation and on the repeatability of the tests

Chapter 3. Review and comparison of the results

In this chapter the results obtained in the studies are presented and discussed in order to define the best way to proceed for interoperability aims in the workflow of a structural engineer. In the first part a brief presentation of each work and the related result is performed, then in the second part different comparisons are performed in terms of time, software, type of exchange, and material. In the last part the final considerations are discussed through some questions that a novice in the subject may formulate.

Only the parts related to the aims of this thesis are discussed, the remaining scopes of the considered work are not presented or discussed.

3.1 Results of the publications

Interoperability in practice: Geometric data exchange using the IFC standard – Pazlar and Turk (2008) [\[25\]](#)

Pazlar and Turk in their work of 2008 performed a BIM-to-BIM exchange providing an object base comparison, in this analysis the IFC file is before exported, imported in a IFC model viewer, then imported and re-exported. At the end the entities and attributes of the two IFC files are analyzed and compared manually, highlighting the differences observed. They used early versions of Revit, Allplan and Archicad. Applications and their interfaces are tested with various sets of simple (wall, wall with openings, etc.) and complex test cases (architectural models of residential and business buildings). In the simple model testing building elements are drawn separately in each application and then exchanged with the same and residue application without any modification.

Considering the simple example of a wall, some differences in the IFC file size are detected and this indicates mapping irregularities. In the self-roundtrip procedure only Allplan and Archicad provide accordance between the two IFC files. In general many problems are identified regarding the mapping of IFC file from the software.

A slightly different testing approach is used in complex model testing. Several dozen of IFC based BIMs are obtained from distinct sources. After ascertaining the origin

application, the re-export procedure is used to create the IFC models in the origin and in the residue applications. After visual checking, the object-based analysis is performed.

In this case visual model checking does not reveal any major problem, however the attribute analysis proves the opposite. If BIM contains more complex artefacts, mapping irregularities become evident. The authors provide an attribute irregularities list for the complex structures:

- Geometry distortion, indeed, columns and/or walls are not aligned, slab and roof elements are misplaced;
- Element connections are not correct, e.g. wall connection;
- Changing in element shape, e.g. circular wall openings becoming rectangular;
- Changed material properties.

In the conclusion the authors state “Although the idea of AEC-FM software interoperability may be easily understandable, the performance of IFC interfaces after almost a decade of existence and development is still not satisfying”.

Benchmark tests for BIM data exchanges of precast concrete – Jeong et al. (2009) [26]

Jeong et al. in 2009 presented a work based on benchmark tests in order to address the exchange of building information models with precast concrete architectural façade panels and related structural elements. A BIM-to-BIM approach is followed exporting models using IFC and SAP (CIS/2) formats from a group A of software: Revit Building, Archicad, Digital Project², and Bentley Architecture (today AECOsim Building Designer) to a group B including Tekla Structures and StructureWorks Precast. However at the beginning a self-roundtrip is performed for each program. It is not clearly defined the IFC version and the relative MVD used in the work.

In the first step, the exported IFC files are examined in independent IFC viewers with text and graphic functions. The graphic viewers are used for visual examination of the geometric shapes, finding some explicit geometric errors. In particular the main drawbacks are:

² Digital Project was a software developed by Gehry Technologies, however is has been buy from Trimble in 2014

- The slab elements show wrong the location and wrong geometric shape.
- Circular holes are mapped into rectangular shapes.
- The void elements are placed or sized incorrectly so they did not fully penetrate the wall;
- Embossed panels show corrupted geometry.
- Precast panel is unified in one element composed of many polygons, which would make it impractical to divide it into sub-units for fabrication purposes.

Then the self-roundtrip tests are performed only using Archicad and Revit because Bentley Architecture ensures compatibility by allowing end-users to freely assign entity types for each object, and Digital Project does not provide an IFC import function. The same inconsistencies that are encountered with the use of IFC viewers take place, with the addition of:

- Inconsistencies related to coordinate systems, elements are shifted because of coordinate system misinterpretation;
- Some object data are changed, e.g. façade panels are imported as reference objects that cannot be edited, losing their meaning and behavior as a particular type of building element.

In the end the exchange from group A and B is performed. Again showing many misrepresentations. The results for exchange with Tekla Structure show that of the 52 distinct features examined, Revit's IFC file correctly represents 50 features (or 96%), Bentley's 41 (79%), Archicad's 31 (60%) Digital Project's 11 (21%). Instead, in the exchange with StructureWorks Precast by means of SAT many problems due to fragmentation of elements are present leading to time consuming recombining procedure.

It is possible to combine the results of the various software. Only Digital Project and StructureWorks Precast do not allow import of IFC files. It is necessary to state that every software maps the IFC file differently due to semantic differences providing also different numbers of entities, in this case Revit provide the greatest number of entities. Any information material missing is reported.

The authors conclude: “Numerous limitations were found in exchanging both geometric shape information and other semantically meaningful information. None of the exchanges was able to completely exchange all of the geometry. The exchange failings

occur both in the export translators of the architectural BIM tools and the import translators into the precast fabrication BIM tools. All exchanges were found to be imperfect, with most problems arising from the lack of uniformity in the way the internal object data were mapped to IFC objects and properties.”

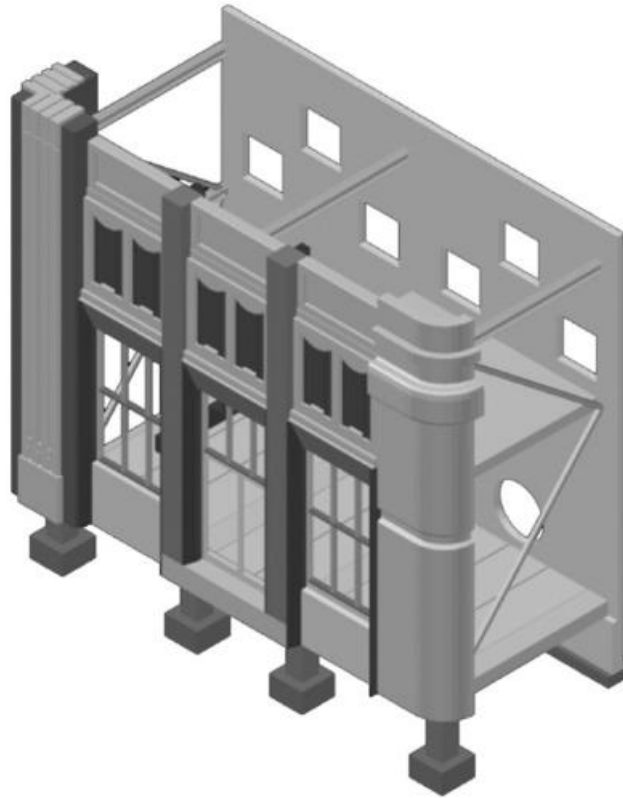


Figure 11 - Jeong et al. test model, taken from [\[26\]](#)

The Rosewood experiment - Building information modeling and interoperability for architectural precast facades – Sacks et al. (2010) [27]

Sacks et al. in 2010 performed an experimental test BIM-to-BIM for the design and fabrication detailing of the precast façade panels for the Rosewood project, a 16-story building. The software that are used are Revit for the modeling and Tekla Structures. The procedure is the following: the IFC2x2 Revit file is used as a background reference model against which the structure could be rebuilt because the objects could not be automatically imported as native objects editable in Tekla Structures.

During the transfer of the IFC file from Revit to Tekla, no grid lines are imported, and some objects are mapped into IFC ‘proxy’ elements, e.g. not specific building objects, but simply ‘blobs’ of concrete. Only the columns, slabs and beams are imported as logical objects because the IFC schema only supports a limited set of structural entities

The authors, regarding the interoperability state: “limitation observed throughout this experiment was that the BIM software applications did not enable full exploitation of the capabilities of the IFC exchange schema. This meant that the model data was degraded through each step, export and import, in both directions. The degree of degradation was such that relatively little more than the basic geometry of the structural components, and only the geometry of the precast façade pieces were transmitted. Among the problems encountered was that some of the façade panels with complex geometry were modeled in the architectural application as mass elements and exported as IFC proxy elements. This resulted in the need to rebuild the objects in the precast engineering application using the IFC model as background geometry only”.

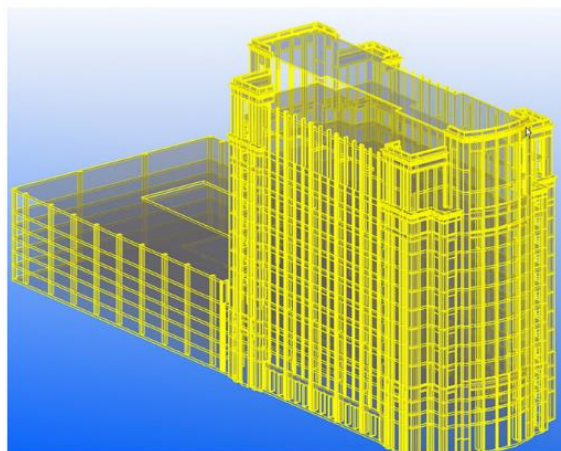


Figure 12 - Rosewood building IFC 2x2 file imported into Tekla, taken from [27]

BIM model analysis on a structural design perspective – Silveira Azevedo (2014) [28]

Silveira Azevedo in 2014 performs a BIM-to-FEM interoperability test in order to execute a comparative analysis between the traditional process and BIM methodology in the structural design phase. For what concerns the interest of this thesis, the model is realized in Revit and then exported in Sap2000 in the first test, and in Robot Structural Analysis Pro in the second one. In this work is selected, as modeling example, a two-story building.

In the first case, the Revit structural model is transferred to SAP2000 through CSIXRevit 2013 plug-in. When the model is imported into SAP2000, there is a correspondence between the section type designation of the beam elements and the SAP2000 database. It is stated that the imported model needs to be completed due to the following limitations:

- Unidirectional information workflow (updates not supported);
- Limitations on the type of elements transferred;
- Difficulty in transposing slabs openings;
- Inability to transfer alignments (grids);
- Failure to recognize the constraints of foundations.

In the second test, the data workflow can be performed in both directions, allowing multiple iterations and updates, although a few parametric objects cannot be transferred with an acceptable effectiveness, but without specifying which. Before exporting the analytical model is necessary its validation. It is explained that Revit has specific tools, in terms of static coherence between the various elements, in particular, their connections and boundary conditions.

In the conclusion the author states: “Regarding the BIM methodologies analyzed, were observed significant differences (...). A unidirectional link between Revit and SAP2000 revealed some disabilities that affect the efficiency and overall quality of the project, namely, the inability to update the BIM model with the design information and the own effectiveness of this information transposition. On the contrary, the link with Robot supports bidirectional workflow, the update of the BIM model information, and the transposition of parametric objects was performed with a high degree of effectiveness.

Current State of Information Exchange between the two most popular BIM software: Revit and Tekla – Nizam et Zhang (2015) [29]

Nizam et Zhang in 2015 present a work in which the BIM-to-BIM interoperability between Revit and Tekla Structure via IFC2x3 in Coordination View 2.0 is analyzed. Two models, one story and two-story building, are modeled on Revit exported in IFC and imported in Tekla Structure. In the new software the model is re-exported. These files are then viewed and analyzed in the IFC checkers and analyzers e.g. Solibri Model checker and IFC Analyzer. The IFC files produced for both the buildings are compared in terms of: physical file-size, differing numbers of instances, inconsistent object types, inconsistent attribute values (missing or new values, loss of numerical precision, string length differences, value differences, reference number differences, etc.), and schema inconsistencies.

Many differences are encountered, in particular the two IFC files differ in terms of dimensions and number of entities, length/area of columns, beams, slabs, and walls.

For these reasons the authors state: “There was an instant small change noticed when the Revit file was converted into IFC, and a significant change noticed when the same file was imported to and exported from Tekla”.

From BIM to FEM: the analysis of an historical masonry building – Crespi et al. (2015) [30]

In 2015 Crespi et al. conduct a BIM-to-FEM test on the south wing of Castel Masegra, an XI century masonry historical building. They develop the BIM model using Revit and export it in the Advanced FEM analysis software Midas FEA. However, the data exchange type is not specified. No particular problems as well as no rework are reported during the exchange of data. In this case too much information are missing to check if no problems are really obtained in the interoperability workflow, or if many problems are encountered and overpassed by the authors and are not cited in the paper.

The effect of interoperability between BIM and FEM tools on structural modeling and analysis - Drávai et al. (2016) [\[31\]](#)

Drávai et al in their MSc thesis in 2016 proposed a series of experimental tests to assess the BIM-to-FEM interoperability of some programs. The BIM software includes Revit, Tekla Structure, AECOsim Building Designer, and ProSteel. Instead the FEM software are: Robot Structural Analysis Pro, FEM-Design, STAAD Pro, RFEM, Abaqus/CAE. Several exchange methods are used, both direct and indirect, including IFC2x3 in Coordination View 2.0.

The analyzed structures are: one simply supported beam in three versions: steel, reinforced concrete, and timber, one steel and one reinforced concrete frame, a steel platform structure, and a steel conveyor bridge. Each model includes information about structural type, material and section properties, boundary conditions, loads and load combinations.

The first test for the beam case is the analysis of the properties, useful in structural analysis, that is possible to define and export for the steel, reinforced concrete, and timber beams in Revit, Tekla Structures, and AECOsim Building Designer. It is observed that it is not possible to define all of them, in particular AECOsim Building Designer presents the worst situation in all the three cases. Indeed, no material properties, load, and boundary conditions can be exported. On the other hand Revit provides better results showing minor property voids.

The second test for the beam case is a one-way exportation. The best solution is the direct link via native file between Revit and Robot. Indeed, just some mechanical properties are lost as well as the reinforcing of the concrete case, however this is common to every scenario.

In general some limitations related to the section and material library for timber are encountered. Again the worst performance are encountered in the AECOsim Building Designer case even in the direct link with STAAD belonging to the same software house, highlighting that this is a good program for architects but not for structural engineers.

The exchange via IFC presents the worst result, showing the necessity to make many adjustments to properly run a structural analysis, in particular common to every model, the structural type needed to be changed from a bar to a beam element. Into STAAD Pro no material properties are exported, and some of the section properties are lost.

Furthermore, loads, load combinations and boundary conditions disappear. The worst situation is encountered in the Tekla to Robot exchange of the steel beam, where the exported element disappears leaving an empty model.

Regarding the frame test, again the direct link via native file shows very good results importing correctly: geometry, cross-section of the beams and columns, material properties, boundary conditions, loads and the position of the analytical line. Instead direct links via API show different results depending on the considered combination of software. In every situation the geometry and cross-section are well interpreted, on the other hand loads and boundary conditions may disappear. Even worse is the situation of the IFC file. In all the cases the links between the beams and the columns disappear. Indeed the analytical model is not transferred, but only the physical model. Due to the cutbacks in the physical model, the different structural elements are not connected. Again the steel frame disappears in the case of Tekla to Robot exchange.

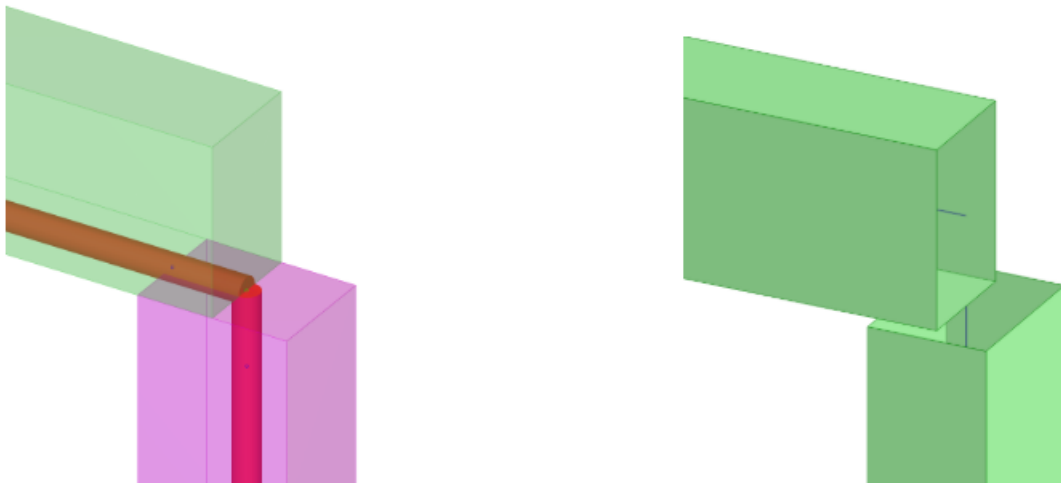


Figure 13 - Difference in the analytical model between Tekla Structure and Robot SA Pro, on the left the analytical model in Tekla Structures, on the right analytical model in Robot SA Pro, taken from [\[31\]](#)

In the last tests on the steel platform structure, and the steel conveyor bridge, the same problems faced in the previous experiments arise even considering different combinations of software.

A common problem in every case is that by default the analytical line of a beam is located at the top surface of the element in BIM applications whereas it is at the center of the cross section in the Structural analysis software.

BIM Software Capability and Interoperability Analysis – Taher (2016) [\[32\]](#)

Taher in its thesis presented in 2016 made an assessment of all the various types of interoperability data exchange, including direct and indirect link via IFC, DWG, and CIS/2 formats, proposing both BIM-to-BIM and BIM-to-FEM tests. The tests are divided in two categories: simple BIM-to-FEM cases, where a simply supported steel column and a simply supported timber beam models are exchanged between Revit, and Robot Structural Analysis Pro or STAAD Pro and then analyzed, and both BIM-to-BIM and BIM-to-FEM exchange of a three-dimensional steel structure between Tekla Structure, Revit, Robot, and STAAD Pro.

The analyzed parameters are:

- Section properties (dimensions, area, moment of inertia, etc.)
- Geometry (length, and effective length)
- Material properties (yield stress, elasticity, density, and shear modulus)
- Loads (load magnitude, and load position)
- Boundary conditions (fixed, pinned, and roller)
- Design data (moment capacity, shear capacity, design factors, etc.)
- Results (deflections, section forces, and Euro code check by employing FEM)

The first evaluation of simply supported steel column tests giving as a result that the direct link from Revit to Robot makes it possible to transfer the whole relevant data such as geometry, boundary conditions and loads. Instead using the CIS/2 format only geometrical model is transferred without any information about boundary conditions or loading, the same situation is obtained for the direct link via API between Revit and STAAD Pro.

Regarding the simply supported timber beam, only the direct link between Revit and Robot is evaluated showing the same results of the steel column.

The BIM-to-BIM evaluation of the 3D steel frame structure is performed giving as results that, using both IFC and CIS/2, the BIM model is missing structural data such as loads and boundary conditions. However the geometry and the entire members profiles are transferred correctly. Instead, using DWG file, only the geometry is transferred.

In the last BIM-to-FEM test, models are created both in Tekla, Revit, and Robot. These in the first two cases are exported in STAAD using CIS/2, the same format is used for a

Robot to Revit exchange, in addition to a direct link test. The results show that again the direct link is the best solution, instead via CIS/2 some data are missed especially with columns profiles, no loads could be imported into STAAD Pro, and some members are lost. At the end the last S-BIM tool test via CIS/2 from Tekla Structure to STAAD Pro highlight the disability to read the format exported from Tekla.

Again a common problem, excluding the column case, is that by default the analytical line of a beam is located at the top surface of the element in BIM applications whereas it is at the center of the cross section in the Structural analysis software.

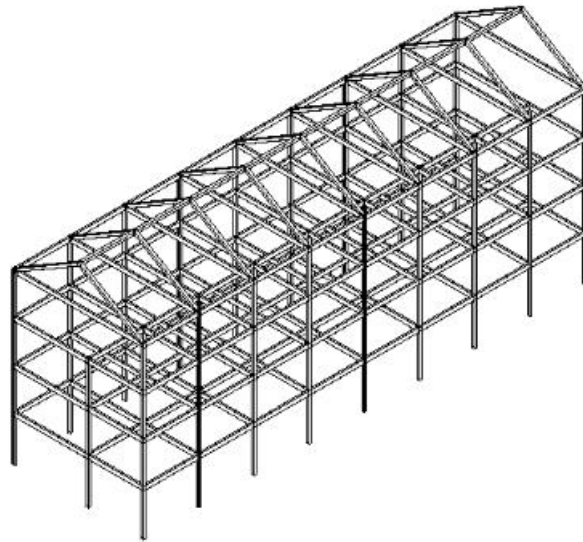


Figure 14 - 3D steel structure after exported to Revit from Tekla Structure via IFC format, taken from [\[32\]](#)

View of Data interoperability assessment through IFC for BIM in structural design, a five-year gap analysis – Muller et al. (2017) [17]

In 2017 Muller et al. present a five-year gap analysis (2011-2016) of the BIM-to-BIM and BIM-to-FEM interoperability by means of a non-specified IFC version, using as BIM application Revit and TQS for structural analysis. In this work the authors consider only cast-in-situ concrete elements, in particular the structures that are considered are: beams, columns, slabs, stairs, ramps (stairs and ramps are included in the category slabs), and a three-story building. For each category the parameters that are analyzed are: material properties, geometry, GUIDs³, placement of objects. The test procedure is not completely clear. Surely a self-roundtrip is performed, then it is assumed that the model is exported to the other program, at the end it is re-exported in IFC in both applications and compared in an IFC viewer. In 2011 TQS is not able to receive IFC files. This is a great problem perceived in the first experiment, so a big part of the transactions was incomplete. This causes users to need to import reference files through CAD systems.

The results are obtained by means of a visual check of the models. The transfers are marked as complete, incomplete, and partial. Scores in a system similar to the Likert scale are attributed: 1 to complete, 0.5 to partial and 0 for incomplete. Then an average is calculated involving all the characteristics of each element. The authors explain that in the second stage of the experiment conducted 5 years later, few changes and improvements are noticed.

What can be concluded is that in cast-in-place concrete the elements get fragmented, so to them are assigned with different GUIDs. In particular, in more complex geometries such as curved elements, or in the case of openings in slabs or walls, these are broken in small pieces. In the second case, some loads are transferred to the slabs differently from the first; furthermore, in some cases the files join permanent and variable loads.

In Figures 15-16 are show the results. It is easy to see that in both cases the biggest problem lies with the material characteristics. The authors state that: “Considering the average total score of the evaluations, it can be perceive that in the five-year gap, there was an improvement of approximately 38% (considering an average of 0.567 for the first analysis and of 0.784 for the second)”.

³ A GUID is an acronym that stands for Globally Unique Identifier used in IFC file to identify elements

OBJECT	GUID	PLACEMENT	GEOMETRY	MATERIAL	TOTAL
COLUMNS	0.583	0.667	0.500	0.383	0.537
BEAMS	0.618	0.667	0.513	0.538	0.583
SLABS	0.583	0.633	0.578	0.525	0.580
TOTALS	0.595	0.656	0.530	0.482	0.567

Figure 15 - Results from the first experiments in 2011, taken from [\[17\]](#)

OBJECT	GUID	PLACEMENT	GEOMETRY	MATERIAL	TOTAL
COLUMNS	0.780	0.800	0.740	0.800	0.780
BEAMS	0.767	0.967	0.767	0.733	0.809
SLABS	0.800	0.933	0.733	0.583	0.762
TOTALS	0.782	0.900	0.747	0.705	0.784

Figure 16 - Results from the second experiments in 2016, taken from [\[17\]](#)

Building information modeling (BIM) collaboration from the structural engineering perspective – Shin (2017) [33]

In 2017 Shin presents an assessment of the BIM-to-BIM and BIM-to-FEM interoperability by means of direct link via API and a non-specified IFC version. Using as BIM applications Tekla Structure and Revit, and Midas Gen for structural analysis. The structure is a steel and concrete frame.

In the first part BIM-to-BIM IFC tests between Revit and Tekla are performed, the model is developed in both software. One way and two-way roundtrip tests are then made for the two models. In both the cases the properties of steel and concrete column change, furthermore the steel beam property is faulty, but the rest of the material, section, and other member properties are delivered.

In the second part BIM-to-FEM tests between Tekla and Midas using direct link via API are performed. The model is developed in both software and one way and two-way roundtrip tests are then made for the two models.

In this case some differences are encountered: starting with the one-way trip from Tekla to Midas, both one- and two-dimensional elements, and the materials are transferred with no errors. However, the steel section is changed to the user-defined type.

This model is then re-exported to Tekla Structures. after attempting information transfer, the geometry of the construction model seems correct. However, omission of information or changes in the information occurs. In particular, structural material information is deleted, the wall height is changed, and the properties of the concrete beam and the column are changed to properties of steel.

On the other hand, in the one-way trip from Midas to Tekla only a small difference arises. In particular an element is divided into two at the X-brace intersection. After the re-export in Midas the model shows no modification.

The author concludes that: “Practical applications of information interoperability between the BIM tools from a structural engineering perspective are a possibility”.

Interoperability analysis of ifc-based data exchange between heterogeneous bim software – Lai et Deng (2018) [34]

Lai et Deng in 2018 analyzed the data exchange of a structural element using IFC format (no specified version) between 3 BIM software, respectively: Archicad, Tekla Structures, and MagiCAD for Revit⁴. In this work a beam and its reinforcing bars are investigated. The procedure is clearly stated: the model is built in Tekla Structures and then exported in IFC format. These exported IFC models are imported into Archicad and MagiCAD. After that the two obtained models are re-exported again in IFC format. At the end these re-exported IFC files are imported into a third-party IFC Viewer, and the differences are analyzed. To evaluate the data exchange the parameters that are considered are: type, geometry, color, property, relation. In the evaluation of the results three scores are designed: 1 for completely correct, 0.5 for partially correct, and 0 for completely incorrect. The results are shown in Figure 17. These values are obtained by means of the following considerations.

Structure	Beam	0.667	1.000	0.714	0.857	0.667	0.781
	Reinforcing bars	0.667	0.857	0.714	0.929	0.667	0.767

Figure 17 - Average scores to evaluate the interoperability for test objects, taken from [34]

When a model is re-exported there are significant differences in file sizes, IFC entities, and property sets. In addition, there was no IfcBeam or IfcReinforcingBar entity in the MagiCAD model. An important aspect is that the file size of the Archicad model has dramatically increased by 19,388.4%. The cause is that domain-specific software tools have domain knowledge to represent the information in their own disciplines. However in some cases is possible that a program interpret specific information from other disciplines, in this case Archicad is much more specialized for architectural tasks and provided IFC architectural elements.

Another aspect is that the entities of the beam and reinforcing bars in the initial Tekla model change from IfcBeam and IfcReinforcingBar to IfcBuildingElementProxy in the MagiCAD model. Through visual inspection, geometrical mismatch representations of re-exported models are present, in particular in the MagiCAD model, only a part of

⁴ MagiCAD for Revit is an add-in for MEP designers using Revit and it is not a stand-alone software

reinforcing bars were displayed. Instead, even if the IFC object entity for the reinforcing bars in Archicad model is `IfcReinforcingBar`, the same as the original one, the geometry is represented in a more complex way, resulting in a different file size. In addition in the MagiCAD model the names of the elements are misrepresented, and the total weight of the reinforcing bars is lost.

Also the relation between concrete objects and reinforcing bars is important and it is referred to by `IfcRelAggregates`. A huge difference is highlighted, in the MagiCAD model only 3 `IfcRelAggregates` entities are present, instead in Archicad model the number is 297, as the original Tekla model.

The authors conclude that: “According to total average scores in test criteria, the geometry and property perform the best among existing criteria, and the most serious issue is the relation information, which has a lowest average score”.

BIM Interoperability for Structure Analysis – Ren et al. (2018) [\[35\]](#)

Ren in 2018 conducted simple experiments in order to evaluate the BIM-to-FEM data exchange using several structural analysis software such as ETABS, SAP 2000, and Robot Structural Analysis Pro. The exchange is performed using non-specified versions of IFC files, these are imported from Revit, in order to conduct structural analysis. Four types of steel objects are used, namely, beam, column, slab, and wall. The material is not specified.

During this import/export process, a few problems occurred that caused unsuccessful import/export results. For example, when IFC files were created in the Autodesk Revit Structure and imported into Autodesk Robot for structural analysis, material property is missing. In the other cases a proper mapping of material and section properties is necessary. Instead, general loads information cannot be loaded as well as boundary conditions.

From architectural design to structural analysis : a data-driven approach to study building information modeling (BIM) interoperability – Aldegeily (2018) [36]

Aldegeily (2018) propose a complete analysis of the interoperability considering three types of BIM-to-FEM data exchange: via direct link through native file, via direct link through API and via indirect link using non specified version of IFC. In its work one concrete and one steel frames are tested. The BIM software are Revit and Tekla, instead the FEM programs are Robot Structural Analysis Pro, ETABS, SAP 2000, STAAD Pro, SAFE, and RISA 3-D.

Information missing are observed in all cases. In particular, all types of boundary conditions in Revit, when are transferred to ETABS and SAFE programs, are treated as pinned. It is noted that the values of multiple material properties such as elasticity modulus, shear modulus, Poisson's ratio and thermal expansion coefficient are changed during the data transfer. Also self-weight is not present in the exchange.

Considering the direct link, some differences are encountered between steel and concrete case. The section properties of concrete like the area and the moment of inertia are not transferred. Instead in the exchange between Revit and SAFE, all the information disappear. Then some particular situations arise, boundary conditions are also missing when transferred to SAP2000 or STAAD Pro. Only in the case of STAAD Pro the loads are lose.

The main problem of data transfer using the indirect link through IFC, in addition to losing self-weight load and boundary conditions, is the missing of loads and load combinations. Also model instability and nonpositive stiffness properties are observed in data transfer results through IFC. This is due to the position of the analytical line that is defined incorrectly in the IFC file, again this is due to the loss of connection between the elements. Just some section properties are maintained.

In the conclusions is stated that:” The experiment showed that all the three types of paths involved a certain level of information missing, where the indirect link through IFC showed the most information missing”.

Evaluation of Interoperability in Construction Programs Using the IFC 4 State of The Art – Quintero (2018) [\[37\]](#)

Quintero in his work of 2018 analyze BIM-to-BIM and BIM-to-FEM interoperability using IFC4 and two different MVDs: Design Transfer View and Reference view. As a case study, a four-story project is considered. The structural material that is used is concrete and the sections are rectangular. The BIM software are Revit and Allplan. Instead Sap2000 is used for structural analysis.

Two separate types of tests are performed. The first in which BIM-to-BIM potentialities are analyzed with a one-way exchange. In practice, the same model is developed in Revit and Allplan, and then it is exported into the other software. Instead, in the second test, the model is created in Sap2000 and then exported into the two BIM software using IFC4. At the end the models are again re-exported back to the BIM application.

What emerged from the results of the first test from Revit to Allplan is that several elements are lost in the imported model, also the grid was not imported. Instead, the imported elements that are not lost during the interchange, are accurate in terms of location, dimensions, and materials. Furthermore, most of the elements are not correctly joined. This result is valid for both the cases of Design Transfer View and Reference view MVDs. Considering instead the opposite situation of Allplan to Revit exchange, materials, geometry, and location of the elements are not accurate. In this case the structural model interoperability is very bad.

Concerning the second test, it is important to note that Sap2000 has two possible MVDs, they are Architectural Coordination and Structural Analysis. Although the model was exported using both options, in the Structural Analysis exportation no element was created in Revit. The results of the Architectural Coordination exportation are mentioned. All the elements are created with consistent dimensions. However grids are not imported, and there are some interoperability problems with the element families and properties. Again, the intersections between elements are not correct. Also in terms of parametrization some drawbacks arise, in particular the vertical elements have only the base floor parameterized, and not the top floor. Regarding the re-export to Sap2000 what emerges is that grids and levels are not imported, all the elements are disconnected and are not drawn in the middle of the axis. All the materials and frame section properties are

imported correctly. These considerations are valid both for Design Transfer View and Reference view MVDs.

Instead, in the case of link between Sap2000 and Allplan the importation is very accurate. All the elements, except one, are imported with the correct location, dimension, and material assignation. The only element ignored is not a regular rectangular section, but an I section. Again the problem of the intersections arises. When the IFC file created in Allplan is re-opened in SAP 2000, no element or grid are created. However, materials and sections properties are created.

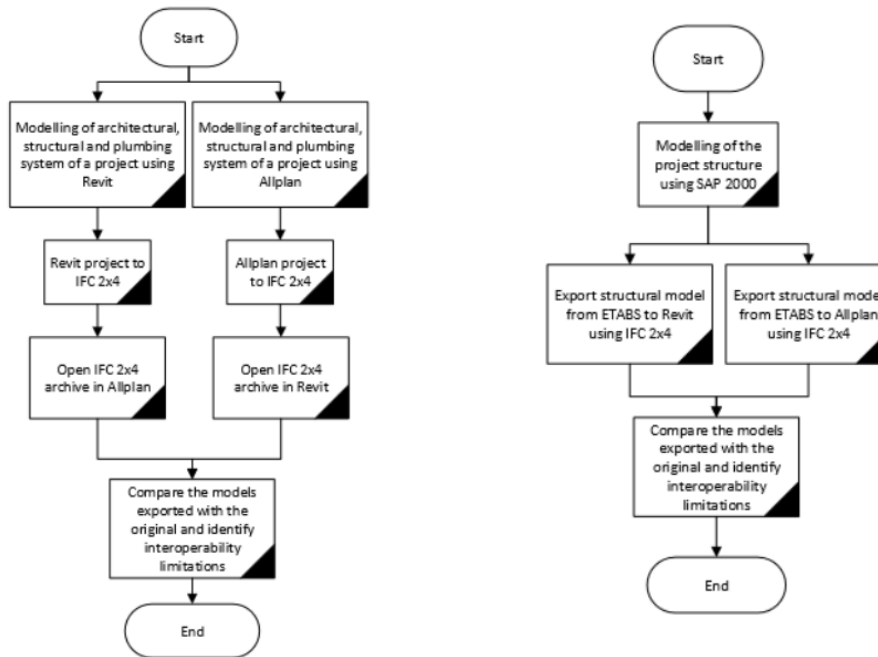


Figure 18 - Workflows used by Quintero to evaluate data exchange, on the left between Revit 2019 and Allplan 2018 using IFC4, on the right between SAP 2000, Revit 2019 and Allplan 2018 using IFC4 Taken from [37]

Analysis of the interoperability from BIM to FEM – Beirnaert et Lippens (2018) [38]

Beirnaert et Lippens in their thesis of 2018 analyzed BIM-to-FEM interoperability using different approaches: via direct link through native file, via direct link through API, and via indirect link using both IFC2x3 in Coordination View 2.0 and IFC4 in Reference View. The simple case of a steel and concrete beam is considered. Many software are used: for BIM Revit, Tekla Structure, Archicad, AECOSim Building Designer, and Vectorworks, for FEM Robot Structural Analysis Pro, STAAD Pro, ETABS, SCIA Engineer, FEM-Design, and RFEM.

In all the cases, except one, it is not possible to export Reinforcement from BIM to FEM software. Furthermore, the analytical model is always set in the middle of the element, so the coordinates are different, and only in a few cases this does not happen. Below the drawbacks related to each case are reported:

- Considering direct link between Revit and Robot no problems are encountered ;
- In Archicad link via IFC to Robot, a clear difference between the steel section and the concrete section can be noticed. It is possible to conclude that the only property of the models that is imported correctly in both cases is the geometry, indeed in Archicad, it is not possible to define boundary conditions, apply loads on the model;
- In AECOSim link via IFC to Robot the same results of Archicad are obtained;
- In Tekla link via IFC to Robot steel beam cannot be imported, the rotation of the cross section, the name of the profile and the height and width are correctly transferred. No material parameters are imported as well as boundary conditions, load cases and combinations;
- In Vectorworks link via IFC to Robot, the concrete beam case is similar to the Tekla one, instead the steel beam case can be imported but with more problems than the concrete case;
- In Revit direct link to SCIA the same optimal results of Revit to Robot exchange are obtained. The only difference is that in this case a mapping is necessary for steel sections;
- In Revit link via IFC to SCIA similar results to direct link case are obtained. The mapping process is slightly more complex. In addition the loads and constraints

are not exchanged. Differently than any other case, the reinforcement is correctly transferred;

- In Archicad link via IFC to SCIA the geometric transfer is not properly done, in particular in the concrete case the height and the width are switched, furthermore, boundary conditions, loads, loads cases and combinations could not be modelled in Archicad;
- In AECOSim link via IFC to SCIA no data exchange is possible;
- In Tekla link via IFC to SCIA, boundary conditions, loads, loads cases and combinations are not exported;
- In Vectorworks link via IFC to SCIA the same problems of the Robot case arise;
- In AECOSim and Revit direct link to STAAD Pro, only in Revit most of the section and material properties of the steel and concrete beam are properly imported. Instead exclusively in the case of the concrete beam modelled in AECOSim, the loads, load cases and load combinations could be transferred to STAAD Pro;
- In Revit link via IFC and direct link to RFEM, in the IFC case none of the properties of the steel profile are transferred. Also the material properties present a partial data exchange. Furthermore, only boundary conditions can be exported. In both cases boundary conditions are sometimes exchanged;
- In AECOSim direct link to RFEM the boundary conditions and the properties of the loads are not converted. Also the material properties are not all transferred without a proper mapping;
- In Archicad link via IFC to RFEM the steel section properties are not exported as well as the material properties, the values for the height and the width of the profile are switched, boundary conditions, loads, loads cases and combinations are not exported;
- In Tekla link via IFC to RFEM the steel section properties are not exported as well as the material properties, boundary conditions, loads, loads cases and combinations;
- In Vectorworks link via IFC to RFEM in the steel case, the geometric and the section properties are not exported as well as the material properties. In both cases boundary conditions, loads, loads cases and combinations are not exported;

- In Revit direct link to ETABS, model exchange is not possible due to the small dimensions of the model;
- In Vectorworks link via IFC to ETABS only the length of the beam is correctly exported in steel case. Instead in the concrete case some section properties can be exchanged. In both the cases boundary conditions, loads, loads cases and combinations are not exported;
- In Revit link via IFC to ETABS, in the steel case only the length of the beam is correct. The rotation of the beam is not exported. Some of the section and material properties can be lost. Also some properties of restraints are lost, but not completely. In the concrete case the height and the width are switched;
- In Archicad, AECOsim, and Tekla link via IFC to ETABS, similar results as Revit are obtained with the exception of a complete loss of Restraint data;
- In Revit direct link to FEM-Design the only problems are related to section mapping, but these are small problems;
- In Archicad, AECOsim, and Tekla link via IFC to FEM-Design only the boundary conditions, loads, loads cases and combinations are not exported;
- In Vectorworks link via IFC to FEM-Design the same problems of the previous case are obtained. However steel profiles are not exported.

Improvements for the workflow interoperability between BIM and FEM tools – Birkemo et al. (2019) [39]

Birkemo et al. in 2019 propose a BIM-to-FEM analysis using direct links, via both native file and API. In this case study a Precast and cast-in place structure is analyzed. A Revit model is developed and then transferred to Focus Konstruksjon, Robot Structural Analysis Pro and SOFiSTiK. In Figure 19 is reported a summary of the drawbacks encountered.

Workflow	Challenges
Revit to Focus	<ul style="list-style-type: none"> • Unable to find steel cross section profiles in Focus RAT • Experienced instability of the model • Unable to export some of the structural elements due to inaccuracies in the AM • Discontinuity in AM • Missing common node in shell → line intersection
Revit to Structural Robot	<ul style="list-style-type: none"> • Unable to find some cross-section profiles • Instability of the model
Revit to SOFiSTiK	<ul style="list-style-type: none"> • Missing or dislocation of nodes • Missing of line intersection points

Figure 19 - Summary of challenges and solution, taken from [39]

According to the results, a lot of geometric errors appear after transferring to FEM applications. The most recurrent errors are: discontinuity in connection points (e.g. slab to column), overlap of line segments (e.g. prefab slabs overlapping) and continuous columns going through several floors. Regarding material properties, loads, and restraints no information are reported. The most reliable situation is the one of direct link via native file between Revit and Robot.

Aspetti di interoperabilità nella digitalizzazione di infrastrutture esistenti con metodologia BIM: il caso studio del ponte Balbis di Torino – Maddaluno (2020) [40]

In 2020 Maddaluno presents a work in which the interoperability between Revit and Sap2000 for an existent bridge is evaluated. An already existent model is present, but the author observed that it cannot be used for the purpose of interoperability with structural analysis software due to the absence of the analytical model. For this reason some portions of the model are rebuilt. Both the IFC data exchange and direct link via API are used.

Considering the IFC case, where both IFC2x3 Coordination View 2.0 and IFC4 Reference View are used, it is possible to see that there are several problems that make the model unsuitable for structural analysis. The first obvious problem is related to the position and geometry of the structural elements. For linear elements continuity is lost, while for two-dimensional elements the wrong structural surface is associated. It is possible to notice that the piers, the arches, and struts that connect the arches and the deck are not imported into the SAP2000 model. Also material properties and restraints are not included.

Concerning the direct link via API. Piers are imported into the structural calculation software, but some problems with the section are present, as a matter of fact their properties are not transferred. However, the constraint conditions and the material properties are exchanged correctly.

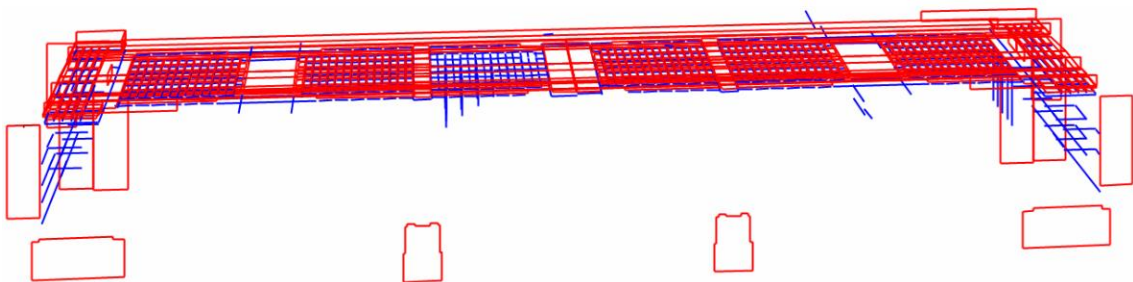


Figure 20 - Front view of the misrepresented analytical model exported via IFC, taken from [40]

Assessment of model-based data exchange between architectural design and structural analysis – Sibenik et Kovacic (2020) [18]

In 2020 Sibenik et Kovacic published a work where a BIM-to-FEM case of a real structure composed by foundations, columns, walls, slabs, and roof is analyzed. The tested BIM software are: Allplan, Archicad and Revit, while as structural analysis software SCIA and RFEM are used. An indirect link by means of IFC2x3 Coordination view 2.0 is used.

The results show that the correct import and interpretation of building elements depends on the combination of software tools used, indeed the IFC files contain different numbers of entities, however building elements are represented similarly, with the same IFC classes. From the geometrical point of view, the interpretation of punctual elements and of the connectivity of interpreted building elements did not take place in any of the cases. Linear and planar building elements are in some cases interpreted, but different performances are encountered depending on the combination of software.

Investigation of data sharing in the Structural Eng. domain.–Rafeequl(2020) [42]

In 2020 Rafeequl presents a thesis in which the BIM-to-FEM interoperability using IFC4 Reference View is analyzed. A steel and concrete structure is modelled in Revit. Then it is exported in the IFC4 file. This file is analyzed into an IFC viewer called FZKViewer, and at the end it is re-exported and imported into SCIA Engineering software.

The basic problem that is encountered is that in the nodes the elements are disjointed. All the aspects related to material and section properties, as well as loads and restraints are not mentioned.

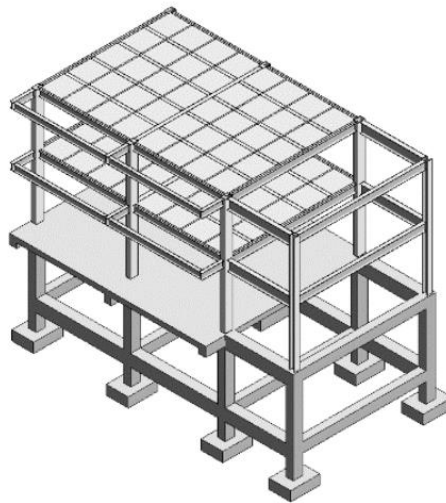


Figure 21 - Model proposed by Rafeequl, taken from [\[41\]](#)

Web-Based Tool for Interoperability among Structural Analysis Applications – Shoieb et al. (2020) [\[42\]](#)

Shoieb et al. in 2020 perform an assessment of FEM-to-FEM analysis using IFC2x3, IFC4 and CIS/2 formats. The same level of interoperability for IFC2x3 and IFC4 is observed. The following software are considered: Sap2000, ETABS, Robot Structural Analysis Pro, STAAD Pro, and RFEM. The evaluated parameters for the information exchange are: geometry (dimensions and coordinate system), section properties (dimensions, area, moment of inertia, etc.), isotropic material properties for steel and concrete (unit weight, Young's modulus, shear modulus, etc.), boundary conditions (fixed, pinned, and roller supports), and loads (magnitude and direction). The evaluation of the quality of interoperability is performed considering three possible results: complete transfer, incomplete transfer, and partial transfer.

The results that are obtained are reported in Figure 22. Although a simple prototype model is used for the assessment, many drawbacks are observed.

No.	Sender to receiver	Mediator	Geometry dimensions X-sections				Material	Boundary conditions	Loads	Evaluation
			Frame	Shell	Frame	Shell				
			1	2	3	4				
1	SAP2000 to ETABS	IFC	X	X	X	X	X	X ^a	X	7/7
2	ETABS to SAP2000	IFC	X	X	X	X	X	X	X	7/7
3	SAP2000 to SPro	CIS/2	X	I	X	I	I ^b	P ^c	X	3.5/7
4	SPro to SAP2000	*.std	X	X	X	X	X	X	X	7/7
5	SAP2000 to RSA	IFC	X	X ^d	X	X	X	I	I	5/7
6	RSA to SAP2000	CIS/2	X	I	I	I	I ^e	X	I	2/7
7	SAP2000 to RFEM	IFC	X	X	X	X	I ^e	X	I	5/7
8	RFEM to SAP2000	IFC	X	X	X	X	I ^e	X	X	6/7
9	ETABS to RSA	IFC	X	X ^d	X	X	X	I	I	5/7
10	RSA to ETABS	CIS/2	X	I	I	I	I ^e	P ^c	I	1.5/7
11	ETABS to SPro	CIS/2	X	I	X	I	P ^f	P ^c	X	4/7
12	SPro to ETABS	*.std	X	X	X	I	P ^g	X ^a	X	5.5/7
13	ETABS to RFEM	IFC	X ^h	X	X	X	I ^e	X	I	5/7
14	RFEM to ETABS	IFC	X	X	X	X	I ^e	X ^a	X	6/7
15	RSA to SPro	CIS/2	X	I	I	I	I	P ^c	I	1.5/7
16	SPro to RSA	CIS/2	X	I	I	I	I	X ⁱ	I	2/7
17	RSA to RFEM	CIS/2	X	I	I	I	I ^e	X	I	2/7
18	RFEM to RSA	IFC CIS/2	I	I	I	I	I	I	I	0/7
19	SPro to RFEM	CIS/2	X	I	I	I	I ^e	X ⁱ	X	3/7
20	RFEM to SPro	CIS/2	X	I	I	I	I	P ^c	X	2.5/7

Figure 22 - Results of the interoperability test performed by Shoieb, taken from [42]

The main conclusions are:

- The shell element cannot be transferred to STAAD Pro from all structural applications through the CIS/2 link, and the boundary conditions connected to the missing shells are also missed. STAAD Pro does not support the IFC standard;
- STAAD Pro exports the roller support with an incorrect form of restraints when using the CIS/2 link;
- The loads cannot be transferred to the Robot from all structural applications under investigation through IFC or CIS/2;
- The IFC mediator file provides successful results for material properties transfer through the processes SAP2000 to Robot and ETABS to Robot;
- There is no link for information exchange from RFEM to Robot;
- Due to a successful mapping for the direct conversion from STAAD Pro to Sap2000 through the STAAD Pro file, the information is transferred correctly. However, interoperability problems may arise if either of the mappings is wrong;
- Sap2000 and ETABS provide a high level of interoperability.

BIM interoperability in structural analysis – Atia (2021) [43]

Atia in its thesis of 2021 exploit an interoperability analysis based on direct links both via native file and API. As BIM software Autodesk Revit is used. Instead, as FEM software Midas gen, ETABS and Sap2000 are used. Single elements of various shape, steel and concrete frame, as well as steel and concrete multi-story buildings. An evaluation of the results is reported below showing good results with the exception SAP 2000.

Revit Category	Robot Structure	Midas Gen	Etabs	Sap 2000
Grids	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Levels	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Material	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Structural Framing	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Structural Column	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Structural Walls	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Structural Slab	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Loads	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Boundary Conditions	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓

Figure 23 - Results from the interoperability test of Atia, taken from [43]

Robot structure shows excellent integration with Revit through the direct link via native link. Only hosted area load ignores the sketched area load.

Similarly, Midas Gen validates excellent integration with Revit through the direct link via API. Some small drawbacks arise: missing of wall’s boundary condition, problems with the self-weight, and the limitation of considering only hosted area load as Robot.

Regarding ETABS and Sap 2000, even if they belong to the same software developer, they produce different interoperability results. ETABS compared to Sap 2000 need minor rework once it is exported. ETABS appear to have few limitations concerning mapping of beam and column profiles, missing support for circular openings, and with boundary conditions. Sap 2000 limitation is extended to include the adjustments related to levels, curved profile for both slabs and walls, the non-integration of all kinds of opening and boundary conditions.

In general the concrete case study shows better results, indeed significant efforts are needed in the mapping of the steel family types from Revit structure into the FEM software databases.

In conclusion the author states: “Straightforwardly, the two case studies provided excellent interoperability demonstrating that the interoperability had saved much time that was previously lost in the traditional CAD workflow even if some adjustments were needed”.

3.2 Comparison of the results

From the sample of works it is possible to perform some comparisons on the results in order to analyze the common drawbacks that are encountered across the research. In particular it is interesting to check if the results are coherent with each other, using as terms of comparison the type of exchange, the software combination, and the time period. In this way it is possible to determine if the role of the end user has a strong influence on the results.

Comparison of the results with the same type of exchange and software combination

In particular it is interesting to compare the results obtained using the same combination of software. This analysis is divided into two parts, one related to BIM-to-BIM interoperability, and one related to BIM-to-FEM interoperability. In the case of FEM-to-FEM exchange the comparison is not possible due to the fact that only one paper is considered in this thesis.

BIM-to-BIM case

Concerning the BIM-to-BIM case, a comparison of the results is proposed considering the Revit to Tekla Structure case. This software combination is chosen because it is the most frequent case and it is not possible to find any other relation with the same number of tests. In particular only the geometry exchange is analyzed because it is the only aspect that is considered in all the works.

Furthermore, it is possible to state that the only type of exchange is the one associated with indirect links via open standards. Indeed, in all the works, the IFC file is used as the main interoperability tool, with some exceptions in the cases where the use of alternative formats is necessary due the absence of IFC import/export tools.

Regarding problems of geometric model exchange, in general good results are obtained in all the cases. However, in one case serious problems arise. In particular, Taher [32], Sacks et al. [27], Jeong et al. [26], and Shin [33] reported no errors in the position or the dimensions of the structure, so the models do not change their geometry. Instead, Nizam et al. [29] observed some changes in the geometry, in terms of length of elongated elements such as beams and columns, and in terms of area in walls and slabs. It is not clear the reason of this difference, indeed it is not a problem of IFC/MVD version because both [32] and Nizam et al. [29] performed the tests in the same years and using the same combination of IFC/MVD (IFC2x3 Coordination View 2.0). It is not possible to state if the problem is due to the software version, because Nizam et al. [29] do not provide this information. In this case it is possible to suppose that the problem is due to a lack of knowledge in the import/export tools, that bring the author to wrong results.

BIM-to-FEM case

In this case much more combinations are possible, in particular the cases that are considered are:

- The Revit to Robot Structural Analysis Pro direct link via native file.
- The Revit to Sap2000 direct link via API.
- The Tekla to Robot Structural Analysis Pro indirect link via IFC.

Considering Revit to Robot direct link via native file, the works of Drávai et al. [31], Taher [32], Aldegeily [36], Beirnaert et al. [38], Birkemo et al. [39], and Atia [43] are used in the comparison. Very similar results are obtained. In all the cases the geometric model is correctly exported as well as the restraints. In almost all the cases are reported small problems with the mapping of sections and with the absence of self-weight load in the exported model. Small problems with some mechanical properties missing are cited in two works, these are uncorrelated and are not present in all the other cases. The same situation arises for loads, indeed in one case some problems with distributed loads are encountered but these are not present in the other cases.

Considering Revit to Sap2000 direct link via API, the works of Silveira Azevedo [28], Aldegeily [36], Maddaluno [40], and Atia [43] are taken into account. In particular, the geometry is always exchanged correctly in the beam elements, instead some problems related to shell elements arise in the representation of voids. Concerning the material properties and loads, good results are obtained with small imperfections in the case of

missing of thermal expansion properties. On the other hand, the section properties encounter in all the cases more problems. The restraints are not exchanged, only Maddaluno [40] showed the possibility to export them.

Considering Tekla to Robot Structural Analysis Pro indirect link via IFC, two cases are considered, Drávai et al. [31] and Beirnaert et al. [38]. In this case very bad results are obtained in both works. The geometry shows the common problem present in all the works where IFC exchange is used, the disconnection between the elements. In addition, all the loads and the restraints are lost. Furthermore, in these papers the disappearing of steel elements is commonly present, as well as the problems with some material properties. The situation that gives less problems is the exchange of section properties, where slightly better results are obtained.

It is also possible to present some common results, in particular considering the direct link exchanges via native files, all the research always provide very good results, and they are never in contrast. Also analyzing the results of the IFC data exchange, it is possible to state that in every combination of software the problems are always the same: geometrical misrepresentation of nodes, complete loss of information regarding boundary conditions, loads, and load combinations.

So in general in all the cases the works present almost the same results. However some “deviations” are observed between the shortcoming highlighted by the authors. Furthermore, in this case is much more present the omission of information regarding IFC and MVD versions. So, it is not possible to define if the differences are related to the use of wrong versions of MVD, to a non-proper use of the interoperability tools provided by the software, or to a lack of knowledge. As well, it is clear that it is not possible to perform the same test. However, in all the cases it is possible to state that is a matter of human error.

Comparison of the results in time

It is necessary to present some considerations that emerged from the analysis of the evolution in time of the problems and of the aims of interoperability.

Considering the timeframe of the samples, a higher level of attention is emerged in BIM-to-BIM cases in late 00s. On the other hand BIM-to-FEM papers are much more present from 2015 on. This distribution in time can be explained considering the evolution of BIM level of development and adoption across the world during the years. Indeed, in

2006 the IFC2x3 is released, and the BIM programs in the first years of the millennium are performing a rapid distribution and evolution in the AEC market. For the first time the problems of interoperability influence the processes of construction firms, and so adequate studies are needed. The very first basic need is the data exchange between BIM software. Once that the problem is analyzed, and under some aspects, solved, the next step is the necessity to exchange data with the other applications of the different professionals involved in the design of the building. However, this necessity becomes crucial only from half of the 10s where the national and international standards start to mandate the use of BIM. It is in this framework that the necessity for a structural engineer to exchange models between BIM and FEM codes become evident, and so many researchers start investigating this problem.

Concerning the results, not so many differences are encountered across the years. This becomes much more evident when comparing the results using different IFC versions. Indeed, no significant differences are highlighted from the authors. This is a concerning aspect, but it is not so difficult to foresee due to the fact that the most important differences of IFC4 version with respect to the IFC2x3 version are related to infraBIM, and not so much attention is related to the aspect of structural analysis. However, a huge difference is related to the enhancement of the IFC import and export tools present in the commercial software. For example in 2009 Jeong et al. [26] highlights the absence of import tools for AECOSim Building Designer, instead nowadays it is possible to import files up to IFC4 version. Nowadays, almost every BIM software is able to import or export IFC files, and most MVDs are implemented. On the other hand, even if a positive trend is experienced, a lack of proper import and export tool in FEM software is experienced, as can be observed in the work of Shoieb et al. [42], where many programs show no possibilities in the exportation/importation of IFC files. Even if not many changes are encountered through the last years, the level of attention of the topic is continuously increasing as it is proved by the high number of works published in the last five-year period.

The reason for the stationarity of the shortcomings in time, in particular concerning IFC, is related to the fact that the need of interoperability in the structural engineer workflow is a relatively new topic, and the market is trying to accomplish it. It is possible to go deeper. Indeed, one big problem is that at each release, the IFC files become more and more complex and structured, and this drastically increases the time necessary for the

implementation of new formats. This is evidently highlighted by buildingSMART in a report of the future plan [44]: "Many of the advanced structures in IFC have been proven to be too complex for software vendors to implement. The time that vendors need to implement IFC is too long, and for vendors that have lower commercial interest in supporting IFC the threshold becomes too high. This results in half-baked implementations that cause problems for end-users". This statement can partially explain the problems experienced in the tests.

For this reason starting from the next IFC version a new philosophy will be followed with the aim to: "(...) move from bespoke solutions and technology to generic technologies and solutions that are scalable, widely adopted and work in a broad range of tools (...). The challenge is to make the IFC schema modular. This will improve stability and quality assurance during maintenance and create more reliable implementations and increase predictability in release cycles" [44]. Is thus clear the will of buildingSMART to rebuild the IFC format from the IFC5 version and the hope is that this "restyling" of IFC format will also improve the interoperability in structural engineer workflow.

3.3 Final considerations

At the end the state-of-the-art of the interoperability in structural engineer workflow is presented making use of some questions for which a professional, who has never faced the topic, may need an answer.

Is the level of interoperability sufficient for structural engineering scopes?

At the moment, the answer to this question is yes! But it is sufficient in just a few cases, and it is strongly associated with the type of data exchange and the combination of software. Considering BIM-to-BIM exchanges, the indirect link via IFC is the most available and widely used approach. However, some problems concerning geometry and information loss may arise depending on the software. It is important to know that every software has its own semantic, and this is reflected in the IFC files in terms of file dimension, number, and type of entities. This difference in semantics may lead to the loss of reinforcing bars in concrete structures, or problems with holes in planar elements like walls and plates.

Concerning the BIM-to-FEM case, that represents the core of the structural engineer workflow, only direct link via native file gives the certainty to be able to provide an acceptable level of interoperability, all the other types of exchange may lead to higher or lower number of misrepresentations of the native model. In particular, the indirect exchange via IFC file provides awful results in terms of geometry, loss of restraints, and loads.

Instead in the FEM-to-FEM case, the implementation of IFC exporting tools is still lacking in the industry and this is reflected in a low number of research on the topic. However, the level of interoperability is generally high and IFC files are nowadays a better solution rather than some other types of formats like CIS/2.

Are the type of exchange and the combination of the software influencing the outcomes?

Considering the results it is possible to state that the type of data exchange strongly influences the interoperability. Regarding the BIM-to-BIM case, only the model exchange via IFC format is evaluated, and no big differences between the IFC versions

are encountered. Instead the drawbacks of BIM-to-FEM data exchange are extremely different depending on the type of data exchange that is decided to use. It is possible to choose between a direct link or an indirect link. Even considering the direct link, the use of native formats rather than API would change the outputs.

In particular, it is evident from the conclusions in the literature, that the direct link via native files provide excellent results with respect to all the other methodologies. The geometrical model is always properly exported, as well as material and section properties. Also loads and restraints are exchanged. The only problem is related to the loss of the levels and grids, but this does not influence the possibility of performing a complete structural analysis.

Furthermore, another aspect to be taken into account is the possibility of bidirectional connectivity. This is a key feature in the BIM workflow, because it gives the possibility to build the model into the BIM environment, export it into FEM code, perform the structural analysis, design and check the elements of the structure (possibly updating the section or the material), and to re import the updated model into the BIM program (also with the opportunity to exchange the rebar in the concrete structures). It is not possible to talk about BIM approach without the possibility to perform a bidirectional data exchange. This is also the aim of the IFC open standard. It should provide the base to enhance communication between software that work with different semantics in a biunivocal way.

In agreement with the findings of the researchers, the less interoperable situation is experienced in the exchange using IFC files. In particular the worst problem is associated with the misrepresentation of the analytical model of the structure. In some cases the position of the elements is lost, but the biggest problem is the missing of links between the elements in the joints. Indeed, in BIM programs there is the possibility to develop in parallel to the 3D physical model an analytical model composed of 1D and 2D elements. Nonetheless what is reported into the IFC files is the Physical model. Thus some voids between the elements are generated. This problem in big structures not only requires time-demanding operations to be performed, but it could also be dangerous due to the fact that some mistakes in the model may not be detected, and the result of the structural analysis may be completely wrong. Another aspect is that no loads and restraints can be traded. Instead, concerning the shortcomings that are associated with material and section properties, it is possible to state that these vary depending on the program combination.

The direct link via API lies in the middle of the two above mentioned cases. Characteristics of direct link via native files or indirect link via IFC are experienced depending on the combination of the software. In some cases it is possible to experience an almost bidirectional interoperability, instead, in other situations, too much information are lost in order to perform a structural analysis without modifying the imported model.

With regard to the question: “Is the combination of the software influencing the outcomes?” The answer is yes! Very different results can be obtained, in particular in the case of direct link via API, but also in the IFC case. In this sense, significant is the work of Beirnaert et al. [38], where almost thirty combinations of BIM and FEM software are analyzed, providing a wide fan of solutions. In some cases the model is completely absent, in others no major problems arise.

In the articles of Jeong et al. [26] and Nizam et al [29] are described differences of the IFC file dimensions coming from different applications. In those cases also the number and the type of the entities are drastically different. Indeed, they start with the same model developed in different software. Once exported the dimension of the IFC files is different, as well as the number and type of the entities. In many cases the authors explained that this is due to three main aspects related to the same problem of semantic inconsistency. First, every object or information is considered differently among the software. Second, the exporting tools of the programs map the information differently, so it might happen that the same object with the same semantic in two different systems is exported into two different entities. Third, the geometric model is not built in the same way in all the software. Indeed many approaches are implemented into the programs for the generation of the element shape and volume.

For all the above-mentioned reasons, it can be concluded that the results are strongly dependent on the type of the exchange and the combination of the software.

Are the results the same for all the materials?

Another possible assessment to be performed is the evaluation of the dependency of the results on the materials that are considered. As specified in chapter 2.2.2 the materials that are considered inside the works are: concrete, that is used in both cast in place structures or in precast structures, steel, masonry, and wood.

Analyzing the outcomes presented in the sample of the literature the answer to the question: “Are the results the same for all the materials?” is no! Indeed, in some cases strong differences are experienced between these structural materials.

First of all the problem has to be faced from a geometrical point of view. In fact, the first difference between these materials is represented by their structural section. Due to the better mechanical properties as well as higher specific weight, steel elements are produced in I, L, T, C profiles. Instead, concrete and wood, due to lower resistance and a lower density, need a rectangular or circular section. This difference is important during the mapping stage; steel section in the BIM environment needs a counterpart into the FEM environment, otherwise the section is arbitrarily chosen by the software or the element disappears. Instead in rectangular sections, it is common that only the height and the width are exchanged, in this way the code uses these two properties to compute all the other properties of the section.

Instead, considering just the material attributes, every material has its own peculiar and common properties with respect to the other materials. For example Young modulus or density are common characteristics, instead yield stress for steel, cylindrical strength for concrete, and tension strength parallel to the fiber for wood are properties peculiar only for each single material. Considering the common ones, it is possible to state that these are always correctly exchanged or not completely exchanged depending from the type of exchange, but not depending from the material, as it can be seen in the works of Drávai et al. [31], Beirnaert et al. [38], Taher [32], Muller et al., and Shin [33]. Instead the peculiar properties are strongly dependent on the type of the material, indeed in some cases, the common properties are transferred, but the peculiar ones not.

It is important to highlight that in some cases it is necessary to also map the material. Every software has its own approach, and could bring different results, indeed in some combinations of programs, very bad results are experienced. A clear example of this is encountered in the works of Drávai et al. [31], Beirnaert et al. [38], where during the sharing of the IFC model between Tekla Structure and Robot Structural Analysis Pro all the steel elements vanish. It is concluded that this problem is due to the mapping process because the same operation in other software such as SCIA, ETABS, etc., the steel members are not lost.

Is it just a problem of the applications or is it also a problem of the end user?

The answer is no! Also the final user needs to be conscious that a good knowledge of the exporting and importing tools of the software as well as of the IFC structure is needed. Indeed, almost all the software that are able to exchange data in a direct way by means of direct link via API, provide mapping tools to match the section and material properties of the model into the two programs. So a proper knowledge of these tools is required to reduce as much as possible the number of mismatching and misrepresentations.

Another aspect, again related to the direct link via API, is that in BIM programs the position of the analytical line is placed differently than the FEM software. In particular, in BIM codes the analytical line (or surface in case of walls and plates) is placed on the upper surface of the element by default. Instead, in the FEM programs the element always represents the centroidal line of the section. This shortcoming can be properly fixed by the end user shifting the analytical line directly in the BIM environment, since the program allows to place the analytical line where the designer prefers the most. Birkemo et al. [39] in their work provide a set of good practices with the aim to reduce the above-mentioned risk of producing BIM models with wrong geometry, including placement of: columns, beams, prefabricated slabs, diagonal bracings, slabs, and walls.

Instead, regarding the IFC format, the user should be aware of what the IFC file includes, and which information are “filtered” by the MVD. However, in order to understand the structure of this format it is necessary that the user possess a slightly good knowledge of informatics. Indeed, buildingSMART states on the current versions of IFC that: “The current standards and solutions operate in a limited environment. The threshold to use openBIM standards is high for people that are new to the community. Many people inside the community even struggle to use some standards and solutions in an efficient way” [44]. It is important to cite that also in the exportation of IFC files it is usually provided the possibility to decide what entities include in the file, and this increases the necessity of a deep knowledge of the standard.

Which are the principal shortcomings that an end user may face during the interoperability process?

The drawbacks of the structural engineer BIM workflow are here reported, divided into the BIM-to-BIM, BIM-to-FEM, and FEM-to-FEM cases.

Concerning BIM-to-BIM exchanges, the end user should be aware of the combination of software who is intended to use, knowing that in some combinations of them many problems may arise, for example:

- Loss of elements;
- Impossibility to modify some elements once imported;
- Change of the geometry of the holes, in particular from circular to rectangular shape;
- Coordinate system shifting;
- Misrepresentation of the geometrical model, traduced in different position of elements, different length, and loss of connection between elements;
- Changing in material properties;
- Fragmentation of complex elements, such as precast facades or curved beams as it can be seen in Figure 24;
- Loss of reinforcement.

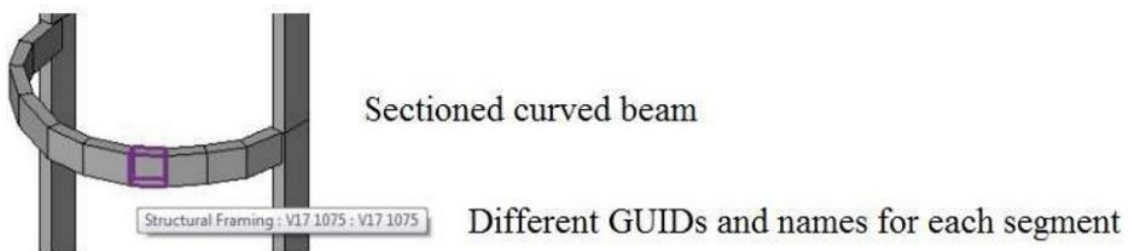


Figure 24 - Curved beam split into smaller parts, taken from [\[17\]](#)

Concerning BIM-to-FEM exchange it is necessary to make a separation regarding the type of data exchange. Again the end user should be aware of the combination of software who is intended to use, knowing that in some combinations of them many problems may arise.

In case of Direct link via native file, no particular problems arise, but in general:

- The self-weight load is not transferred;

- The reinforcement is not transferred from the BIM software to the FEM one.

In the case of direct link via API, the user should be able to properly map the sections and material properties in both BIM and FEM programs. In this case the dependency of the combination of programs shows its higher presence. Very good results can be obtained as well as very bad results. The possible shortcomings are:

- Misrepresentation of the position of the analytical model due to different positioning in the two programs, as it can be seen in Figure 25;
- Loss of elements;
- Loss of loads;
- Loss of boundary conditions;
- Loss of some of material properties;
- Loss of some of section properties;
- Exchange of boundary condition;
- Misrepresentation of the geometrical model, traduced in different position of elements, different length, and loss of connection between elements;
- Loss of reinforcement;
- Change of the geometry of the holes, in particular from circular to rectangular shape.

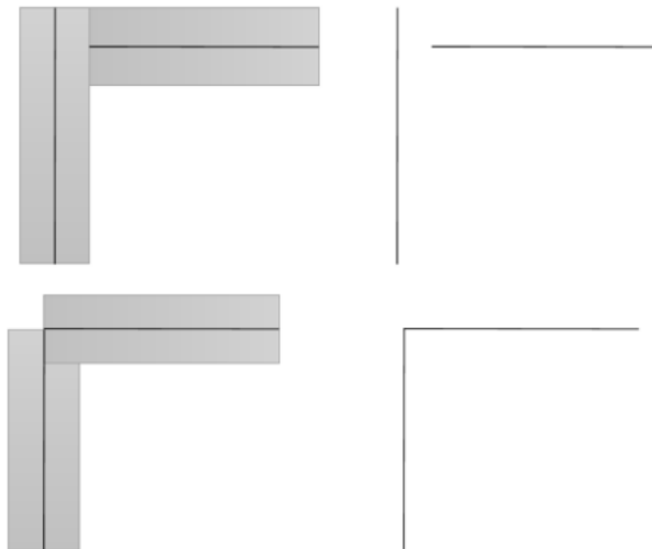


Figure 25 - Nodes dislocation due to non-overlapping members (Above) and nodes are joint at one point due to overlap of members (Below), taken from [\[41\]](#)

In the case of indirect link using IFC format, very bad results are obtained. The results are very similar to the ones of direct link via API, but are not dependent on the program and are so systematically related to the type of exchange. In particular the most severe are:

- Systematically misrepresentation of the position of the analytical model due to different positioning in the two programs, that also provide a poor representation of the joints, as it can be seen in Figure 26;
- Systematically loss of loads;
- Systematically loss of boundary conditions;

In this case the end user must be aware that huge errors are present in the geometrical model and a particular attention has to be put in the procedures of fix of the model.

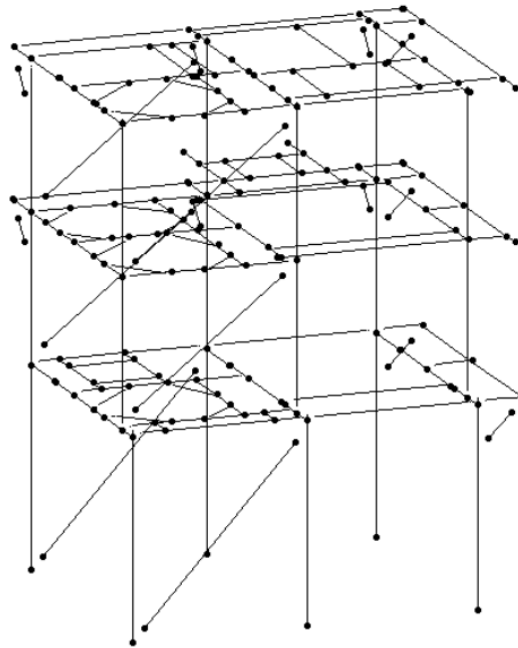


Figure 26 - Wrong analytical model exported from Revit to STAAD.Pro, taken from [\[31\]](#)

Regarding FEM-to-FEM exchange the biggest concern is the partial absence of proper export/import tools in FEM software. Indeed, despite the fact that a huge effort is put on the implementation of such tools, their availability is not sufficiently spread. However, in the cases in which these tools are properly implemented, the problems are influenced by the combination of software. Indeed, in some cases, like the exchange between SAP2000 and ETABS, all the information are exchanged. The principal loss is related to material properties.

Chapter 4. Conclusions

BIM has become established as the leading process in the complete digitalization of the modern architecture, engineering, and construction (AEC) industry. Through the last five/six years, the introduction of new standards mandates the use of BIM methodology in an increasing number of projects requiring a huge effort in terms of training of professionals, certification, etc. The structural engineer is not excluded from the group of professionals that have to change their design workflow, shifting from the use of CAD systems to the BIM environment. Many new possibilities are now given to optimize the processes, experiencing reduction of time, costs, and errors.

The necessity of exchanging models into this framework covers a crucial role, an engineer should be able to trade models without information loss in order to always have a reliable basis to work with. Furthermore, structural analysis and design, the most important processes for a structural engineer, are performed in a FEM environment, very distinct from the BIM one. For this reason also the interoperability between these two worlds is a key point to implement. In some minor cases it is also needed the possibility to switch models between the same FEM software in order to let other professionals check the models and results on which the project is carried on.

The Aim of this thesis is to investigate the methodologies and the results in the literature regarding the theme of the BIM workflow for the structural engineer considering in particular the BIM-to-BIM, BIM-to-FEM, and FEM-to-FEM model exchanges.

The work is subdivided in three principal chapters. In the first chapter the concept of BIM and BIM interoperability fundamentals are introduced in order to contextualize the framework in which the thesis is developed. In the second chapter is conducted an analysis of twenty-one works, in which many tests are performed with the aim of determining the problems related to the interoperability in the structural engineer workflow. In particular, the methodologies, the procedures, the programs, the complexity of the structure examined, and the material used are analyzed. In the third chapter the

results of the above-mentioned tests are described and compared in order to present the main problems and detect the presence of incoherencies in the results.

From the analyses of the works it has emerged that three different kinds of data exchange are present in the workflow of a structural engineer: BIM-to-BIM, BIM-to-FEM, and FEM-to-FEM exchanges. Even if all of them are important, the second one is at the core of the whole design workflow and so it needs special attention. The possibility of exchange data is provided by three types of links: direct link via native file, direct link via API, and indirect link via open formats, in this thesis the IFC format is considered as the main open format to be analyzed.

Many strategies are used by the authors to assess the interoperability. Even if the most used approach is the one-way trip, where the model follows a linear exchange from a software to another, the most important procedure is the two-way roundtrip, where the model follows a circular path between two or more software. Indeed, the possibility of a seamless information exchange in a bidirectional way is at the base of BIM methodology and represents a crucial task. Despite this necessity, only in 19% of the works the drawbacks of a two-way roundtrip are analyzed.

Another important aspect is the complexity of the structures that are analyzed in the works. As it is possible to see in chapter 2.2.2, considering the exchange of single elements many problems arise. So it is questionable the decision of more than half of the authors to focus only on composed structure, in many cases also very complex. Considering the results the wisest approach would be the analysis of single elements in a first moment, and only after that, a simple combination of them, in order to detect possible problems with the joints.

Again, another problem that is noticed in the sample of works, is the omission of some important information related to the tests. Due to these gaps it can be stated that only 12 works over 21 could be repeated. Furthermore, the details that are excluded may lead to drastically different results, so it is not only a problem of repeatability, but it is also a matter of trustworthiness of the results. Fundamental is the absence of information regarding the MVD version, indeed different versions of MVD filter out elements and properties, reducing the value of the data exchange. Indeed in some cases where no information about the IFC or MVD version are provided, it is experienced the absence of some model properties.

Concerning the results, it is possible to conclude that nowadays the most interoperable type of exchange is the direct link via native file, indeed it provides the possibility of very efficient bidirectional model interchange. Also the direct link via IFC provides good results depending on the combination of software. Instead, beside the fact that the open and neutral IFC standard should be the most effective type of exchange, in practice this is not true, indeed many problems are experienced, in particular regarding the geometry.

Furthermore, during the literature review and the analysis of the results many inconsistencies between the works are experienced. It is possible to conclude that such dissimilarities are not dependent from the epoque of submission of the work or to the version of IFC in case of indirect links. So, the only possible explanation is that the authors do not follow a proper approach. This can be reduced basically to two possible cases: accidental errors, or systematic errors due to a proper knowledge of the tools and how they work. The second aspect is the more probable, indeed, also the developers and promoters of the IFC standard, buildingSMART, have recently published a report [\[44\]](#), in which is stated that they are conscious of the fact that threshold to use openBIM standards is too high and that a new paradigm in the IFC standard development need to be followed in order to reduce such limit.

In conclusion, it is possible to suggest a proper methodology to follow in the future tests in order to provide all the necessary information, and to analyze all the most important properties necessary in the structural analysis and design procedure.

Procedure

Here below are reported the most important aspects that should be taken into account during the conceptual phase of the experiment, its preparation, and implementation.

- Analyze all the typologies of data exchange, in particular the IFC one;
- Set the test in order to analyze the bidirectional data exchange;
- Firstly analyze single elements, varying their shape, material, rotation, etc.;
- Secondly analyze simple combinations of single elements;
- The parameters that have to be considered are: geometry and analytical representation, section properties, material properties, loads and load combinations, restraint, exchange of reinforcement or steel connections.

Necessary information

Here below are reported the most important information that should be included and reported in the papers or in the thesis. It is necessary to include:

- The procedure;
- The type of exchange;
- The software used and their versions;
- The parameters analyzed;
- The versions of IFCs and MVDs.

For future works that will have the same aims of the present thesis, it would be very useful, in terms of time and clarity, if many researchers will follow the suggested procedure, and present papers in which all the necessary information are clearly stated.

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