Univerza *v Ljubljani*
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in geodezijo

AZINWIE ZAMA AMBE

A STUDY OF PRACTICAL BIM INTEROPERABILITY FOR IMPLEMENTATION OF WORKFLOWS FOR STRUCTURAL MODELING, ANALYSIS, AND DESIGN

MASTER THESIS

SECOND CYCLE MASTER STUDY PROGRAMME BUILDING INFORMATION MODELLING – BIM A+

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A STUDY OF PRACTICAL BIM INTEROPERABILITY FOR IMPLEMENTATION OF WORKFLOWS FOR STRUCTURAL MODELING, ANALYSIS, AND DESIGN

ŠTUDIJA UPORABE INTEROPERABILNOSTI BIM Z IMPLEMENTACIJO DELOTOKOV ZA MODELIRANJE

BIM A+ European Master in Building Information Modelling

Master thesis No.:

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Izvleček:

Informacijsko modeliranje stavb (BIM) ima edinstvene prednosti in potencial v konstrukcijskem inženirstvu. Njegova metodologija podpira sodelovalno delo, ki temelji na centralizaciji vseh informacij v zbirnem modelu BIM in učinkoviti ravni interoperabilnosti med platformami BIM. Vendar pa za konstruktersko modeliranje, analizo in potek dela načrtovanja zmogljivost interoperabilnosti najpogosteje uporabljene programske opreme predstavlja omejitve, ki jih je treba rešiti z ustreznimi rešitvami. Ti pomembni izzivi ovirajo izvajanje delovnih tokov BIM v projektivih birojih konstrukterjev, ki načrtuje z BIM. Ta študija skuša analizirati proces prenosa konsturkcijskih analitičnih modelov in podatkov med orodji za modeliranje, statično in dinamično analizo in konstruiranje, medtem ko razvija edinstven potek dela za implementacijo znotraj teh orodij, platform BIM in projektantskih skupin. Študija primera je bila razvita za preizkušanje praktičnega delovnega toka interoperabilnosti med Trimble Tekla Suite (Tekla Structural Designer, Tekla Structure in Tekla Tedds), SCiA Engineer, Revit in IDEA StatiCa. To je za identifikacijo in odpravo omejitev, vključenih v procese prenosa pretoka podatkov med to specifično konstruktersko programsko opremo BIM. Postopki prenosa informacij in modelov so dvostranski, z uporabo izvornega formata podatkov in IFC (angl. Industry Foundation Classes) ter univerzalnega standardnega formata prenosa podatkov. Konstrukcijsko modeliranje BIM in zrelost projektiranja BIM sta razmeroma premalo izkoriščena. To je predvsem posledica težav z interoperabilnostjo. Kljub omejitvam in izzivom rezultati študije v okviru razvoja študije primera kažejo, da ima delotok BIM veliko prednosti pri razvoju projektov BIM in njegovem izvajanju v projektantskem biroju, ki uporablja BIM za projektiranje konstrukcij.

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BIBLIOGRAPHIC– DOKUMENTALISTIC INFORMATION AND ABSTRACT

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Abstract:

Building Information Modelling (BIM) has unique advantages and potential in structural engineering. Its methodology supports collaborative work based on the centralisation of all information in the federated BIM model and an efficient level of interoperability between BIM-based platforms. However, for structural modelling, analysis and design workflow, the interoperability capacity of the most used software presents limitations that must be resolved with immediate solutions. These significant challenges hinder implementing BIM workflows in a structural BIM design office. This study seeks to analyse the process of transferring structural models and data between modelling, structural analysis, and design tools while developing a unique workflow for implementation within these tools, BIM platforms, and design teams. A case study has been developed to test a practical interoperability workflow between Trimble Tekla Suite (Tekla Structural Designer, Tekla Structure, and Tekla Tedds), SCiA Engineer, Revit, and IDEA StatiCa. This is to identify and fix the limitations involved in the transfer processes of data flow between these specific structural BIM software. The information and model transfer processes are bilateral, using the native data format and the Industry Foundation Classes (IFC), the universal standard data transfer format. Structural BIM modelling and design maturity are relatively underutilised. This is mainly due to interoperability problems. Despite the identified limitations and challenges, the study outcomes within the case study development illustrate how the workflow has excellent advantages in developing structural BIM projects and its implementation in a structural BIM design office.

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1 INTRODUCTION

1.1 Generalities and Scope

Building information modelling (BIM) technology has advanced significantly recently, making it a hot topic of interest in the building and construction IT industry. BIM allows the design team's input to be graphically analysed and combined into a 3D computer model. BIM is relatively new, yet structural modelling and design tools have been around since the 1990s. Enhanced interoperability, which uses industry-standard formats like IFC (Industry Foundation Classes), native data formats, and other technologies like the Microsoft.NET platform and API (application programme interface) technology, has enabled this (Robinson, 2007).

The application of technological advancement to the construction industry has created the possibility of accelerating the development of many building-related projects, monitoring the construction process, and eventually managing the building itself. Computer-aided design (CAD) first appeared in the 1960s, transferring paper project designs to a computer screen and making it easier to complete project graphic documentation and share digital drawings with the design team. CAD systems are known to have advantages, but they cannot guarantee that all technical drawings for a construction project will fit together perfectly (Mehran, 2016). Although it is critical for the various experts working on a project to communicate quickly and ensure that data is sent correctly from one phase to the next, the traditional support of paper drawings or even digital drawings can bring some inaccuracies (Gao and Pishdad-Bozorgi, 2019).

The adoption of the BIM approach is fundamentally altering how structure-related data is maintained and shared among all parties involved in the Architecture, Engineering, Construction, and Operations (AECO) sector. In the 1970s, Eastman (Rafael Sacks *et al.*, 2018) came up with the idea of creating a digital model that could contain all the information about the development of an entire project. The term "Building Information Modelling" (BIM) was first used in 1987, when the first commercial BIM product, ArchiCAD, was released. The BIM methodology, currently supported by advanced technology, allows the ability to visualise a representative three-dimensional (3D) model of the building and centralise all the information associated with the building project (Pishdad-Bozorgi *et al.*, 2018). The BIM model is developed based on multitask collaboration between all stakeholders and expertise that contributes to the project's completeness.

Despite the benefits of implementing BIM in the construction industry, its adoption within companies and design offices has presented significant organisational challenges related to internal cultural adaptation regarding workflows, data transfer processes between disciplines, and communication between team members and partners. As a result, it may be necessary to make an initial investment in

technology and training. Furthermore, though the available BIM support technology permits a relatively integrated approach to the digital representation of all building disciplines, there are still gaps that this thesis wants to address (Gouda Mohamed, Abdallah and Marzouk, 2020). Recent research points toward two primary directions (Sampaio, 2017):

- Software developers now have the option to gradually **integrate** functionalities known as extensions, add-ins, and plug-ins based on the primary system's native format;
- The international organisation BuildingSMART, which brings together construction industry professionals from different nations, issues the standard data format, **Industry Foundation Classes** (IFC), and has been releasing new versions with increased efficiency.

1.2 Main Focus

This research focuses on interoperability among structural BIM applications in conjunction with collaborative delivery of structural BIM projects by interdisciplinary teams. It also aims to create a BIM-based workflow necessary for developing a structural BIM design office and teams while verifying data quality when models are exchanged between modelling and structural analysis tools. In other words, implementing BIM in structural engineering and design teams is impossible without collaboration, interoperability, and a sufficient level of development (LOD). As one of the methods to achieve high-performance workflow for implementation in BIM structural engineering while avoiding repetitive work in modelling and design, interoperability plays a vital role in shifting the traditional design practice towards the new approach.

Research shows that BIM applications for structural engineering have constantly been growing, with a sudden increase after 2014. On the contrary, the number of studies on structural engineering and BIM is still relatively insignificant and less implemented compared to other areas of BIM application (Vilutiene *et al.*, 2019). Recent BIM structural topics include interoperability, data management, simulation, automation, cost-benefit assessments, and model view definition. According to (Shin, 2017), the efficiency of collaborative work is based on a high level of interoperability that can be achieved using an Open BIM platform. Furthermore, the definition of models reaching LOD 300 determines the quality of structures.

From a BIM perspective, (Musella *et al.*, 2020) offer solutions to limit the devastating consequences of earthquakes on the occupants of a building and improve the management of an emergency that invariably follows a seismic event in the facility. To keep track of all the data generated and changed due to the earthquake, the researchers turned to the Open BIM platform built on the Industry Foundation Classes (IFC) standard data format. BIM is an integral part of structural engineering because of the

importance of interoperability and the types and quantities of information that may be included in a BIM model. Therefore, this study aims to understand better how to use BIM platforms in the structural sector.

1.3 Structure of Thesis

Despite professionals' general recognition of interoperability's workflow and implementation as progressive and promising for the structural design office, it is not yet widely used in practice. As a result, another goal of this study is to review the workflows, methods, and tools available in the literature review and test a few simple projects to validate the theories identified. In addition to the practical test, the thesis conducts a global survey of some BIM design offices to ensure that our conclusions and findings from the literature are correct. The thesis is organised as follows:

Chapter one introduces the topic, in which the main focus of the work and the study's objectives are outlined, and discussed issues are highlighted.

Chapter two introduces and expands on a literature review of structural BIM discussion, BIM interoperability, the BIM workflow implementation approach, and various methods, tools, and supporting standards found in scientific papers and other resources. Furthermore, the benefits and drawbacks of structural BIM interoperability, as reported by sources, as well as knowledge gaps and challenges encountered during its implementation in structural modelling and design, are discussed.

Chapter three explains the research approach. It analyses BIM adoption and develops interoperability workflows for BIM structural projects and design teams. Business Process Re-engineering (BPR) improves processes from conventional design to IFC exchange and integrated modelling. Different software in integrated workflows of Tekla Structural Designer (TSD)-Tekla Structures (TS), Tekla Structural Designer (TSD)-Scia Engineer, Tekla Structural Designer (TSD)-Revit, Tekla Structural Designer (TSD)-IDEA StatiCa, Revit-Tekla Structures (TS) and Tekla Structural Designer (TSD)-Tekla Tedd are introduced and discussed as a case study. Interoperability within and between processes is being studied. Case studies provide the research with more control and depth.

Chapter four covers the experimental work, where the workflows will be applied particularly to the case study. This will involve modelling, checking, analysing, exchanging models from one software to another, and discussing the proposed processes for implementation. The applications are judged according to several criteria, including their modelling capabilities and quality, analytical model configurations, structural analysis, design and detailing, automation, interoperability, accurate drawing and documentation capabilities, quantity estimations, reporting, IFC information exchange quality, and exported model reliability and accuracy.

Chapter five expands on the conclusion of the research, survey, and experiment findings and further application and adoption based on the case study outcomes. Finally, the findings of each chapter, particularly the fourth, are summarised and discussed with conclusions.

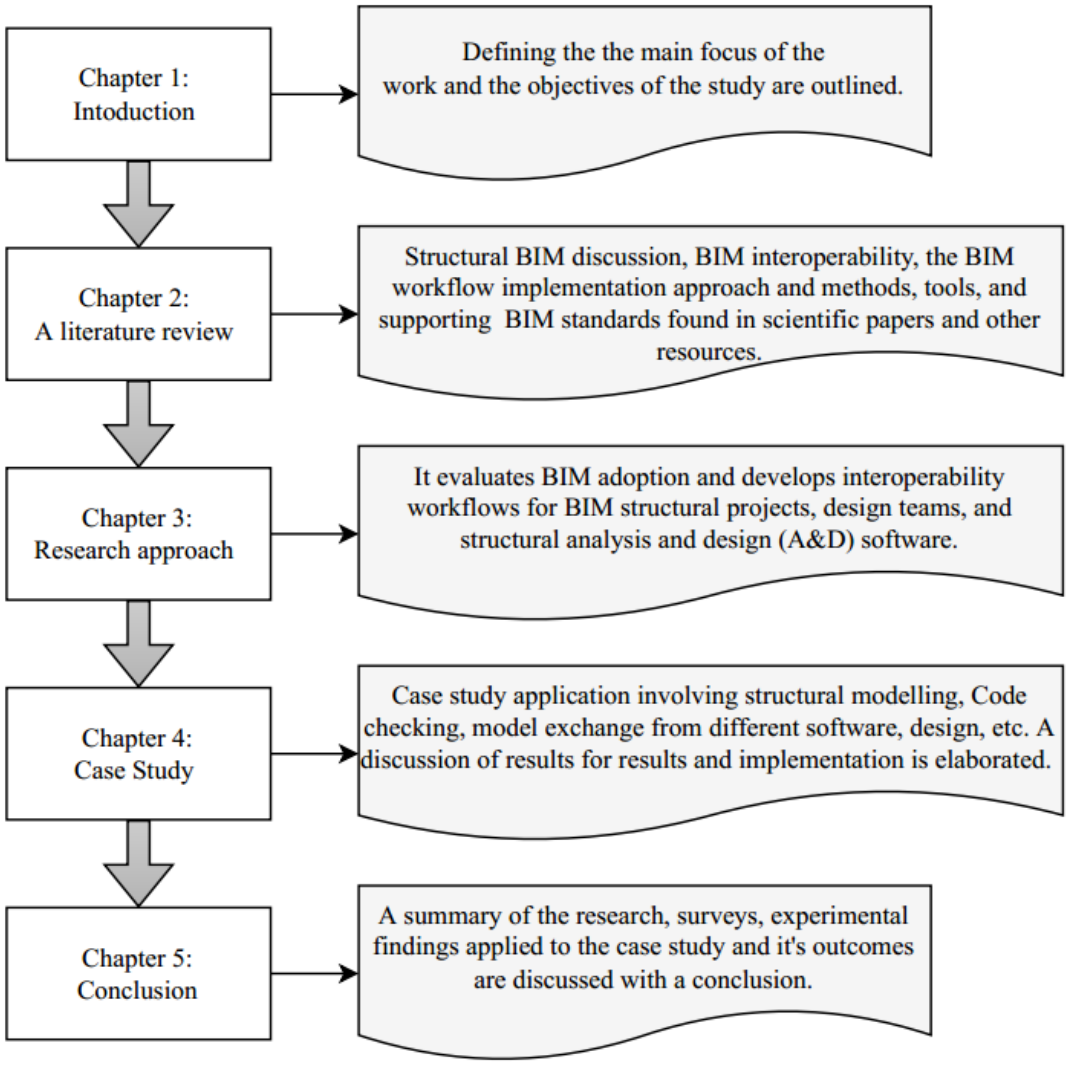


Figure 1: Thesis development workflow (Author's own)

1.4 Problem Discussion and Research Questions

When using BIM-based platforms to develop structural BIM projects, the structural engineer must be aware of the limitations in interoperability that remain with the systems, primarily focused on the two-way data flow processes between the modelling and structural tools. This dissertation examines two research perspectives:

- Transfer of models performed based on the native format of data;
- A transfer based on IFC format.

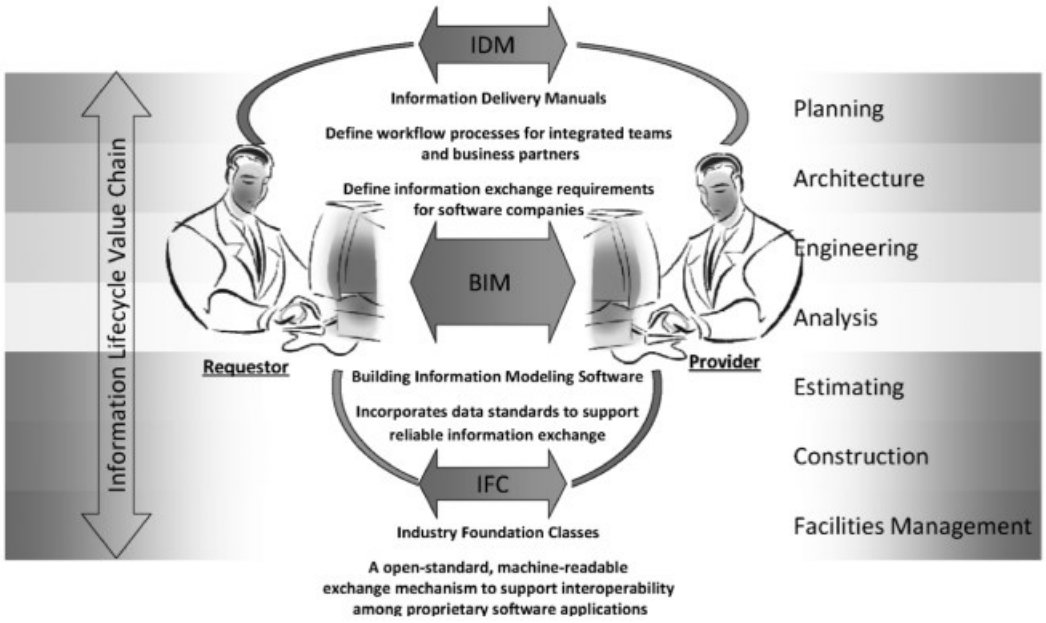


Figure 2: Information Lifecycle Value Chain for data Exchange

The following are the primary research concerns and questions addressed in this thesis:

- ✓ It is widely acknowledged that interoperability issues exist and what methods should be used to bring these issues to light? What are the specific issues?
- ✓ Is it the software or the standards that cause interoperability problems? Can software companies catch up with the development of standards?
- ✓ Why is interoperability valuable? Why is it significant? How do issues of interoperability affect interdisciplinary collaboration in Structural BIM? Is it possible to quantify the impact of interoperability issues?
- ✓ Is IFC mature enough to be considered a standard? Is the IFC addressing current interoperability issues? How expressive and adaptable is IFC? Is there a standard way of dealing with non-standard extensions in IFC?
- ✓ How reliable is interoperability? Can data and information shared by project team collaborators be trusted? How can checks be made?
- ✓ Is interdependence between distributed team members affecting BIM interoperability? What recommendations could be made to improve interoperability amongst interdisciplinary collaboration?
- ✓ What causes interoperability problems? What are the challenges? How can we overcome them?

Some answers to these questions are provided as the thesis progresses. As a result, constructability solutions for practical BIM interoperability and structural BIM workflow are implemented in the case study.

2 LITERATURE REVIEW

The literature review introduces key findings and milestones that demonstrate prerequisites and background for general changes in the building and construction IT industry, and also the development of new approaches in structural BIM design and data exchanges in particular. The main focus is on structural BIM interoperability workflows, their implementation in the early design stage, and the method's benefits and limitations. In addition, the key events that contributed to its emergence and development and the various principles and frameworks used are also discussed. The knowledge gained from the literature review is then communicated in the next part of the thesis. This knowledge is directly related to the research problem and is required for most of the research presented in this master's thesis. Therefore, much technical material had to be read for the research, and it was essential to give full credit to the authors by citing the sources, as seen in the text and the main body of the research.

2.1 Current State of AEC Business Model

In the past, building a facility was a piecemeal process that relied on 2D drawings to communicate. Errors and missing information in paper documents often lead to unplanned field costs, delays, and even lawsuits between the teams working on a project. These problems make things difficult, expensive, and time-consuming. Different organisational structures have been used to solve these problems, like the design-build method, real-time technology, project websites where plans and documents can be shared, and 3D CAD tools. Even though these methods have easy ways to exchange information quickly, they have not done much to reduce the number or severity of conflicts caused by paper documents or their electronic versions.

One of the most typical drawbacks to 2D-based communication throughout the design process is that generating critical evaluation information about a proposed design might take significant time and cost. These studies are typically carried out at the very end after it is too late to make significant changes to the design. This lack of iterative improvement necessitates value engineering to remedy problems, which typically demands redesigning the original design project.

According to Maged Abdelsayed of Tardif, Murray & Associates, a construction company in Quebec, Canada, managing a project involving many people and documents is challenging, regardless of the contractual approach used (Hendrickson, 2003).

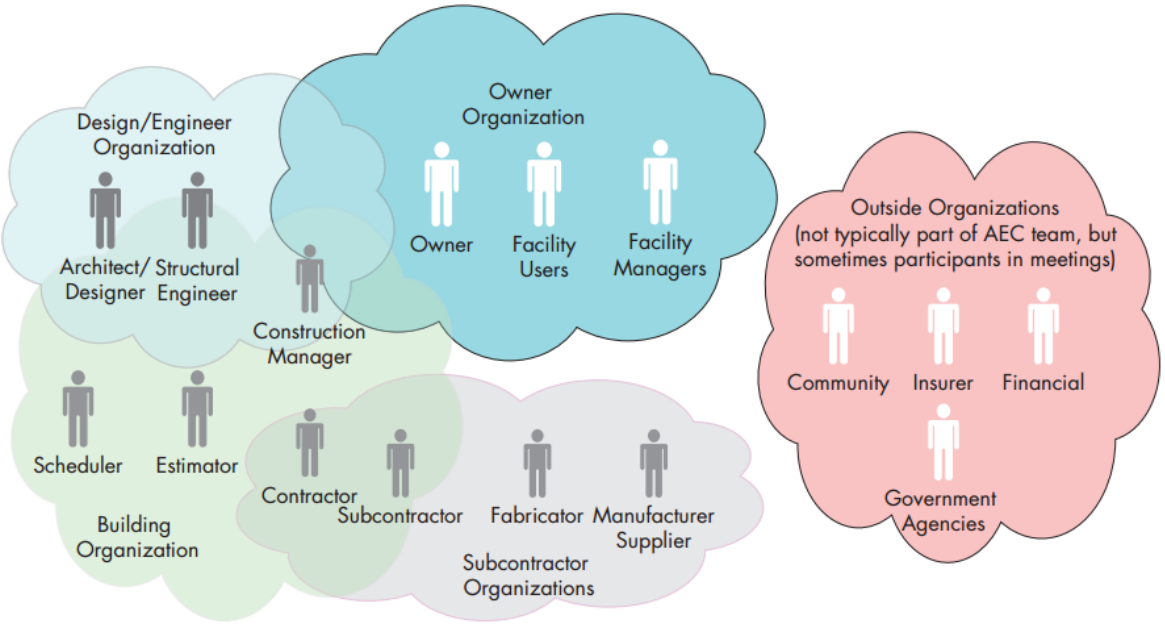


Figure 3: Conceptual diagram representing an AEC project team and the typical organisational boundaries (Rafael Sacks *et al.*, 2018).

2.1.1 How Design Teams Collaborate

Every project begins with a knowledge gap. To fill this gap, design teams provide a wealth of information throughout the project supply chain. In contract details, information entanglement is typical, especially when multiple design sectors and trades are involved. In addition, information about the architect, engineer, and contractor is not usually included. The contract workflow only concerns scheme, tender, construction, and as-built data. This prevents design or client changes as the scheme evolves.

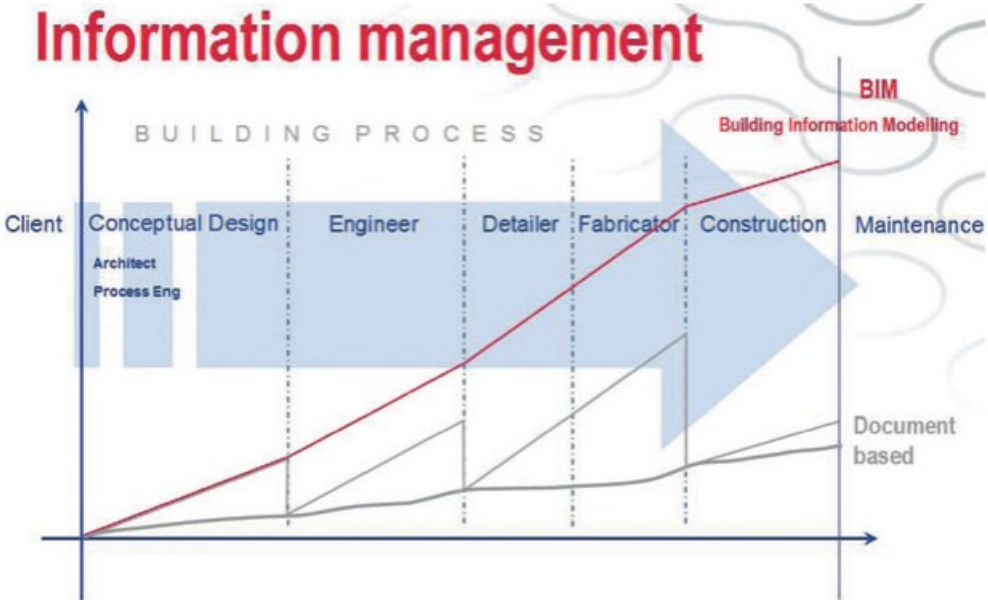


Figure 4: Project Workflow (Robinson, 2007)

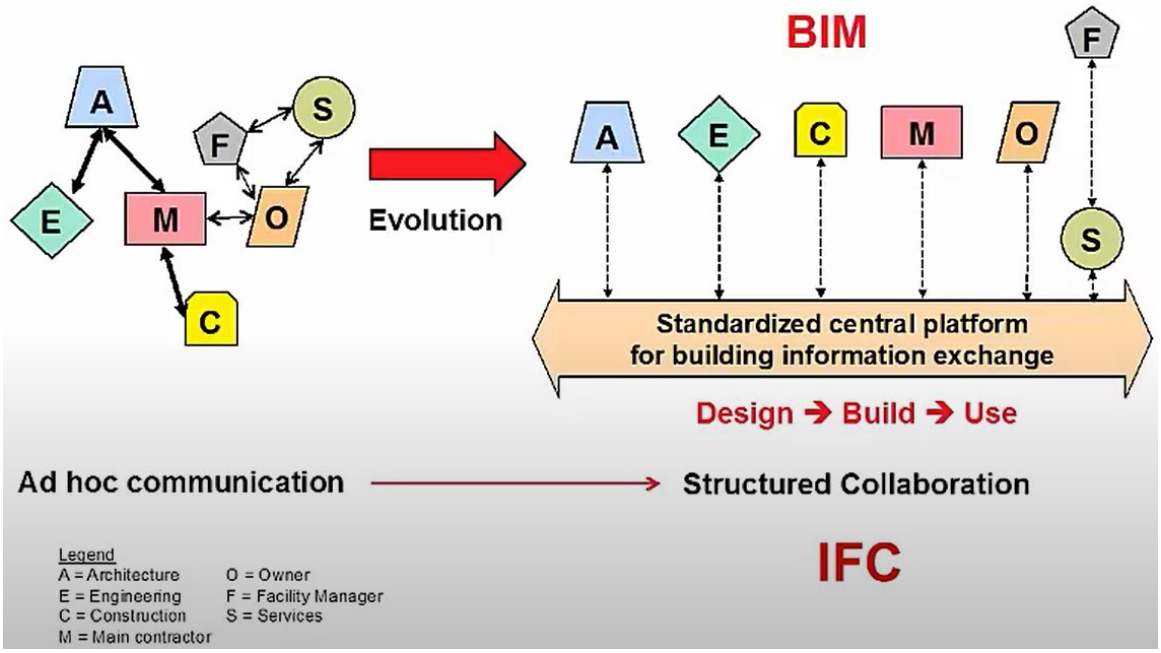


Figure 5: Evolution of structured collaboration within the design team.

The majority of scheme information is currently communicated in 2D. Architects, engineers, and some structural contractors can now share 3D model information thanks to BIM platforms. General contractors are more interested in the model with more excellent scheduling and productivity utilities now that 4D (time) information can be encapsulated in BIM. In the future, specialist contractors may generate BIM data and join the design team. The modelling specialists could be hired for contract control by the client or by any design team members. The client, quantity surveyor, or project cost controller would be interested in using the model to control costs. With 4D programming and time reversal, BIM can be used for visual project management. BIM is excellent for experimenting with new ideas and solutions.

2.2 Current State of BIM Adoption and Data Exchange Practices

The rapid growth of the Building Information Modelling (BIM) sector is revolutionising the AEC (architecture, engineering, and construction) industry. BIM represents a paradigm shift in the construction process and necessitates novel solutions to the problems of data sharing and definitions of intellectual property rights (IP). It is a complex platform that aims to preserve all pertinent information about any phase of the construction lifecycle and requires multiple diversity of data exchange capabilities.

Consequently, interoperability, "*the capacity to exchange data between applications,*" is a significant component of the process, which helps to smooth the workflow while facilitating automation. In Europe, where regulatory organisations have established new laws to encourage the digitalisation of the civil

engineering profession, the demand for interoperability between different software packages has increased (Liao and Teo, 2017).

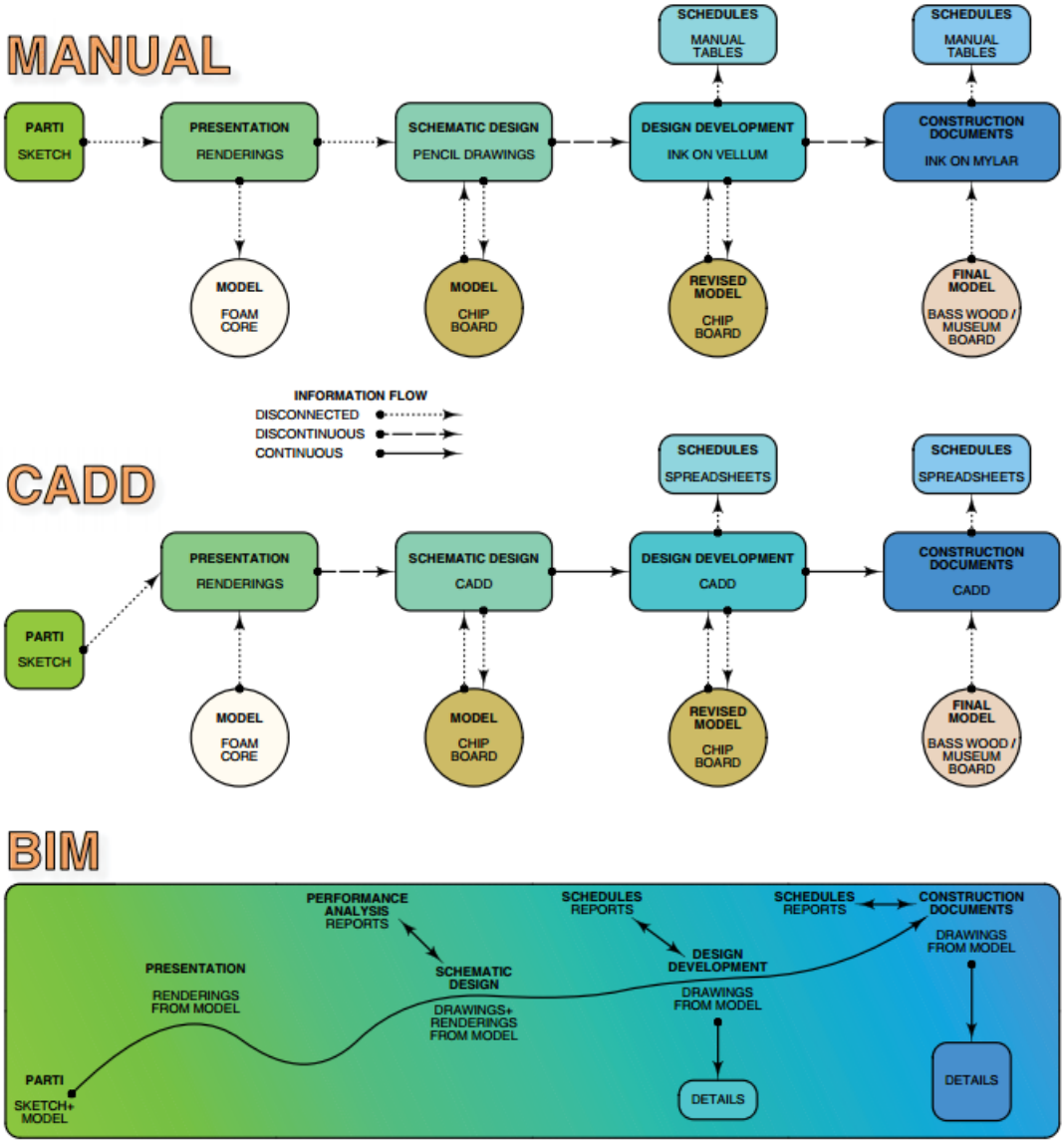


Figure 6: Simplified diagram of three design workflow: Manual drawings and modelling, CAD drafting and manual modelling, and BIM (François Lévy and Jeffrey W. Ouellette, 2019).

2.2.1 History of CAD and CAE for BIM Interoperability

Large-scale adoption of the BIM platform has increased the demand for efficient information exchange processes that protect data quality while allowing it to be exchanged quickly and the importance of substantially integrating various disciplines associated with the AEC industry. Furthermore, in any design situation where collaborators use more than one software package and a group of local or national authorities must collaborate with everyone involved, full interoperability is expected (Bernardino, Davardoust and Osello, 2015).

Regarding the design of new structures, architects and engineers collaborate closely on construction projects. Computer-aided design (CAD) is a typical modelling platform for architectural design, whereas computer-aided engineering (CAE) is used for engineering design in a simulation and analysis environment. The migration from CAD to CAE is, therefore, one of the fundamental elements of the BIM process. A prevalent trend in the design process is toward a completely collaborative design environment that integrates geometric modelling and computer simulation jobs until the final design is achieved (Gerbino *et al.*, 2021).

Gerbino et al. stated that given effective and dependable software interoperability, one could switch immediately from CAD to CAE models. This is conceivable if all software tools can share data from the same digital heritage model. However, interoperability is a complex and undefined notion. Firstly, a general differentiation is based on the workflow path of the user (Bernardino, Davardoust and Osello, 2015). *Horizontal interoperability* is data communication between two architectural BIM software systems, like CAD-to-CAD. *Vertical interoperability* refers to data sharing between architectural and structural software environments. Data exchange from/to any computer-aided (CAx) environment (i.e., CAD-to-CAE-to-CAD) must occur bilaterally.

Depending on how the data is shared, there are two basic types of data transfer channels between two design environments:

- Direct Link (DL) connects two software environments automatically via a plug-in. Data from the sending environment is mapped onto data from the receiving environment. Therefore, no additional intermediate data translator is necessary. The exchange procedure is incredibly efficient, despite using proprietary formats.
- A neutral link (NL) adopts an independent exchange format and is the best strategy for a BIM-oriented methodology which is a crucial step for the BIM environment. Most building data is collected and managed in a neutral format, including building disciplines and building lifecycle phases. Neutral formats ensure long-term data access without legal or technical uncertainty. BuildingSMART-developed Industry Foundation Classes (IFC) are BIM's most widely used open-neutral format. It is the accepted format for describing objects, their characteristics and specifications, and their relationships. It is accredited (ISO 16739-1:2018) and defines the standard for the technical exchange of files with model data. IFC ensures BIM software interoperability independent of CAD/CAE (Aldegeily, 2018).

The most significant benefits of an IFC-based BIM approach are combining the features of multiple software packages, comparing the findings of multiple analysis runs, and sharing project materials across disciplines and phases (Bianconi, Conti and di Angelo, 2006). Information sharing for an architectural model can be effectively managed using BIM-based CAD software because IFC-based horizontal interoperability is widely used. BIM interoperability, which involves sharing CAD and CAE

software, raises several problems. Vertical interoperability reveals shortcomings when switching from a geometrical/architectural model to an analytical/structural model for structural study. This demonstrates that despite the IFC format's ability to handle structural information, the software can still not utilise all of its features. A recent comprehensive assessment of BIM CAD-to-CAE interoperability was reported, demonstrating crucial connections between structural elements regardless of the tested software (Sibenik and Kovacic, 2020).

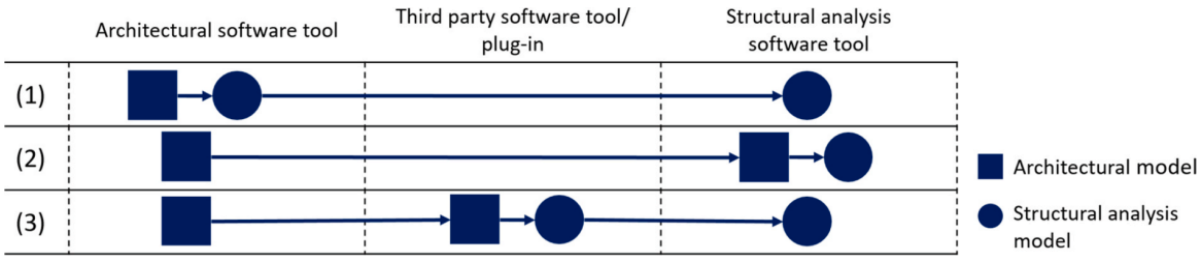


Figure 7: Ways to generate a structural analysis model based on the authoring tool (Sibenik and Kovacic, 2020)

The level of interoperability attained by several widely used commercial CAD and CAE BIM-based software that implements the IFC format has been examined in this thesis. The evaluation was created to offer a qualitative and quantitative study of the problems in data exchange processes employing NL procedures to the technical community and the authorities in charge of managing complicated civil engineering undertakings.

The software packages' handling of the geometry and extra data generated and imported in the CAD-CAD and CAD-CAE bidirectional routes, adopting both the most popular (IFC 2x3) and most recent (IFC 4) formats, attracted attention. A crucial component of BIM interoperability, CAD-CAE bidirectional compatibility is another area of emphasis. The receiving application is anticipated to be able to alter the shared building information model, and the end-user is anticipated to have access to all of the model's data and be able to make changes as needed.

Furthermore, the results of self-tests (from CAD and CAE to IFC, then back to CAD and CAE) are reported to understand better how a software environment can handle IFC entities. Finally, suggestions for valuable and significant outcomes go deeper into the software's translation and mapping capabilities.

2.3 A Brief History and Definitions of BIM

Research suggests that professionals with the appropriate competence may successfully adopt BIM in design practice. BIM facilitates more efficient workflows, saving time and money in the design and construction process of projects. Effective BIM workflow necessitates the use of highly-skilled

specialists. According to research, implementing BIM approaches results in higher-quality deliverables and a more profitable project.

BIM is a software-based collaborative tool used in the AEC industry. BIM includes all building components or objects, their geometry, spatial relationships, attributes, and quantities, as well as all services and equipment information for building life cycle management and demolition. AEC design teams can use physical or reference models from other team members without having specialised industry knowledge. BuildingSMART defines BIM as »*a digital representation of a building's physical and functional features*«. BIM is a common knowledge resource providing information about a facility from conception to demolition.

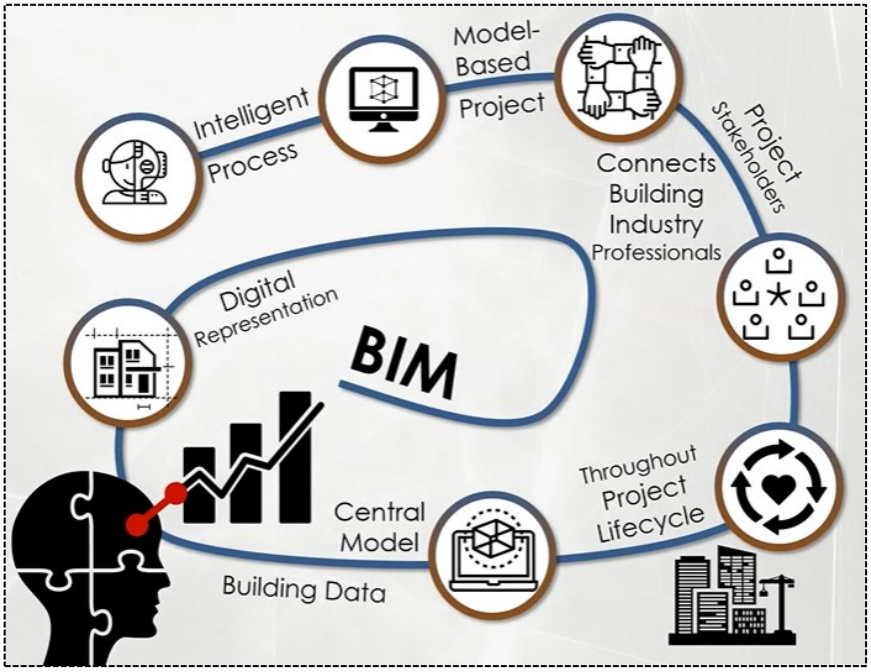


Figure 8: Illustration of BIM Definition

BIM typically refers not only to the technology but also to the associated processes, standards, and protocols for information exchange. As seen in Figure 11 below, all of these BIM components must be coordinated. However, as the diagram also suggests, despite tools or technologies, standards, and processes functioning flawlessly, the most significant influence is always that of people, economics, and politics, which can break an excellent and effective BIM-based procurement project method.

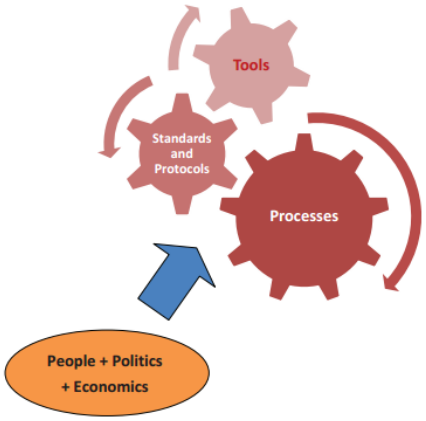


Figure 9: Interaction among BIM processes, standards, technologies, and people (Bimal Kumar, 2015).

2.3.1 BIM Maturity Levels

As BIM technology progresses, there is also a growing need to measure the level of development of this new method based on criteria that have already been set. BIM maturity levels evaluate how far BIM technology has progressed in the AEC industry by examining how successfully different stakeholders and teams collaborate in a project and share information.

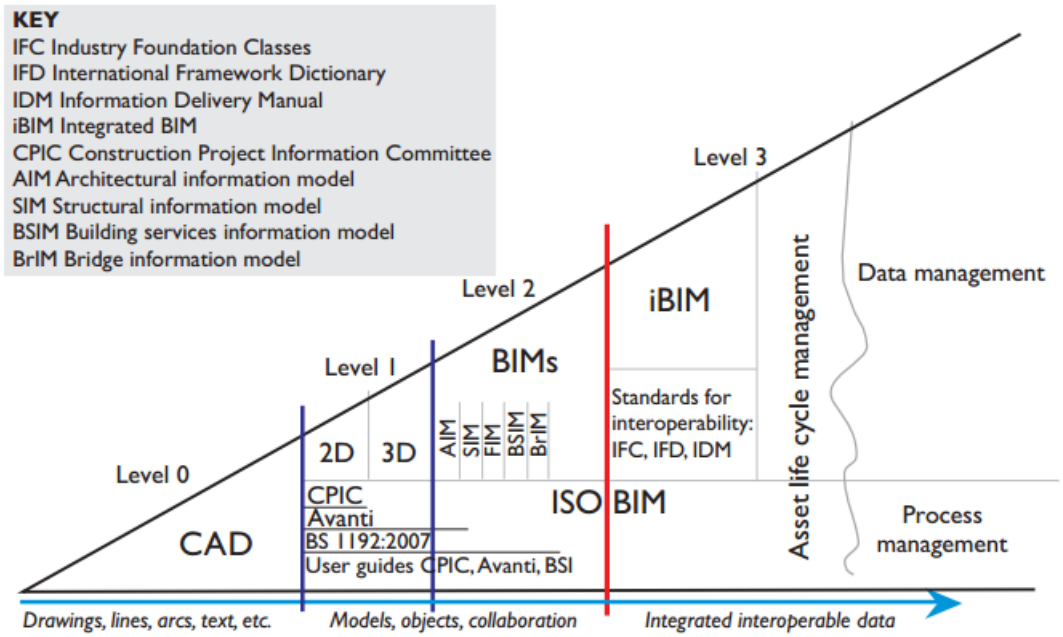


Figure 10: BIM Maturity 'Wedge diagram' (Redrawn from Bew-Richards, 2008)

To support BIM adoption at a higher level, particularly regarding interoperability, the UK government released in May 2011 a futuristic construction strategy outlining an extensive subset of the possible

stages at which a company can implement BIM in design, construction, and facility management projects. These are called BIM maturity levels and are characterised as levels 0, 1, 2, and 3. Additional levels may be added in the future as technology evolves. However, Level 3 is currently the maximum achievable level. The BIM stages of maturity are defined based on the substance of UK regulations (PAS 1192-2 and strategic plans on applying BIM technology in the AEC industry). According to NBS, Publicly Available Specifications (PAS) are rapidly-developed standards, specifications, codes of practice or guidelines. PAS 1192 outlined four distinct levels of digital maturity as follows:

- L0 - Low collaboration: Working in 2 dimensions with Computer Aided Design (CAD) software or on paperwork;
- L1 - Partial collaboration: Working in 2D or 3D with digital files in 3D CAD software;
- L2 - Full collaboration: Working in 3 dimensions;
- L3 - Full integration.

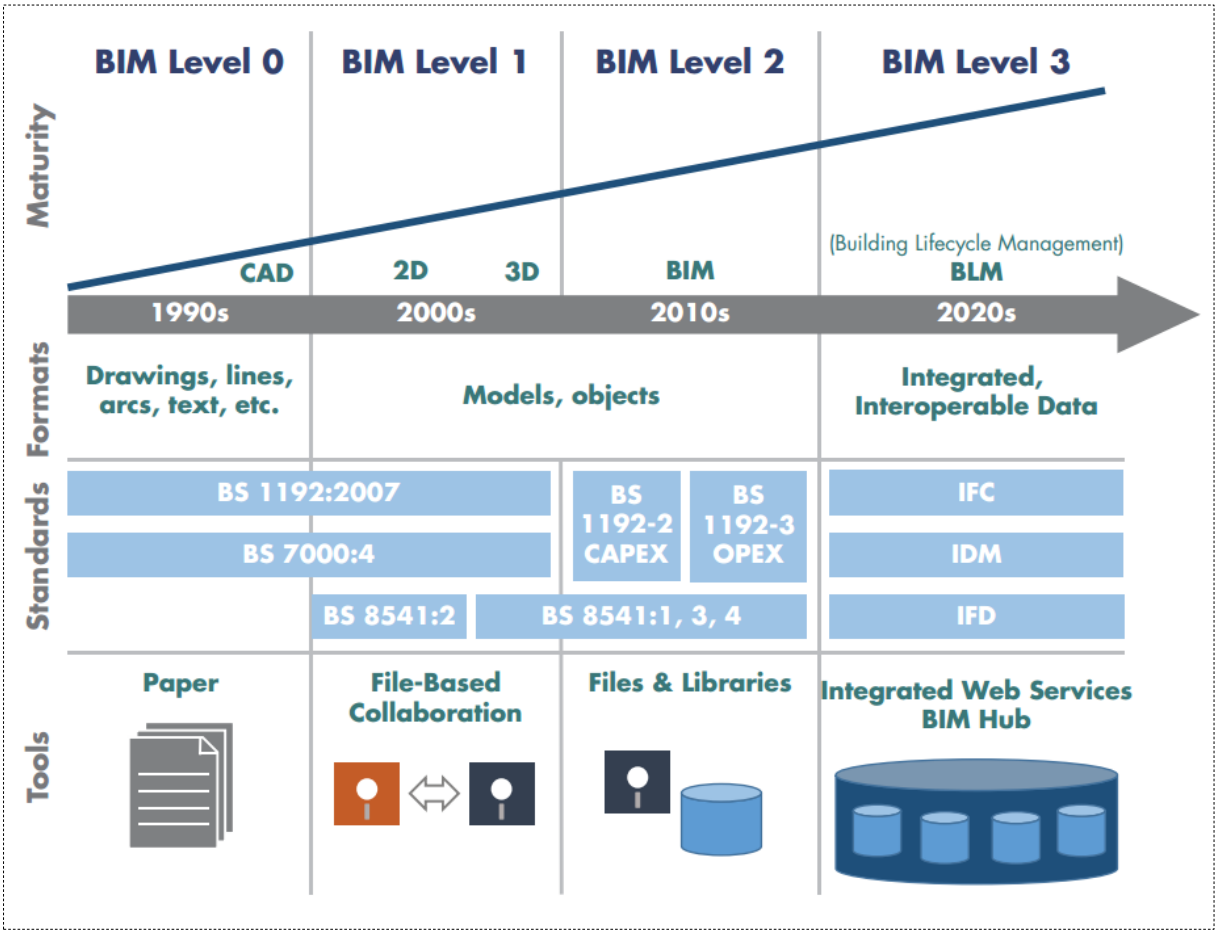


Figure 11: The four (4) levels of BIM maturity (Source: Mark Bew and Mervyn Richards, Reproduced based on PAS 1192-2:2013 (BSI, 2013) and BS 1192-4:2014 (BSI, 2014a)

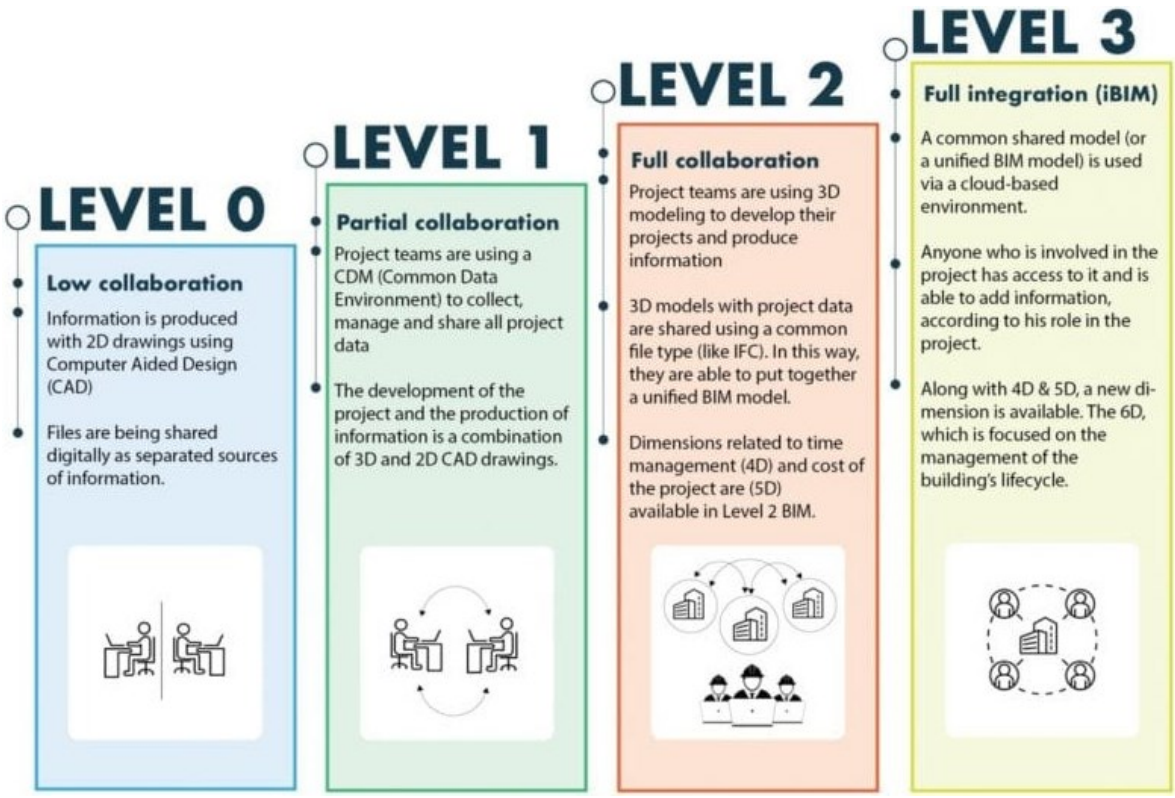


Figure 12: BIM Maturity Levels

2.3.2 BIM Level of Development (LOD)

The Level of Development (LOD) Specification is a reference that enables practitioners in the AEC Industry to specify the content and reliability of BIM models at various stages in the design and construction process. It has also been developed to communicate the complexity of BIM geometry and the dependability of data. In 2014, the LOD specification was released. It aids in defining BIM modelling efforts and requirements in a BIM Use or a final output by project teams and owners. At different stages of the model development, BIM managers utilise LOD to describe the requirements for information reliability (Houssam Sleiman and Lucian Burdi, 2015). The American Institute of Architects (AIA) first used LOD in 2008 when it established five distinct levels of development to specify the level of detailing in a BIM model.

Nevertheless, LOD was an idea that existed much before. This clear articulation allows model authors to define what their models can be relied on and permits downstream users to clearly understand the usability and the limitations of the models they are receiving. With the addition of LOD 350, there are now six levels of development, and it is observed that 80 to 90% of the elements in a model should at least reach LOD 350 for considerable interoperability.

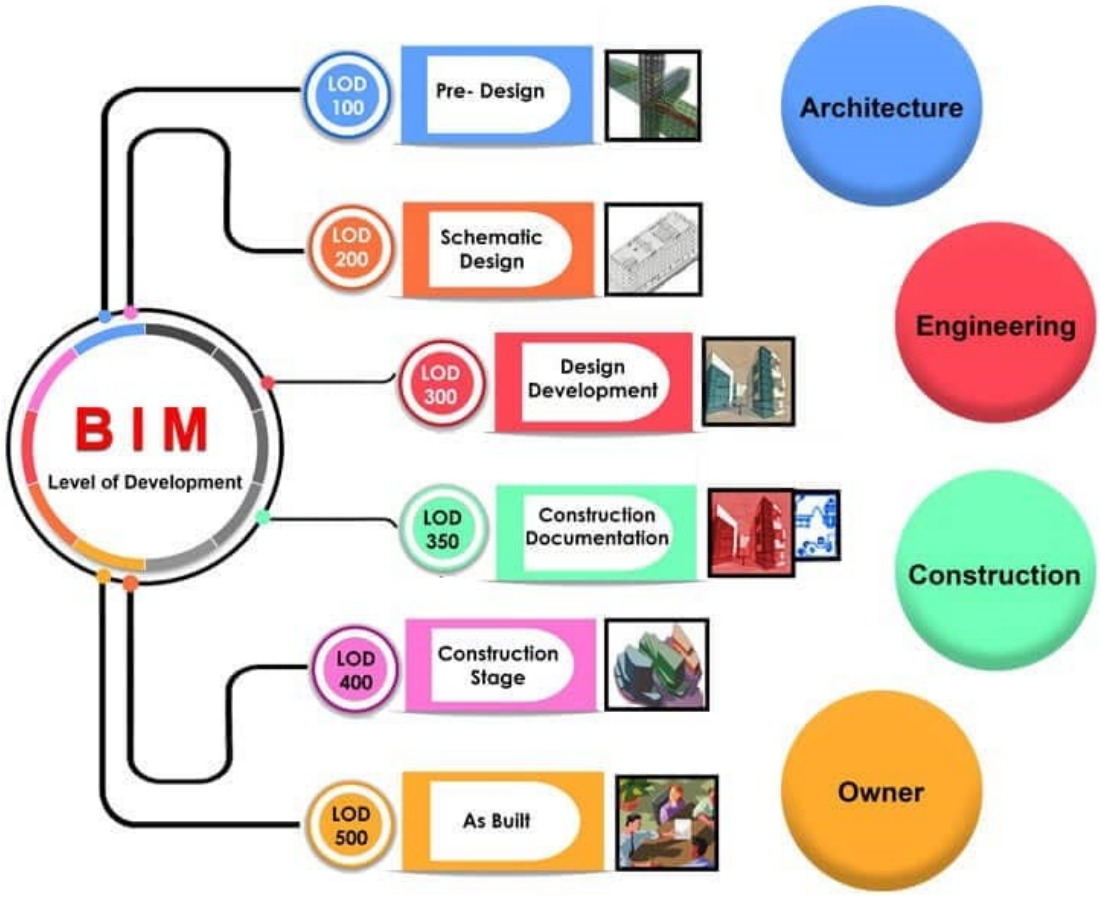


Figure 13: Level of development LOD in BIM (Source: Google image)

2.4 B IM Standards, Data Model, and Specifications

Standards ensure that products and services have the intended quality, dependability, efficiency, and interoperability while remaining within the expected cost parameters. Products that are unreliable, of poor quality, and composed of components that do not fit together correctly or are incompatible with other components that are supposed to operate together are clear indicators of a lack of standards. According to the International Organisation for Standardisation, when a product, system, or gadget functions correctly, it is almost always because it complies with a particular set of standards. Knowing BIM standards ensures the best practices for BIM implementation. The AEC industry has seen the evolution of the UK PAS 1192 standard, transition guidance to BS EN ISO 19650 documents, and revised to form the ISO 19650 standard. This is the ISO's editorial requirement for international projects fully implemented today.

ISO 19650 (parts 1 and 2) were published in 2018, creating new worldwide, EU, and state regulatory scenarios. This standard is the reference for all others. ISO 19650-1:2018 actualises BIM Maturity with a Bew-Richards triangle schema. It defines 3 BIM maturity stages as follows:

- **BIM STAGE 1**, 2D CAD deliverables and 3D BIM models are merged to meet national regulatory project management criteria.
- **BIM Stage 2** is reached when the BIM models for the various disciplines (structural, architectural, MEP) are federated and conform to ISO 19650 international standards. This ensures that the project is managed in a unified, cohesive manner.
- **BIM STAGE 3**, wherein the structured database systems of the BIM models are immediately queried, enabling the adoption of Open-BIM as a project management system.

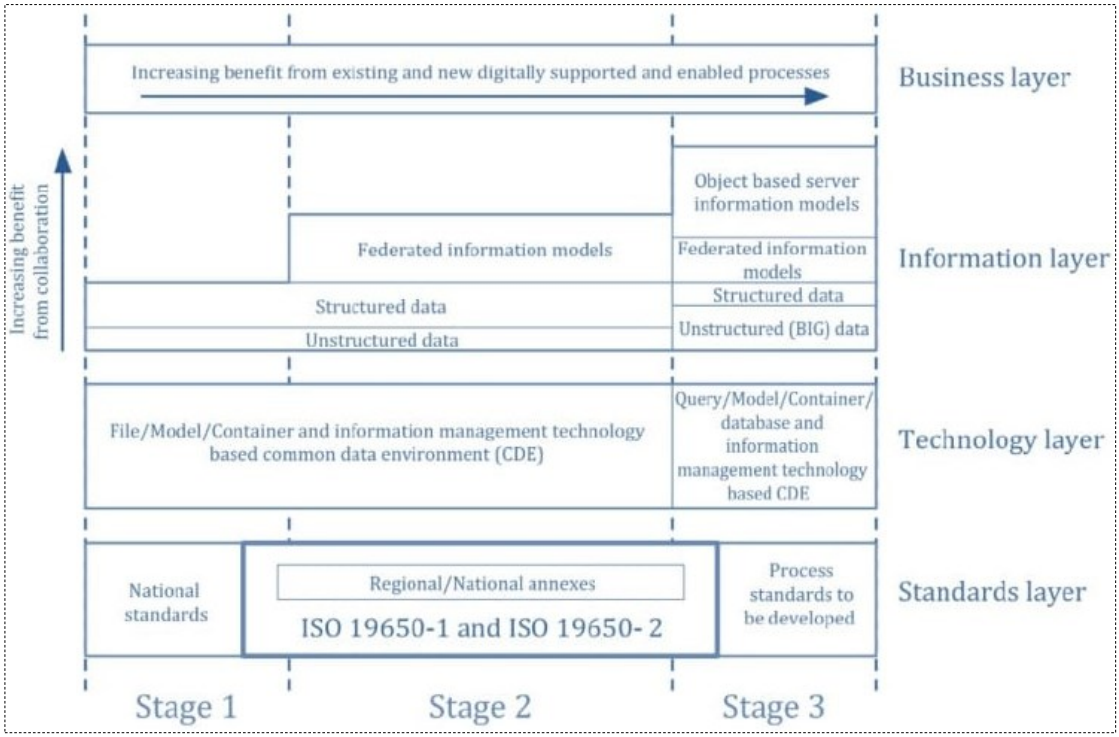


Figure 14: Matrix scheme-BIM maturity level according to ISO 19650 (Biblus accasoftware, 2018)

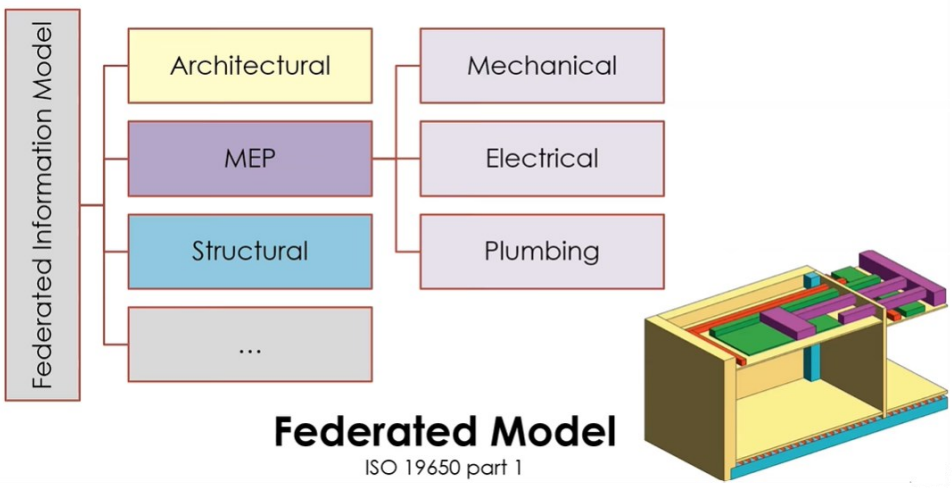


Figure 15: Federated BIM model according to ISO 19650 part 1 (Source: BuiltEvolve Channel).

2.4.1 Industry Foundation Class (IFC), a Brief Overview

Industry Foundation Classes (IFC) is a well-known open data exchange standard for BIM. The IFC file format ".ifc" permits sharing data about the geometrical qualities of structural components and different attributes, including mechanical and physical properties, costs, and time. It is intended to make the object-oriented data model of the AEC software packages compatible. The first data model standard, IFC 1.0, was released in 1996, and BuildingSMART has been evolving the IFC architecture continually. The IFC structure is based on the Standard for the Exchange of Products (STEP) standard. In addition, It was developed an open standard for exchanging building data models across different technologies and facilitating the transmission of data between different teams involved in the project lifecycle. When transmitting 2D information, such as plan views and annotations, the native file format offered by Revit and collaboration solutions like Autodesk BIM 360 should be preferred (Autodesk, 2021).

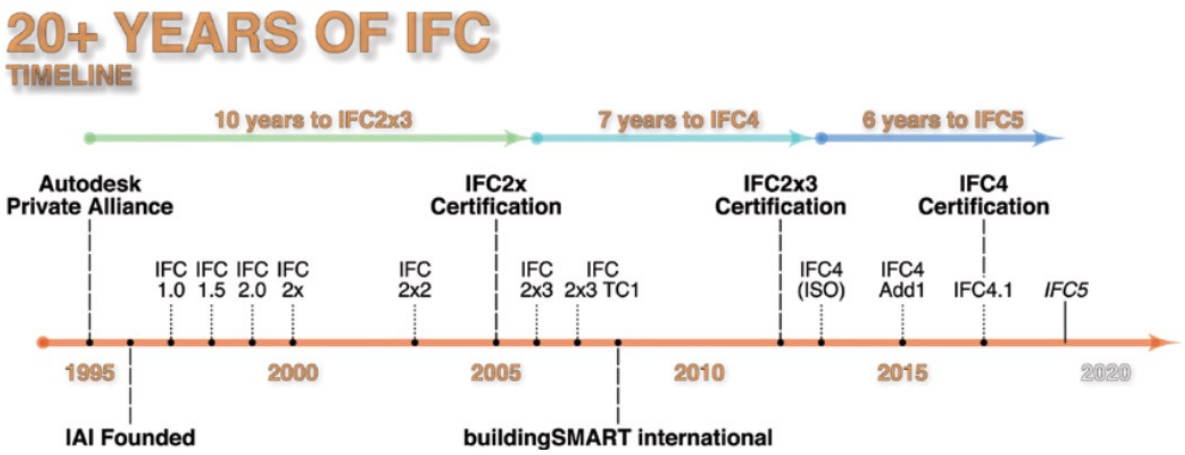


Figure 16: A timeline (Road map) of IFC adoption (François Lévy and Jeffrey W. Ouellette, 2019).

IFC 4.1 is the current version. Based on lessons learned through implementation and usage, each proposed update to the IFC specification has included new concepts to describe existing words further and capture more interchange use instances. The described approach is supported by an evaluation of the IFC 2x version from 2000. According to BuildingSMART International, IFC 2x3, introduced in 2006, has recently received a significant promotion from all software vendors and is frequently accompanied by buildingSMART's certification of conformity.

IFC 4 is the most recent release since 2013 (ISO 16739:2013) and was upgraded in 2018. (ISO 16739-1:2018). BuildingSMART recommends IFC 4.1 (2018) for current projects and developments. IFC 4.3 is an unfinished version that extends the IFC schema to include trains, highways, ports, and waterways. With a new documentation format, structural IFC extensions, and geometry enhancements, IFC 4 has

improved. Nevertheless, IFC 4 addresses the shortcomings of prior data-exchange formats between different systems (Golabchi and Kamat).

The more the intricacy of the activity to be performed, the broader the range of professional abilities required. Consequently, the higher the amount of information to be transferred, the more efficient the exchange will be. Sadly, most of this information is redundant or irrelevant for certain design phases of the building project lifecycle's workflow. This results in inefficiency in the work stages and problems managing the kinds of information transferred. This exchange must be supported by all software packages involved in the process throughout the lifecycle of a structure. Therefore, the precise interpretation of the information provided is crucial. This notion serves as the basis for the model view definition (MVD), a subset of the IFC scheme that enables the interchange of information at various phases of a building's design, defining the dataset to be transmitted based on the intended usage (Gerbino *et al.*, 2021).

Every IFC version has a corresponding set of authorised buildingSMART MVDs. Coordination View 2.0, which is related to IFC 2x3 and can manage architectural and structural analysis data, is the most used model view in BuildingSMART. The CV 2.0 schema is thorough and includes information on CAD and CAE workflows. The BuildingSMART-released IFC 2x3 TC1-adopted MVD, known as the structural analysis view schema, is also referred to as the Structural Analysis View (SAV) by (Ramaji and Memari, 2018). Data about structural engineering (load cases and conditions, boundary conditions, constraints, materials, and element connections) are collected and combined by the SAV.

Geometries and parametric data, building services and structural domains, and GIS mapping are now better supported in IFC 4. The Reference View (RV) seeks to define an essentially unchanging reference model. The data interchange in this scenario is unidirectional and primarily concerned with project validation and verification, such as code checking and clash detection, and the resolution of geometry-related difficulties. The Design Transfer View (DTV) addresses the need to transfer data in various situations, including design, analysis, cost, and facility management. It enables the receiver system to adjust the model while facilitating data transmissions such as MEP, structural analysis environment, and management (building service information). The DTV is referred to as a CV 2.0 with an extended range. Contrary, the IFC 4 RV schema is identical to the CV 2.0 but provides slightly fewer possibilities for changing receiving environments. According to Gerbino et al., IFC translators can be employed by following the usual protocol and then being reviewed by BuildingSMART before receiving formal certification (Gerbino *et al.*, 2021).

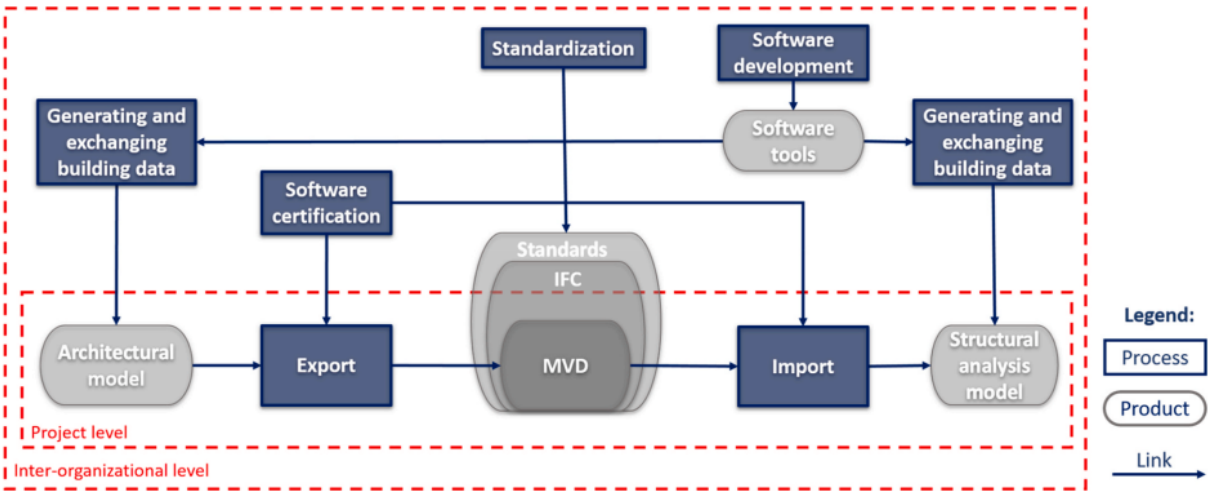


Figure 17: Data exchange ecosystem: Process within the project and inter-organisational level (Sibenik and Kovacic, 2020).

2.4.2 IFC Certifications

The IFC certification procedure was utilised to certify IFC-compliant applications operated by BuildingSMART, formerly known as the *International Alliance for Interoperability (IAI)*, the organisation responsible for creating and implementing IFCs. The process of importing and exporting a set of IFC files while the programme was being certified was required for certification, as described earlier. The certification was for the IFC2x3 version and View Definition (VD), a particular subset of IFC. The comprehensive coordination view was the only VD that was approved for certification. This view is utilised for architectural coordinating, building service, and structural disciplines involved in a construction project throughout the design phase. These include the following:

- The building's spatial structure,
- Information about the building elements,
- The connection between elements and spaces,
- 3D geometry for clash detection,
- 2D/3D visual design intentions (colour, hatching, rendering), and
- Building elements Property data

Certification of applications that pass conformance testing, primarily by comparing a product to a reference system, is more accessible with buildingSMART's continuous platform and procedure. (Lipman, Palmer and Palacios, 2011) Studied construction products of data exchange standards test suites and looked into various approaches and procedures for specifying the structure, level of detail and verdict criteria.

2.5 Structural BIM (S-BIM)

Implementing BIM on large projects combining architectural, structural, and service object information presents a challenge for the AEC industry and design team. Due to the required volume of information and subsequent data compression, this may not be practicable. When this type of solution is established, all interfaces will be modelled using the best-of-breed solutions in their respective domains, one of which will be structural BIM. The most crucial topic for structural engineers to understand is structured BIM. This multi-material (steel, concrete, timber, masonry) subset containing physical, analysis, and design (A&D) information can be utilised to generate all drawings and reports for a design project. *Structural BIM is the part of the BIM process when the majority of multi-material structural data is created and refined to build the actual structure* (Robinson, 2007). The models of architects are excluded from the scope of structural BIM because they lack the same conceptual base as this model. Analysis and detail models are isolated from the structural BIM models. The detailed model contains architectural model components, geometrical shapes, and sectional elements.

On the other hand, the analytical model includes geometrical properties derived from the structural model, such as axis position, member size, and space layout. The link between architectural models and structural BIM is an obvious way to aid in the future development of intelligent integration, and reference models should always be available. These reference models may contain 2D data for usage with non-BIM software.

The S-BIM model emerges during the engineering phase when conceptual judgments on structural forms are established. It is sometimes assumed that the design aspect of A&D is primarily concerned with the actual sizing of structural elements. In practice, it should also involve project value engineering, which examines all materials, how they interact, and how they relate to architectural objects and concepts.

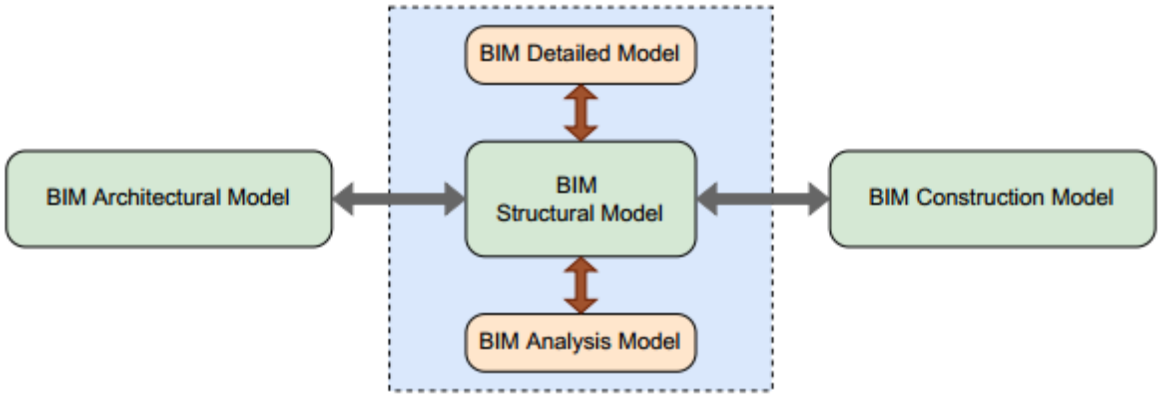


Figure 18: Data Transfer in BIM Model (Author's Own)

The S-BIM model begins to grow as conceptual judgments on structural shapes are made during the engineering stage. The physical sizing of structural elements is frequently thought to represent the design aspect of A&D, which is erroneous. However, this is only a portion of what is necessary for practice; it should also include the linked architectural objects and concepts and a complete value engineering of the project's materials. S-BIM is a subset of the BIM model that may contain helpful information and data for structural engineers, such as loads, geometry, material boundaries, load combinations, and sectional properties. The load-bearing structures are developed and integrated into the model at this point, and A&D play a significant role, although not in the classic sense of deploying separate, independent tools. Open interfaces are essential for structural BIM solutions' interoperability, customization, and localization. S-BIM A&D is an output that may be generated and maintained through the physical model, allowing A&D findings and other outputs to be updated appropriately when parametric objects adapt and respond to changes. In addition, open interfaces make adding plug-in software modules to structural BIM systems easier.

(Robinson, 2007) states that S-BIM is not an interoperability island. Therefore, it must communicate and synchronise with other applications and data. Historically, the Steel Detailing Neutral File (SDNF)2 and CIMsteel Integrated Standard Release 23 (cis/2) were used to transport 3D steel model information using Globally Unique Identification (GUID) numbers to track element history between analytical and physical models and to monitor change. Since structural steelwork was the only industry that could sustain interoperability, the market for structural steelwork primarily dictated these shapes. IFC improvements are the only means of facilitating the round-trip of natural multi-material objects, enhancing BIM's interoperability and making it more transparent and comprehensive in recent and subsequent years.

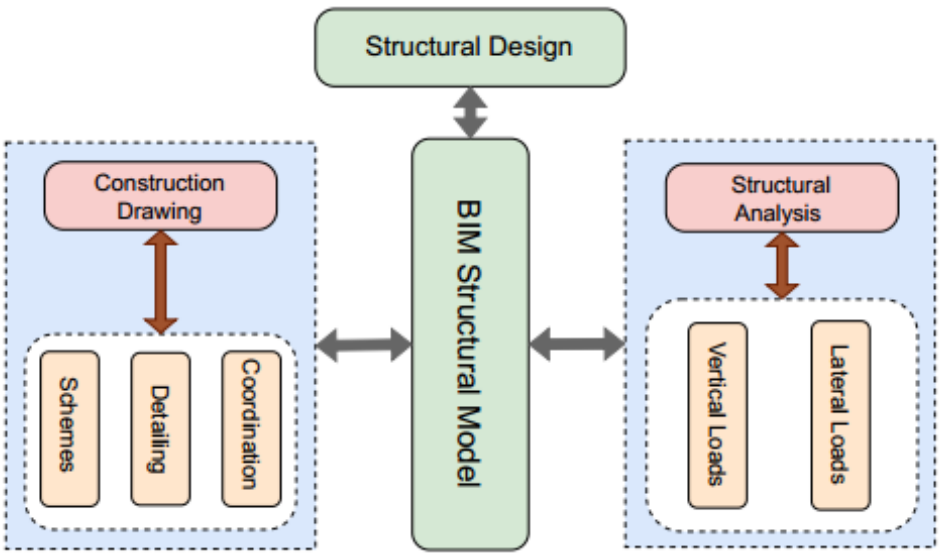


Figure 19: Data Transfer in BIM Structural Model (Author's Own)

BuildingSMART has certified several tools and applications that support IFC-format data input and output. Some BIM tools used in the A&D of S-BIM include Autodesk Revit, ArchiCAD, Trimble Tekla, and SCiA Engineer. When these tools' numerical modelling is precise and valuable, they can be utilised to build structures dependably.

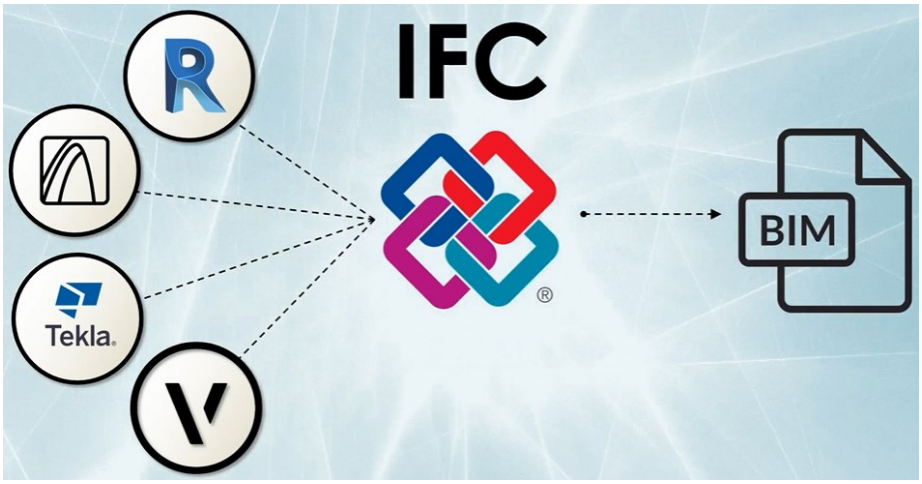


Figure 20: Exchange between Software and BIM

2.6 BIM Interoperability

Small businesses confront unique hurdles when deploying BIM, yet a BIM workflow helps their projects in unique ways. Because of the benefits of coordination and interoperability, more notable firms and significant projects use BIM. *Interoperability refers to the ability of one tool to explore data supplied by other systems*. The International Alliance for Interoperability (IAI) developed the first standard data format for communicating product model data in the 1990s, allowing designers to share files. The IFC standard was created, which provides a multi-level hierarchy for an internal organisation that is ideal for granting access to a BIM model database. In 2005, the AIA became a member of buildingSMART, which is in charge of developing standards for data transport (IFC), processes (Information Delivery Manual, IDM), and terminology (International Dictionary Framework, IFD).

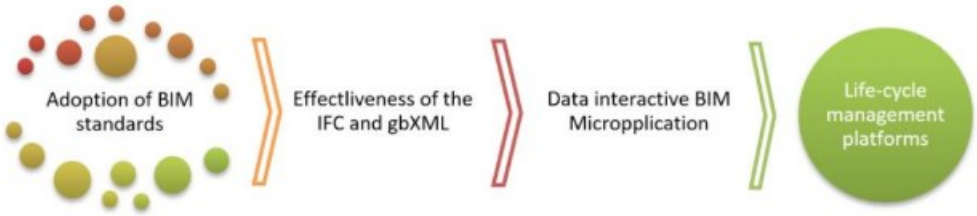


Figure 21: An overview of interoperability research interests amongst students and professionals *(Bercerik-Gerber and Kensek, 2010)*.

However, commercial software that can read the IFC format only permits limited data interpretation, as the optimum degree of efficiency has not yet been reached. Therefore, the current study investigates the extent of interoperability between several BIM systems and the structural design of the building case.

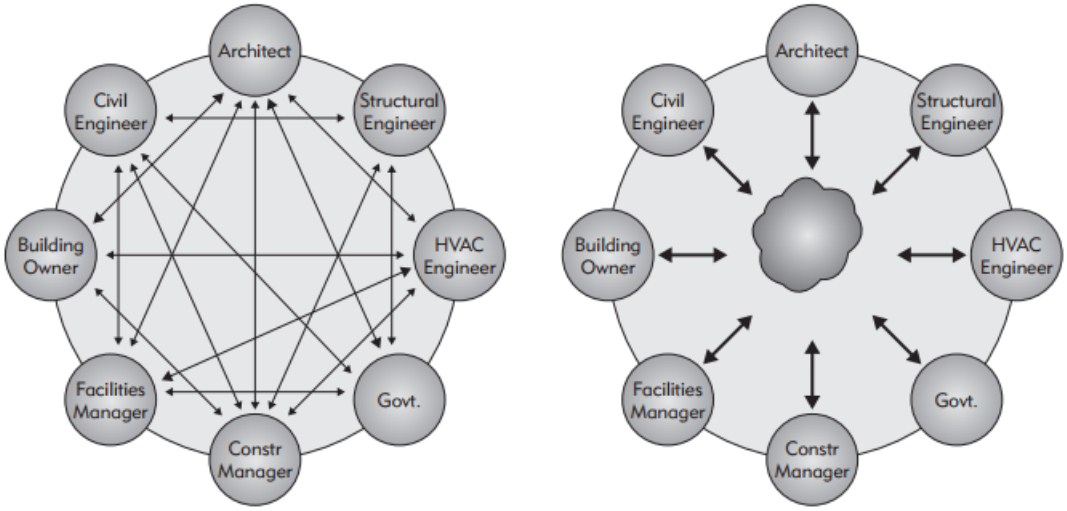


Figure 22: An interoperability view

Interoperability between distinct software programmes can be attained in a number of ways:

- Using software that directly reads the proprietary file format of the BIM software application, as will be the case with a suite of software applications made by the same software vendor;
- Utilising an Application Programming Interface (API) makes it simple for software from different companies to work together.
- In addition, the programme supports data interchange protocols, including the IFC format (Gayer, 2009).

Here, the significance of BIM interoperability is highlighted. It will be analysed in the next chapter, presenting the most authoritative studies on the subject, particularly with data sharing in the workflow of structural engineers. Then, interoperability between Building Information Modeling (BIM) and Finite Element Method (FEM) software is examined, covering all feasible data-sharing techniques. Finally, the IFCs and MVDs, two associated buildingSMART international standards, are described and analysed in this topic. This section provides all the necessary context for understanding the interoperability tests in subsequent chapters.

2.6.1 Importance of Interoperability

The AEC industry has been historically significant in every culture and country. Its productivity has evolved alongside manufacturing for ages. Since digitalisation began in the 1970s, manufacturing productivity has doubled. However, on-site construction productivity remains stable.

A US National Institute of Standards and Technology NIST-commissioned report emphasises the necessity of digital information interchange. According to interviews and surveys, non-optimal interoperability in the AEC industry cost $15.8 billion in 2002 in the US market. In addition to the stated costs, respondents reported that interoperability concerns had considerable additional inefficiencies and lost opportunity costs. Some sectors are more interoperable than others. For example, BIM tools and structural analysis software are essential to us. Increasing structural engineers' interoperability is crucial in BIM's seamless workflow. According to McGraw Hill Construction report, the BIM engineering analysis has a low value/difficulty ratio. This ratio for structural analysis is negative, so a structural engineer is better off developing a structural analysis model from scratch than reusing the BIM model from the architectural design process. Rework reduces productivity and increases time and expenses.

3 RESEARCH APPROACH (METHODOLOGY)

This study seeks to identify the process's significant benefits and limitations to demonstrate that BIM-based technologies facilitate the construction of a structural BIM project with improved performance. Two ways of data transfer were evaluated: add-in (links) and the IFC standard. We created an appropriate procedure for structural engineers since we retained essential insights. As a methodology:

- The study investigates how structural BIM models are created, exchanged, and validated at various phases of project development.
- The task entails the selection and application of BIM-based technologies, as well as the identification and preparation of data for use in the modelling, analysis, and design phases.
- Following each transfer step, a comprehensive code check of data analysis consistency is performed, and any necessary modifications are applied.

As a result, the primary benefits identified are demonstrated by addressing the current restrictions and establishing a suitable action plan for workflow implementation in the structural design sector to adopt BIM in engineering offices.

Any AEC project requires one or more structural engineers to conceive, analyse, and design the structural skeleton. Structural engineers must work closely with architects, MEP engineers, cost managers, and other professionals. CAD technologies streamline the structural engineer's process and save time over hand drafting. Numerous issues, such as obsolete drawings, and non-automated clash detection, could be overcome using BIM and its collective capacity.

Investing in BIM workflows can pay for itself many times over because of the time and money saved from not having to start from scratch. Sharing data with other AEC professionals is crucial for the success of BIM collaboration. Due to the fluid nature of the building research and design process and the varying needs of the various stakeholders, information must be freely shared and exchanged. In addition, the architect provides the structural engineer with information, including 2D space drawings, initial dimensions, and section sizes. The engineer uses this data to create an analytical model (AM) in Finite Element Method (FEM) software, applying his knowledge of creating an AM and how the loads should be applied. However, whenever there are changes to the architectural design, it is tedious and challenging to update the analytical model manually. In this instance, the ability to import or export models between BIM and FEM Software is essential. As a result, the time required to create a new model from scratch is reduced.

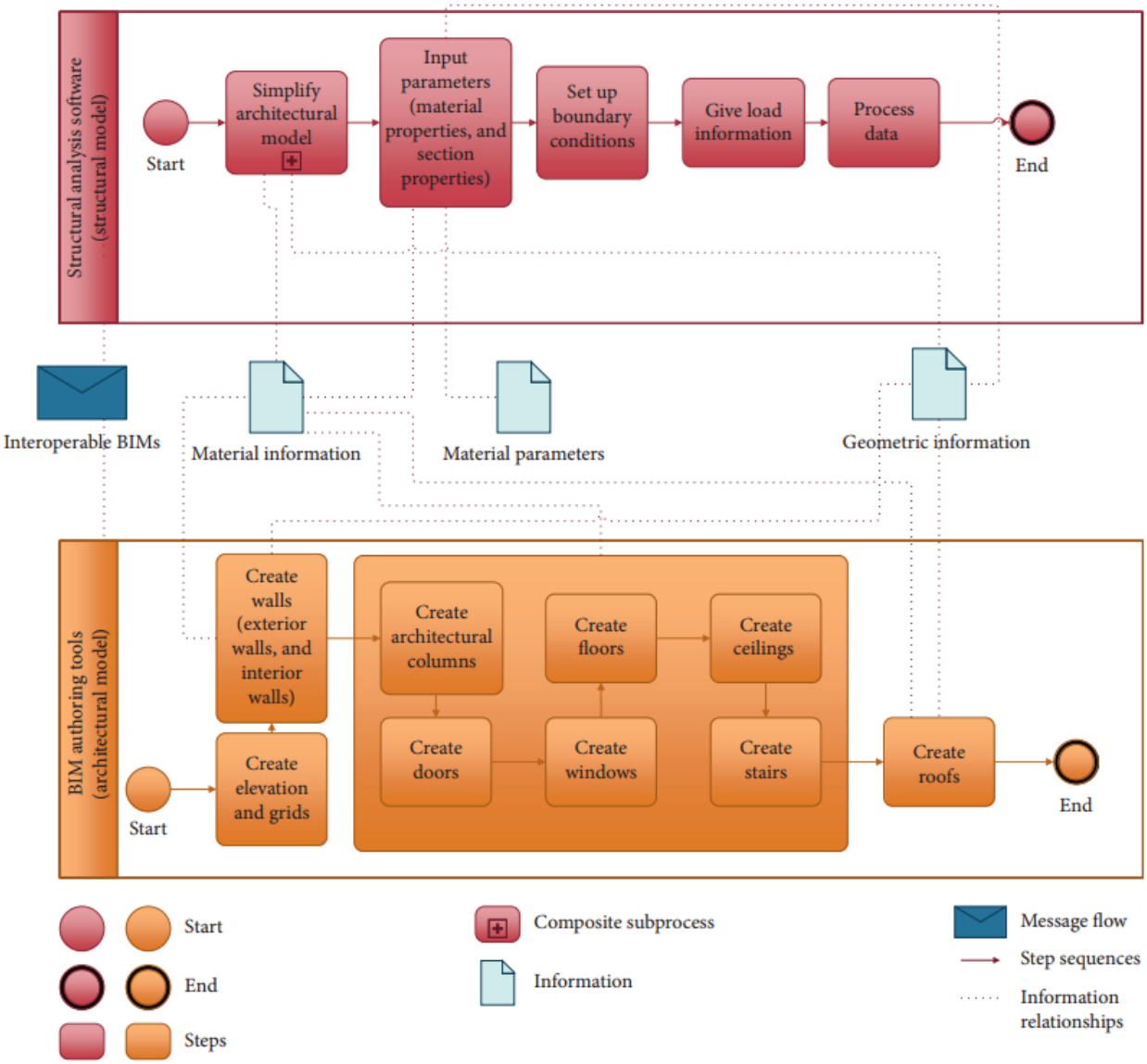


Figure 23: BIM Interoperability Workflow between Architects and Structural Engineers

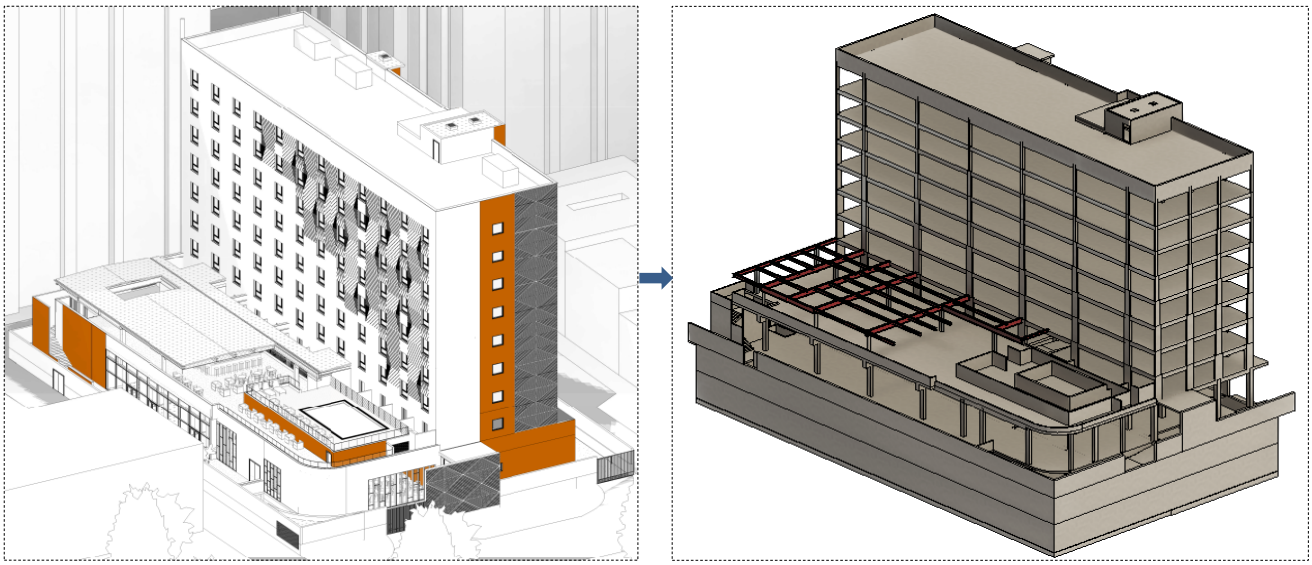


Figure 24: BIM Workflow between Architects and Structural Engineers (Author's Own)

Several researchers have written about the interoperability of BIM and FEM tools in the literature review. For example, according to Dravai et al., both the Revit-Robot Structural Analysis (RSA) and Tekla Structures Learning-RFEM links have tremendous potential because they can share all the information required for structural analysis quickly. However, even though there is compatibility between BIM and FEM Software, a structural design office and engineers encounter challenges if the architecture team and designers do not follow the proper workflow for better collaboration. One reason is that the design process and workflow must change and adapt to a BIM-based one. Unfortunately, there is substantial resistance to this transition from many engineers and structural design offices, who insist on using outdated design methodologies and lack a suitably developed workflow for implementation.

3.1 The Utilisation of BIM as a Tool for Structural Engineering

Typically, the suggested building design is shared with the structural engineer, who analyses and designs the structure to withstand external loads and actions. If this idea is presented as a conceptual BIM model, the first step will be to convert the conceptual model into a structural BIM model. Elements such as columns, beams, and walls must be allocated attributes that define their structural properties. This approach may entail collaboration with the architect from the conceptual design stage, especially if the project is expected to need extensive structural design. Furthermore, collaboration might begin as early as the conceptual design phase. After creating the structural BIM model, the structure may be analysed with FEA (Finite Element Analysis) or FEM (Finite Element Modeling) software. It is up to the engineer to determine whether the analytical model should be defined within the BIM model or if it should be defined outside the BIM model by the FEA/FEM programme. As shown below, there are several methods for transferring the structure to the FEA/FEM tools, independent of whether the AM will be described inside the BIM model.

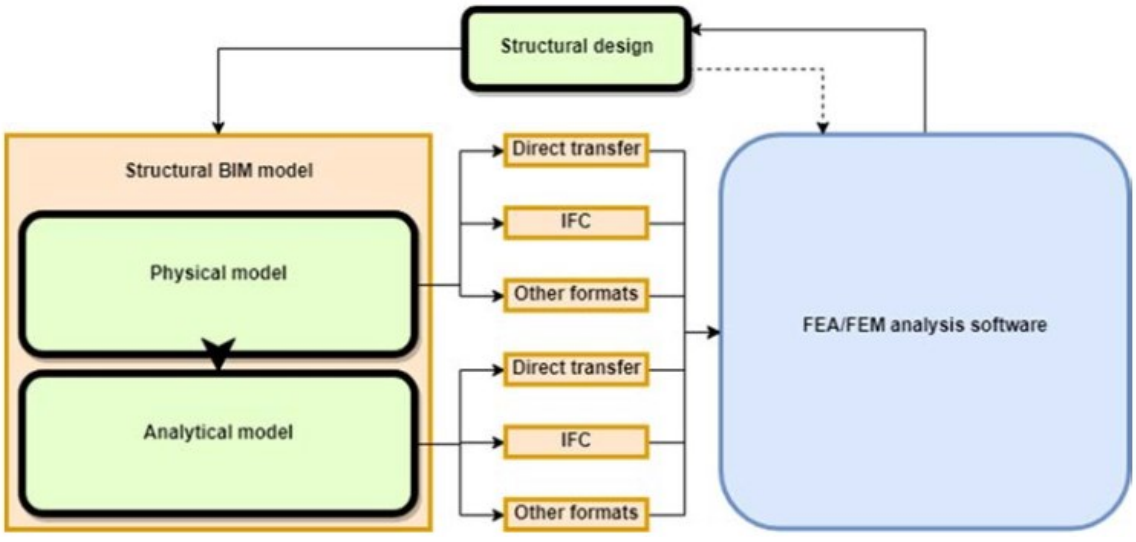


Figure 25: Typical BIM to FEM Workflow

This section describes BIM uses in structural BIM to present recent experiences with BIM tools and methodologies in structural engineering. The reference workflow for BIM use in structural modelling and analysis is shown below. In addition, the BIM Project Execution Planning Guide (Messner *et al.*) refers to this as the process map of BIM use in structural analysis.

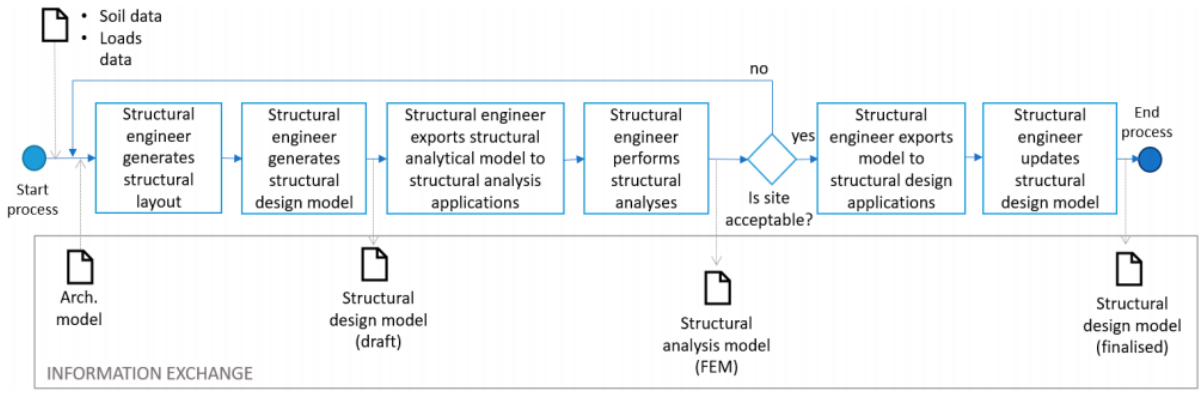


Figure 26: BIM-use reference workflow for Structural Analysis (Ciotta *et al.*, 2021)

The workflow begins with a concept design of the load-bearing structure, which generates an architectural information model and incorporates the foundation soil and loading conditions. Structural engineers then create a draught structural information model, which is utilised to develop a structural analytical model that may be exported for future structural analysis applications. These can execute FEA computations on a FEM-converted structural analytical model. Consequently, structural engineers must determine if they notice problems with the site parameters and the architectural model's compatibility. They might demand significant modifications to the design principles of the structural and architectural models. As seen in Figure 26, the entire process would need to be repeated in this instance.

However, the structural design can be finished if no difficulties are identified. This is accomplished by completing the ultimate structural design according to the reference standard with structural member evaluations, reinforcements, and connections utilising post-processing plug-ins or equivalent interoperable software. Finally, the procedure is completed with the last step of upgrading the structural information model.

Shop drawings of structural parts and systems are created using BIM techniques. The high-level reference method for manufacturing them is depicted in Figure 27. This workflow will be used in various simulations by practitioners in a design office performing advanced professional practises on BIM design projects. This is now referred to as *"BIM Sustainable Integrated Design"*. A high-level implementation workflow is developed so the design team can utilise it as a guide.

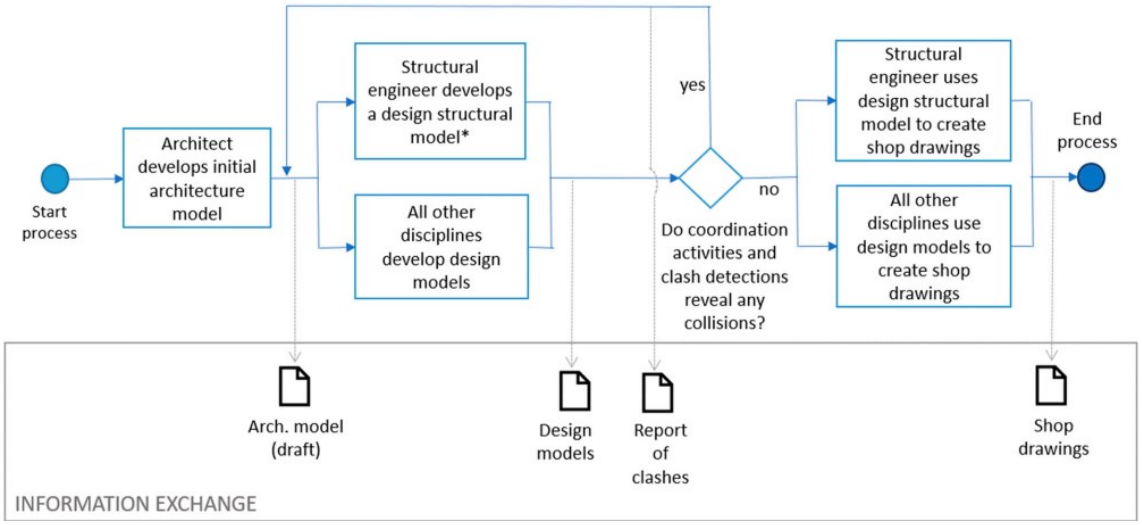


Figure 27: BIM-use high-level workflow for the production of shop drawings

An architect begins by developing an initial architectural model, which is then utilised as a conduit to develop design models for all other relevant disciplines. Most of the effort is spent on developing parametric libraries of details, connections, and objects, ensuring that the modelling is efficient and that nearby component are geometrically compatible. Next, a structural engineer specialising in the structural discipline develops the structural design model, which should be built utilising the approach depicted in Figure (26). The built model contains information on the composition of 3D elements such as beams, columns, and walls. This model will eventually be combined with design models from other disciplines to create federated versions (i.e., where the structural and architectural BIM models, the MEP and HVAC BIM models, can be merged). Coordination and clash detection is then performed using suitable interoperability applications and collaborative platforms that provide a structured, cooperative environment where information from many disciplines may be exchanged and shared. If no issues arise, the procedure continues, and the structural engineer may generate views, 3D views, and shop drawings fast utilising an integrated structural model. This also applies to other fields. The operation is then finished. Because model changes are translated to shop drawings, time-consuming reworks are avoided if revisions are made later. Furthermore, this guarantees that the drawings constantly reflect the model's current state.

In a conventional CAD-based procedure, the geometry of structural elements may be represented in a two-dimensional environment. Alternatively, it is possible to construct real-time virtualization of the structural system in a BIM-based form, with its geometry and details modelled in a 3D environment. The former handles individual shop drawings. Simultaneously, the latter generates a BIM structural model from which shop drawings and other construction deliverables, such as quantity take-offs and cost estimates, may be derived. The previously described BIM tools and procedures are being utilised successfully.

3.2 BIM Interoperability Workflow and Software

Two primary approaches were selected to address the exposed objectives of this thesis. Firstly, a comprehensive assessment of BIM tools applicable to structural engineering and their interoperability capabilities for architects and engineers. Secondly, the development of a workflow with a practical experimental application of BIM interoperability on a hypothetical project is accomplished with a selected early design stage performance tool that interoperates with other BIM tools in a structural design office and design teams. The practical application is intended to identify issues with workflow implementation in structural BIM from the designer's point of view and compare its approach to a conventional one. One of the biggest challenges during the practical case study was the absence of a tried and proven methodology implemented early in the design and a standard workflow for the overall modelling and analysis process. Furthermore, the conventional approach usually involves one cycle of workflow: modelling - analysis - design - improvement; meanwhile, most design offices currently practice more than one such cycle.

3.3 BIM Tools for Design and Collaboration Interoperability workflow and software

As BIM in structural engineering evolves, various tools have been created, particularly for structural BIM. The purpose of this study was not to compile an exhaustive list of available software or to compare and pick the best modelling tool. Nevertheless, a decision was taken based on the tool's popularity at a design firm. The following evaluation highlights the interoperability of the top three BIM modelling and design software solutions. Revit, SCiA Engineer, Trimble Tekla Structure & Designer, and IDEA StatiCa are the software packages used. The most popular BIM programme, Revit (version 2022), was chosen as the principal software to receive data from architects and other design teams in the present study. In addition, a thorough investigation of workflow implementation is conducted using Trimble Tekla Structures & Designer and SCiA Engineer, which are structural engineering software used primarily for modelling and designing structures in the Slovenian market and design firms. Finally, Tekla Tedds will be assessed, with IDEA StatiCa serving as the primary software for designing steel connections.

Various structural analysis software and models are utilised in complicated structural projects to ensure safety and compliance with the proposed design. Furthermore, the literature analysis reveals that shared data is one of the most common BIM-based ways of assisting diverse applications to operate together (Hu et al., 2016). This is because shared data organises and standardises data pieces.

Hu et al. (2016) say that the information in the architectural models relevant to the structural model is found, categorised, processed, and then sent to the structural model during the conversion process between the two models. This makes the architectural design and structural design processes much more

compatible with each other. The algorithm also changes structural design models into architectural design models. First, it sorts the different types of elements and finds geometric information about them in the structural design. Then, it turns them into their architectural models. SCiA Engineer is a tool for structural and architectural engineers that is complex, flexible, and easy to use. It is powered by an analytical engine and a design tool that has never been seen before. It has been shown to be the most useful, flexible, and all-purpose tool for building structures on the market. It makes it easy for structural engineers to make models quickly and without a long learning curve.

The design models generated by the Tekla BIM tool include the precise, comprehensive, and dependable data essential for practical BIM and construction execution. It facilitates coordination amongst the many building parties. Using the Tekla BIM platform, the complete construction workflow can combine their models, communicate information, and check for discrepancies. In addition, this application supports the majority of current design file formats, including DXF, DGN, DWG, and IFC. It integrates diverse file types and models from several BIM applications into a single project. This facilitates the collaboration of architectural and structural designs.

3.4 Autodesk Revit

Revit and ArchiCAD are the most popular BIM tools for architecture, as both can manage huge BIM design models. In addition, FEM-design tools are used for structural engineering analysis and design. The Autodesk Revit software is designed for BIM, enabling professionals to design, construct, and manage more high-quality structures. Using the information-rich models generated by Autodesk Revit, architects, engineers, and construction firms may make better-informed decisions early in the design process to expedite the delivery of projects. Moreover, any design modifications created in Revit models are instantly updated across the model, ensuring that designs and documentation remain coordinated and dependable. Autodesk Revit has tools for architectural design, mechanical, electrical, plumbing, structural engineering, and construction, giving a comprehensive solution for the entire building project team. Revit's capabilities range from 3D modelling and animation to the visual effects of CAD for detailed drawings. Revit solutions are designed for BIM projects and encompass a significant portion of the construction planning process. Revit is a multi-discipline design collaboration programme that supports:

- conceptual design with a particular set of tools;
- interoperability through the formats like IFC, DWG, DWF/DWFx, gbXML, HTML, DXF, DGN, SAT, ADSK, and FBX;
- architectural, structural and MEP modelling;
- built-in graphical programming interface Dynamo.

The Revit format identifies each component with a unique number. The ID is made up of six numbers and is used to keep track of everything. When a file is exported from Revit to the IFC format, the tools change the IDs to GUIDs. Autodesk Revit's ability to build and interoperate a structural model via direct and indirect linkages makes it a good fit for 3D structural design. Formal structural analysis, including property profile, load, load combination, and boundary conditions, may be performed on the model's many materials. Revit's flexibility and ability to get updates are two of its most robust features. As a result, the collaboration between architects and structural engineers is smoother than before.

3.5 SCiA Engineer

SCiA provides excellent structural analysis tools and top-tier support by combining the knowledge and experience of structural engineers and designers with the most advanced technological capabilities available today. Therefore, they enhance the BIM workflow of structural engineers and increase productivity for routine and extraordinary buildings. SCiA Engineer's CAD-like user interface makes it easy for professionals to construct, analyse, and optimise 3D models of any structure, material, or load situation with speed and precision.

SCiA Engineer was conceived as a tool for BIM workflows and built accordingly. With the architect's help, it transfers models to the tools used by the rest of the project's design team and the people who will be affected by the outcome of the project.

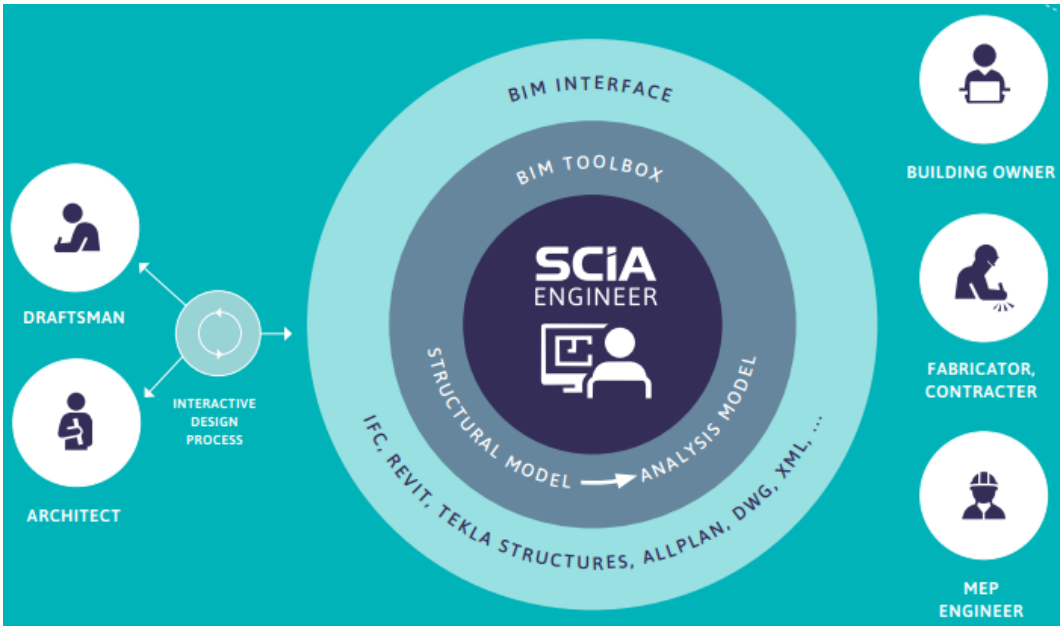


Figure 28: BIM workflow with SCiA Engineer (Source: SCiA Engineer)

SCiA Engineer's drive comes from the company's dedication to Research and Development (R&D) and innovation and from the company's openness to user feedback and outside inspiration (SCiA, 2019). The following are some of how it stands out:

- Comprehensive, Adaptable, High-Level Analysis

Effective and efficient modelling software, the visualisation, and analysis of buildings, materials, and stresses are now possible using sophisticated 3D modelling software.

- The Ultimate Way to Increase Efficiency

SCiA Engineer's streamlined operation results from the software's well-thought-out user interface, straightforward workflow, cutting-edge technologies and potent capabilities like load generators and instant report updates.

- Get hold of your model and learn how to use it.

Engineers will have complete command over all data in models large and small as they plan a BIM building project to meet all applicable international standards. Modify the report, so it fits the needs of the client.

- Increasing Involvement in BIM Processes

SCiA Engineers can communicate with other BIM programmes that AEC, government, and construction industries use. In the long run, this makes it less costly and more convenient for users to collaborate with industry partners, reuse existing data, or update models.

- Constant Guidance from Industry Professionals

Expert technical assistance is available from structural engineers. They are familiar with the programme and may utilise their knowledge to assist users in learning it quickly, gaining a deeper comprehension of the findings, solving model-specific issues, and implementing individualised parameters and formulae.

3.5.1 SCiA AutoConverter

By facilitating OpenBIM collaboration, the SCiA AutoConverter has the potential to revolutionise how engineers work together. It is the only available tool of its kind, and it helps structural engineers transform any CAD model into an analytical model for use in an OpenBIM workflow. Uploaded structural models from any CAD system may be converted into a structural analysis model via a controlled automated approach. Avoiding tedious and uncomfortable activities frees structural engineers' time for more critical work. The simplified handling of changes results from the enhanced collaborative process incorporating change management. When a change is made to the structural model, the corresponding analytical model is updated instantly. A result of this is that an engineer is less likely to lose valuable analytical data, such as the weights applied within the tool.

The SCiA AutoConverter drastically cuts down on the amount of time and effort put into projects, the number of potential mistakes made, the amount of data that needs to be recreated, the amount of time and money saved, and the total amount of money saved. The SCIA AutoConverter is a time-saving, trouble-free, precise, and trustworthy tool.

3.5.2 Interoperability with SCiA Engineer

SCiA Engineer may be seamlessly integrated into existing processes to streamline project management, reduce manual labour, and speed up development. Using their respective data and digital models, architects, engineers, and other project stakeholders may work together on a project.

Through a comprehensive set of integrated interfaces, data can be transferred to and from several CAD programmes quickly, easily, and without mistake, allowing for seamless collaboration among all project participants.

- Bi-directional links with **Revit, Tekla Structures and Allplan.**
- Easy **parametric modelling** via plug-in for Rhino3D and **Grasshopper**.
- **IFC 2x3** and **IFC 4** support for sharing of structural models.
- **SAF 2.0** support for exchange of analysis models.
- Other widely used file formats like SDNF, Frilo GEO, DXF, DWG, and VRML.

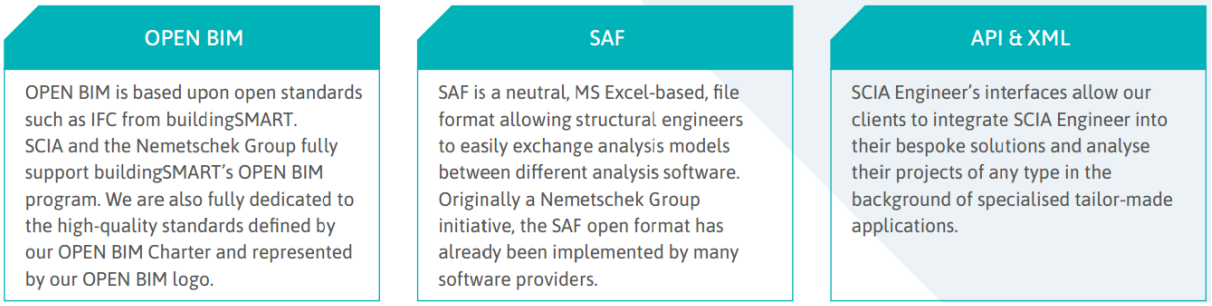


Figure 29: Interoperability Formats (Source: SCiA Engineer)

3.5.3 Workflow for SCiA Engineer and Revit Structure Direct Link

For those that use Revit, SCiA Engineer is a must-have tool. With the two-way connection between Revit and SCiA Engineer, engineers may begin a project in either software and have their changes updated instantly in the other.

The link supports:

- Import/export slabs, floors, walls, shells, beams, columns, and bracing in various materials (steel, concrete, timber), and mapping of all possible geometries and construction types.

- Import/export analytical elements: supports, hinges, loads and load combinations.
- Export results back into Revit: Deflections, stresses and beam end reactions.
- Change Management. All changes are tracked and highlighted so an engineer can easily see the edits coming in from the other program.
- Reinforcement export.

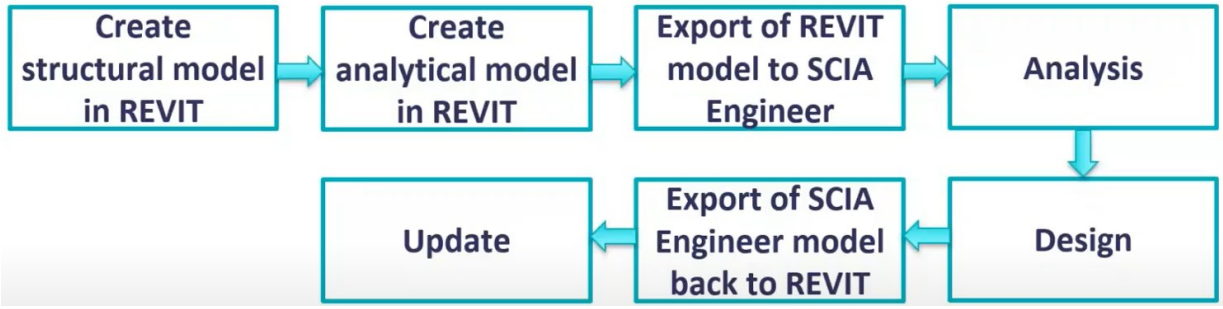


Figure 30: Revit Structure to SCiA Engineer Direct-Link workflow (Source: Authors' Own).

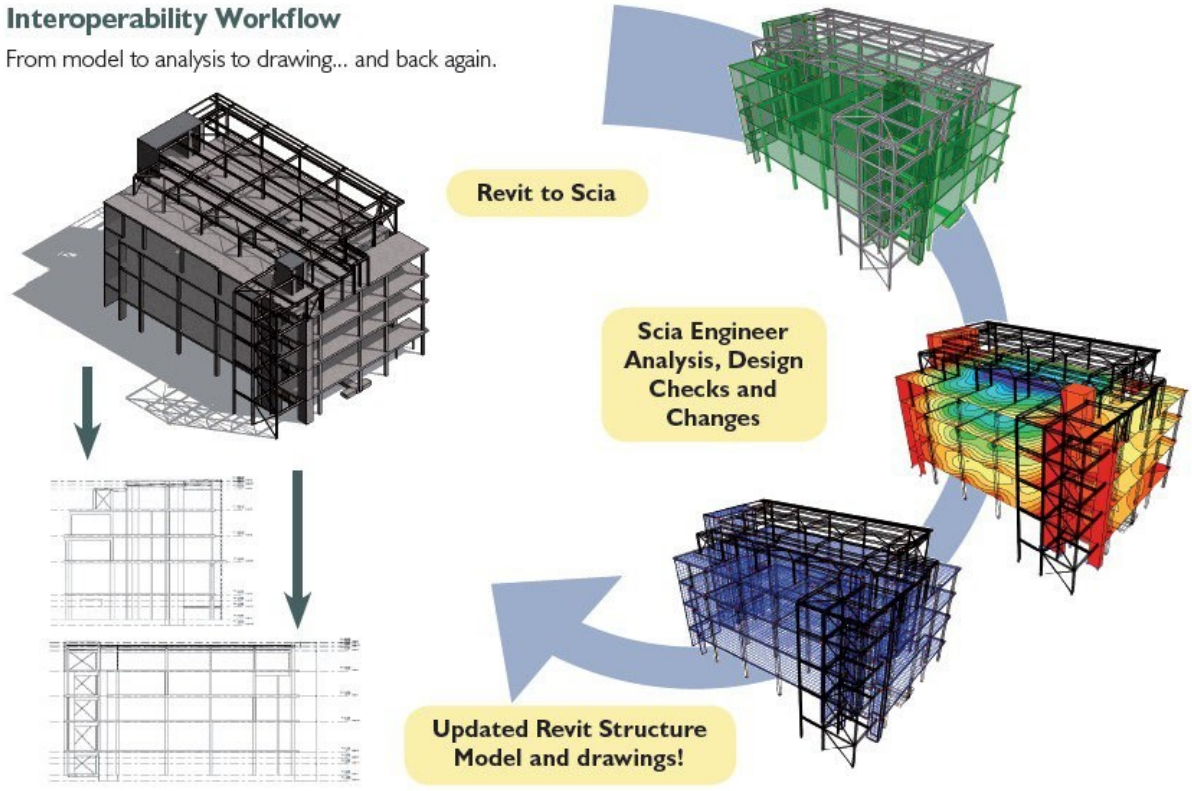


Figure 31: Revit to SCiA Engineer Interoperability Workflow (Source: Scia Engineer)

Figure 30 shows the nature of the direct link exchange scenario developed by the design team between Revit and SCiA Engineer. The link facilitates the bidirectional exchange of structural engineering data between both programmes through export and import settings. For instance, using the direct link, a Revit analytical model is sent to SCiA. After SCiA Engineer analyses the model and designs the structural

elements, the revised model is sent back to Revit. Before exporting, the Revit-SCiA link interface examines the Revit model and organises structural elements into categories. The Revit model may then be exported to SCiA based on the sorted list of items indicated in the dialogue option. A log dialogue box will display a list of mapped and exported structural data after the export is complete.

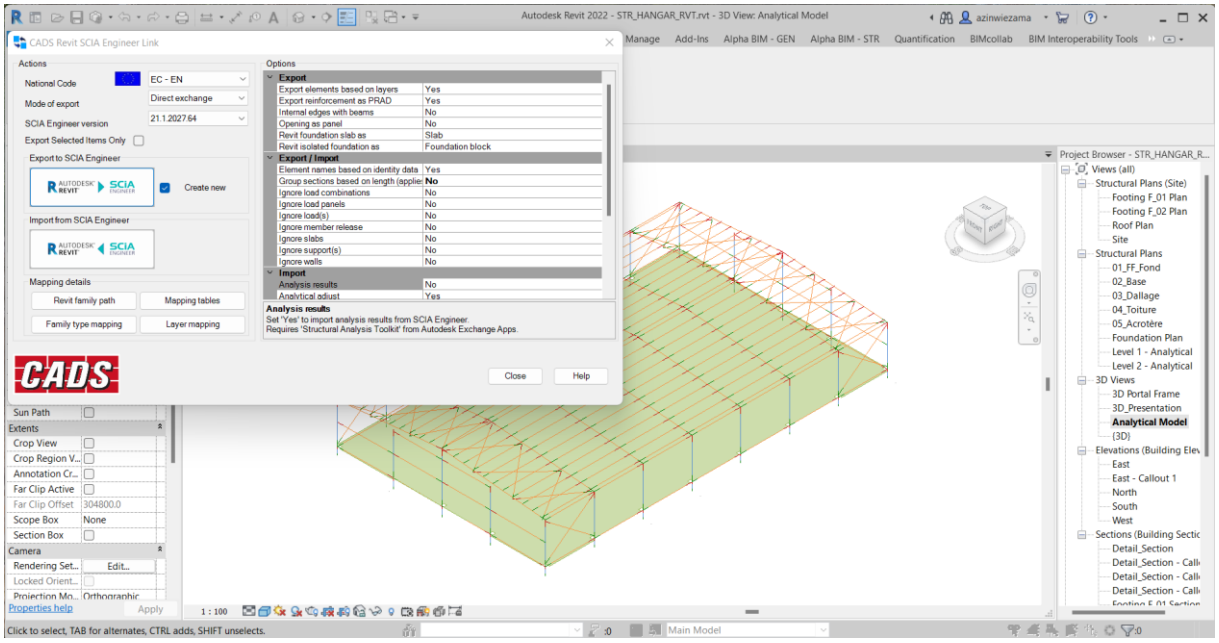
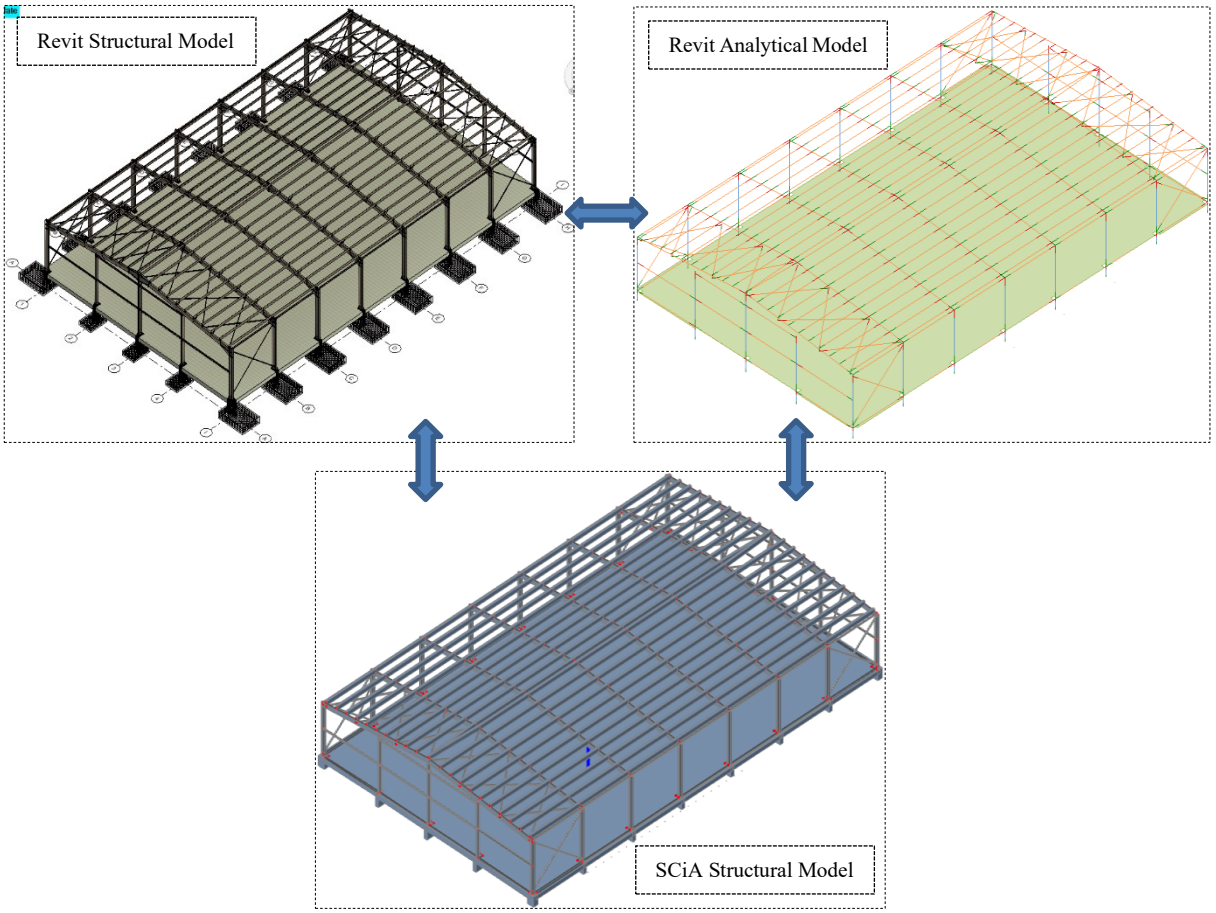


Figure 32: CADS Link for Revit - SCiA Engineer: Revit Structural Model to Analytical Model to SCiA.



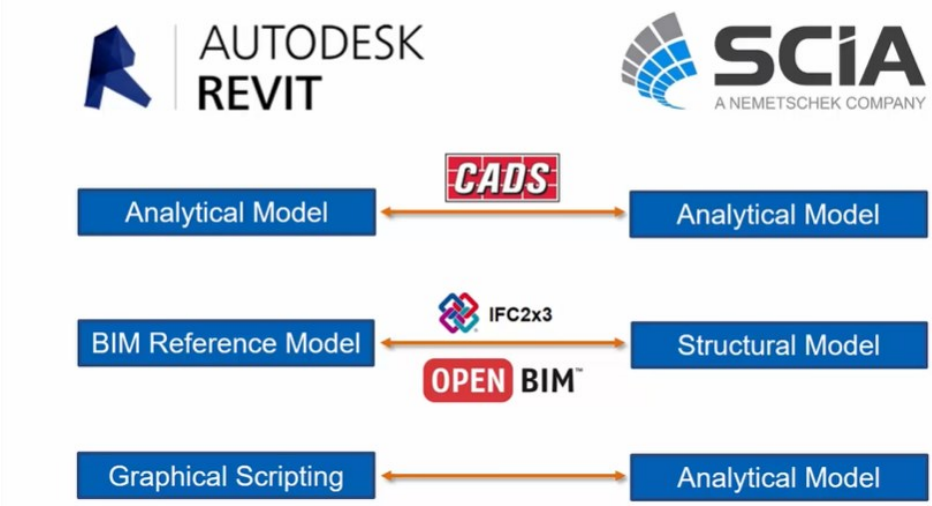


Figure 33: Data-Exchange workflow with SCiA

Table 1: Pros and Cons of Different Data-Exchange Methods with SCiA Engineer

Transfer Method	Pros	Cons
CADS direct link	• Supports direct data transfer based on member mapping • Link is bi-directional, i.e. changes can be easily pushed on either direction. • An expandable mapping table takes into account custom families.	• The lack of an analytical model in Revit means no transfer. • An unmanaged analytical model will lead to alignment/ connectivity issues. • Cross-sectional types not in the library would not be transferred (Cellular beams, 3 plate members)
BIM reference workflow	• No limit to geometry type that can be transferred (taped members, shells) • The open file format allows for exchange with 150 different BIM applications • Non-analytical data (Architecture, MEP, Civil) can also be imported.	• No mapping table means no direct mapping of elements. • Alignment issues occur due to a lack of analytical model • Conversion of general geometry is required (BIM Tools in SCiA)
Graphical scripting	• Ability to quickly create,/edit complex 3D geometries • Create automation using parametric elements • Bi-directional exchange using XML	• Requires some computer programming experience • Not practical to typical structures

3.5.4 Workflow for SCiA Engineer and Tekla Structure Direct Link

SCiA Engineer is a powerful solution not only for the structural analysis itself, but it also features extensive interoperability options. There are various options - Open and Closed BIM - based on the IFC format and proprietary direct links with other software. An example of the latter is our Tekla Structures link. This interface lets us transfer Tekla Structures and SCiA Engineer structural models. Furthermore, the link is bi-directional, permitting a workflow between engineers to update their models from both sides.

The primary feature and advantage of the direct link are that engineers may transfer the entire model or only a part of it. It is not uncommon to have many analytical models for the same construction, each representing a different material or element (such as steel or concrete). In addition, a dialogue box reveals which objects have already been transferred, allowing you to monitor the transfer process in real-time. After the transfer is complete, you can see and save the whole report. SCiA Engineer enables you to choose between several national standards for materials and cross-sections. The link makes it simpler to map resources from one undertaking to another. Any mapping table you make will be archived alongside your project when you save it. This chart features steel profiles. Parametric profiles need mapping due to the variety of dimensions involved. The data being sent over this connection includes:

- 1D as well as 2D elements,
- Constraints/support
- hinges
- rigid links
- export of reinforcement for beams and columns (user reinforcement, converted reinforcement and free bars) from SCIA Engineer to Tekla
- export of 2D reinforcement from SCIA Engineer to Tekla
- Import reinforcement for beams and columns from Tekla to SCIA Engineer
- Import of paired cross-section from Tekla to SCIA Engineer

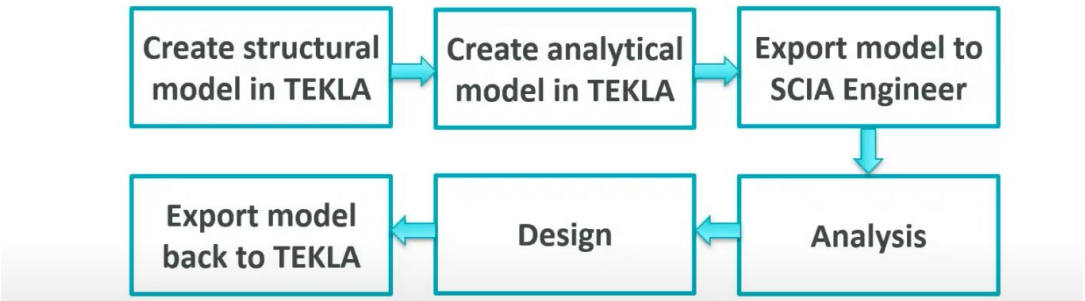


Figure 34: Tekla Structure to SCiA Engineer Direct-Link workflow (Source: Authors' Own).

The following case study is a practical reversed Tekla Structure direct-link interoperability workflow on a multi-story steel structural building modelled in SCiA Engineer (Student version 21.1.2017.64), transferred to Tekla Structures.

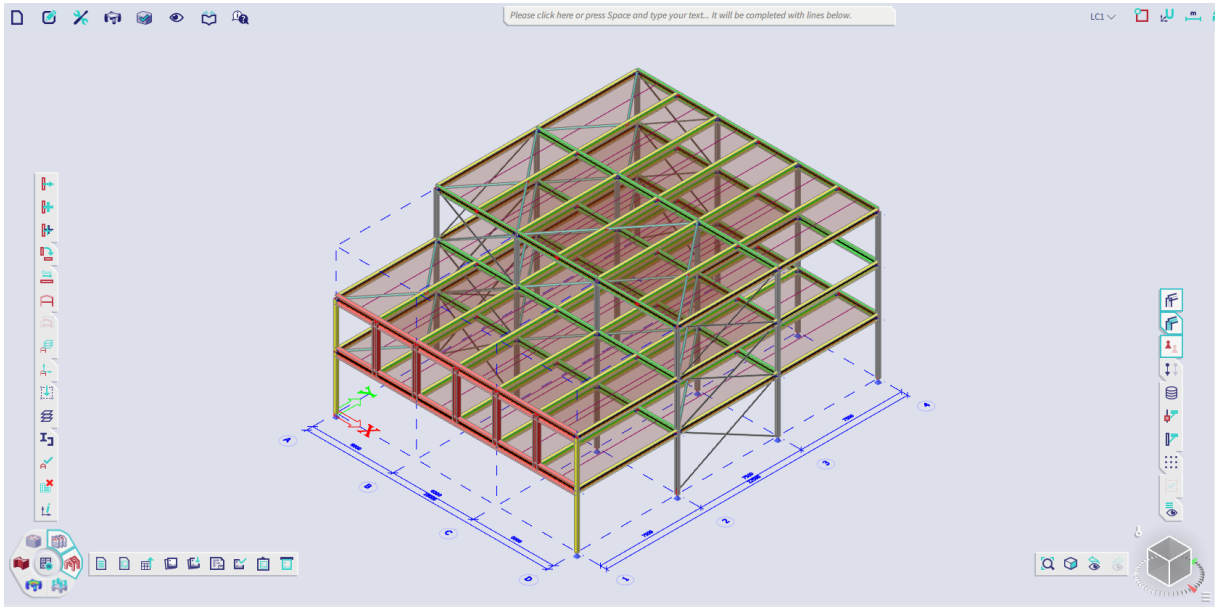


Figure 35: Multi-Storey Steel Structural Building Model in SCiA Engineer (Source: Authors' Own).

The CADS SCiA link is launched from a compatibility Tekla structures 2022 version, automatically starting SCiA Engineer in the background with properties options in the dialogue box.

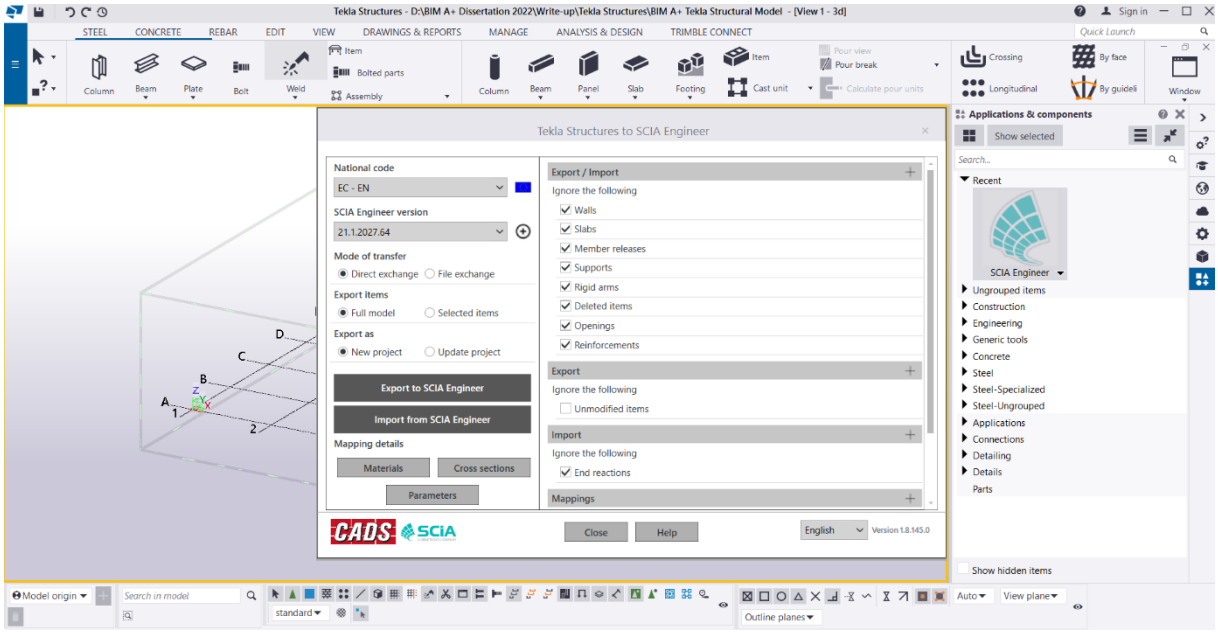


Figure 36: Launching CADS SCiA Direct-Link in Tekla Structure (Source: Authors' Own)

The steel building structural model from SCiA Engineer is automatically translated into an analytical model with all applied forces, loading conditions, and calculated results available for exploration.

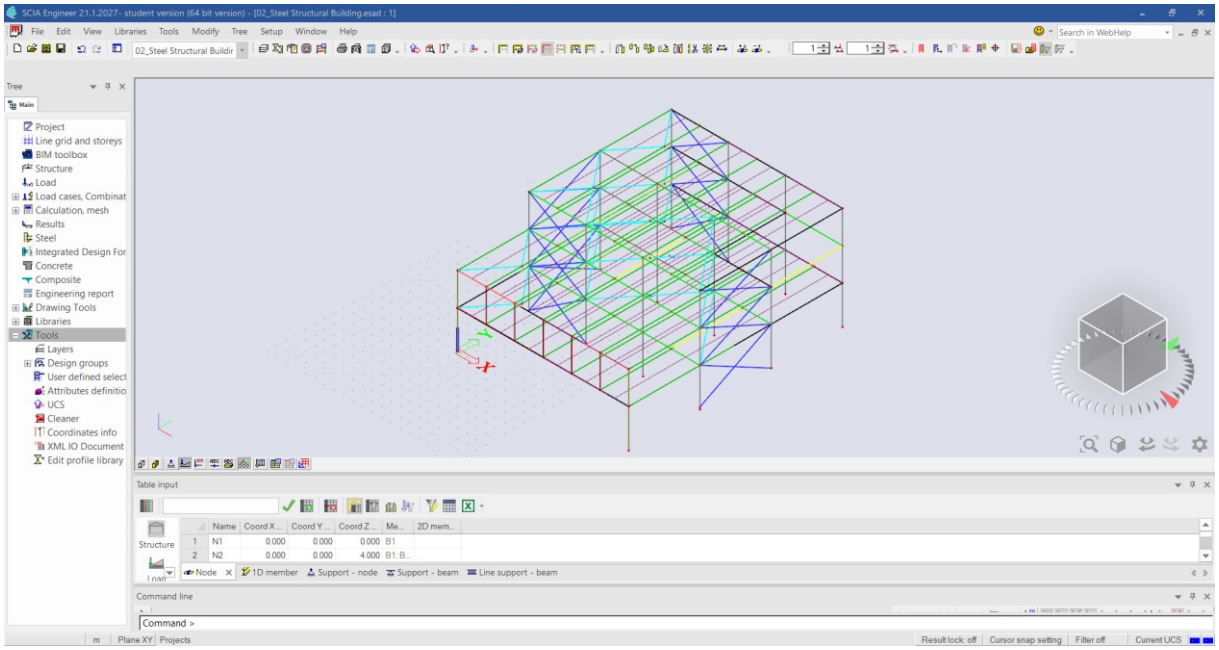


Figure 37: Analytical Model in SCiA Engineer through the Tekla Structures Direct-Link.

We observe that if the design Codes and standards in SCiA Engineer are different from the ones in Tekla Structure, proper materials and cross-sectional elements are mapped into the Tekla Structure interface to compatible cross sections.

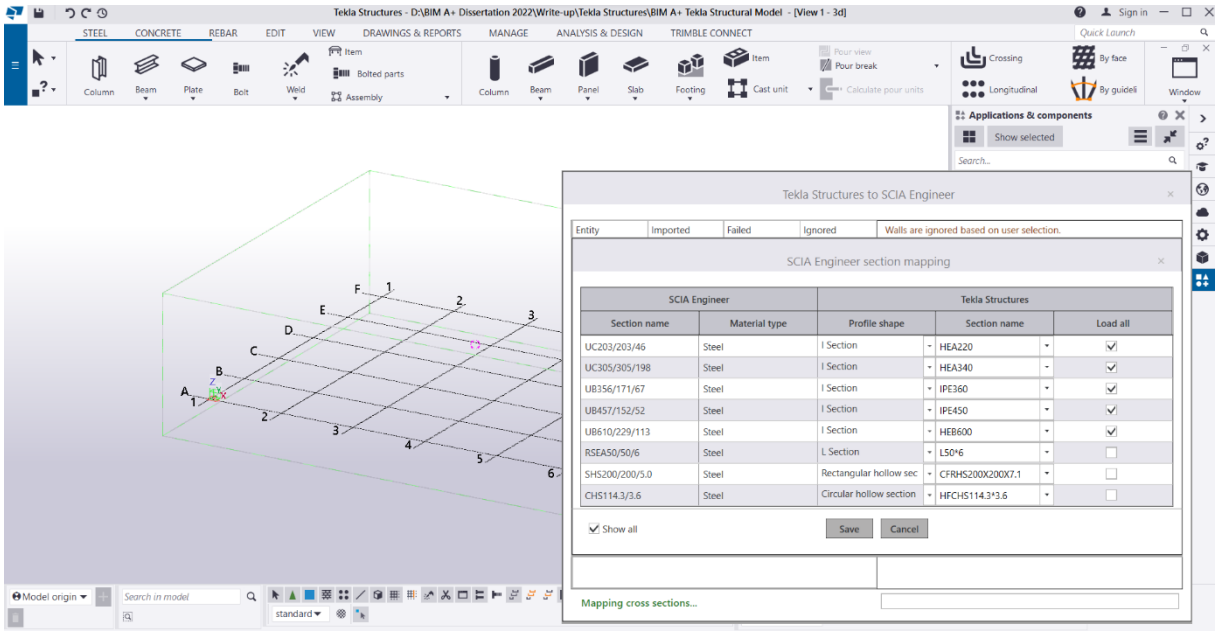


Figure 38: Materials and Cross-Section Mapping from SCiA to Tekla Structures (Source: Author's Own)

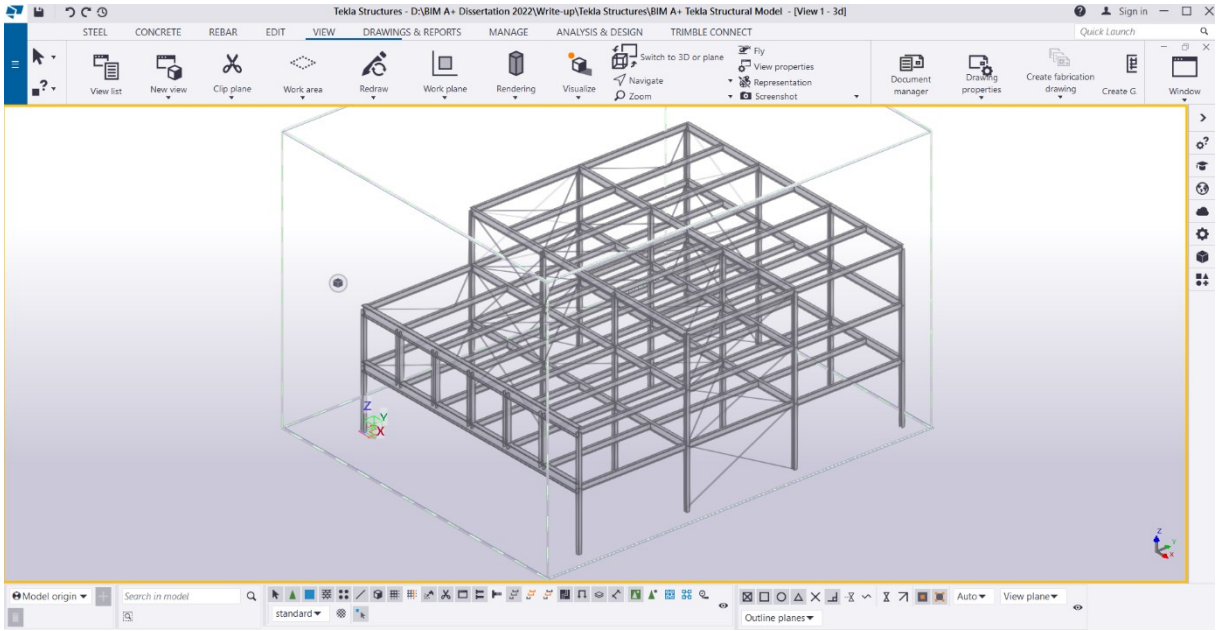


Figure 39: Interoperable SCiA Structural Model in Tekla Structures (Source: Author's Own).

Finally, the model is mapped successfully with a report of all mapped and transferred materials and cross-sectional members. There is a possibility to make changes to cross-sectional members and update the structural model in SCiA Engineer via the CADS-link for checks and further analysis.

3.6 Trimble Tekla

Trimble is a global provider of tools, technology, and services for the AEC industry. Trimble's groundbreaking approach to empowering teams throughout the construction lifecycle improves collaboration and information sharing among project participants at all stages. Trimble's Connected Construction method empowers users by putting them in charge of their operations using cutting-edge tools and a centralised database. Trimble provides the tools for construction professionals to improve productivity, quality, transparency, safety, and sustainability by automating processes and modifying workflows.

Each year, Trimble updates the Tekla software it uses to facilitate constructible BIM, structural engineering, and steel fabrication management. As of March 9, 2022, SUNNYVALE, California, reports that Tekla released four new products aimed at structural engineering firms: Structures 2022, Tekla Structural Designer 2022, Tekla Tedds 2022, and Tekla PowerFab 2022. The newest Tekla software improves automated and integrated workflows for all project phases and stakeholders and facilitates green building design.

Figure 40: Tekla Products for Structural Engineering Offices (Source: Trimble Tekla)

3.6.1 Tekla Structures (TS)

An advanced structural BIM software lets designers and engineers create, combine, manage and share multi-material 3D models with valuable construction information.

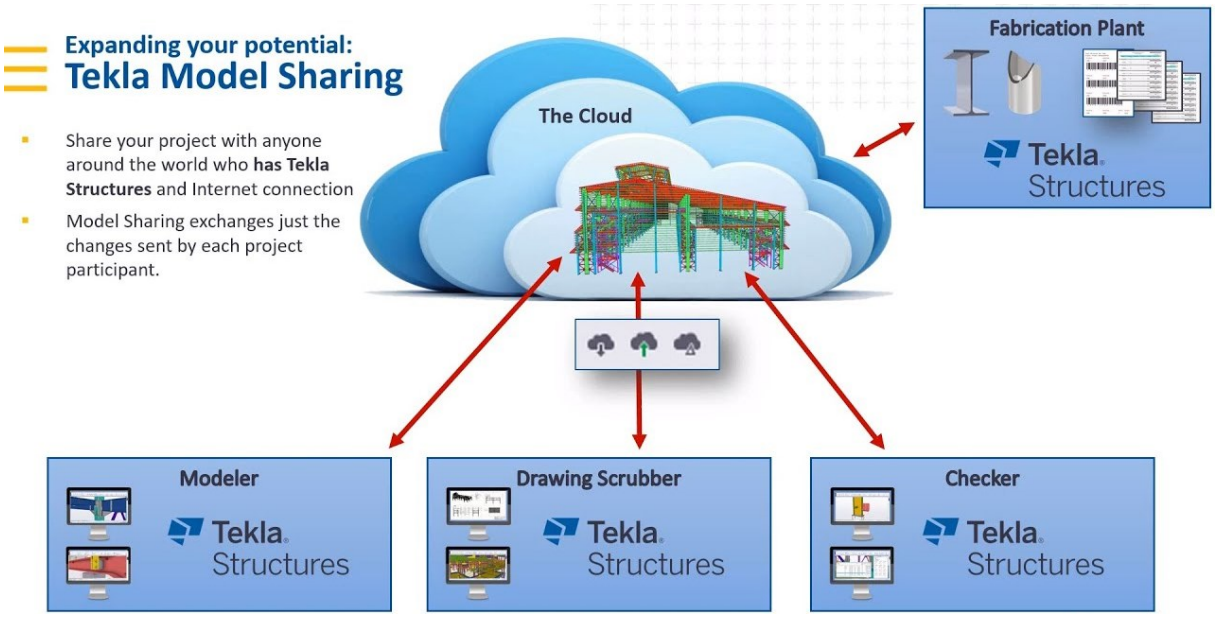


Figure 41: Tekla Structure Model Sharing (Source: Trimble Tekla Structure)

Tekla Structures (TS) permit direct conversion of imported IFC elements to native objects. In addition, TS offers good interoperability with a wide variety of tools and immediately recognises the analytical geometry of the physical and structural elements included in IFC format files. In contrast, Revit cannot do these procedures automatically without the assistance of other software and tools. Tekla Structures can achieve an as-built LOD 500, which is interoperable with other applications that can manage digital tools and IFC formats and transfer data directly to fabrication machinery. Tekla Structures is an OpenBIM software that interfaces with another modelling, analysis, design, construction, and management tool. The Open APIs of Tekla Structures provide collaborative workflows with excellent information sharing. TS integrates exceptionally well with analysis and design tools such as TSD, SCiA,

Dlubal, and STAAD.Pro, Midas, Cype, RSA, SAP2000, and StruSoft. In addition, It also connects to fabrication machinery, like the rebar processing systems, using BVBS formats, PXML, Unitechnik or proprietary formats of aSa, LP-System, Arma+.

- ***Tekla Structures – Revit collaboration via standard IFC file***

Tekla Structures and Revit has a workflow that enables data exchange of structural BIM models amongst each other through IFC and .rvt geometry file exchanges.

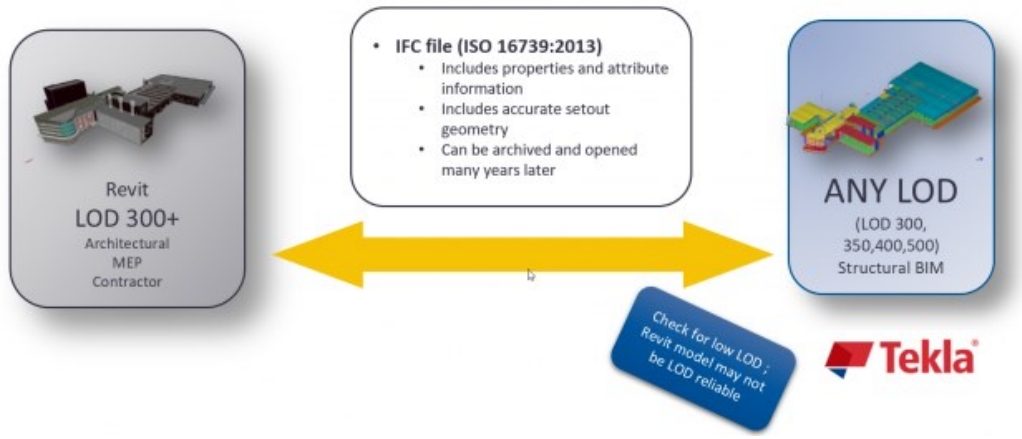


Figure 42: Tekla Structures and Revit BIM workflow through standard IFC file exchange.

- ***Tekla Structures export to Revit (.rvt geometry)***

The Tekla Warehouse plug-in lets engineers create .rvt geometry files straight from Tekla Structures. The .rvt file has no drawing sheets, legends, optimised families, types, or project levels. Similar to 3D DWG and 3D DGN, this file is used for project collaboration.

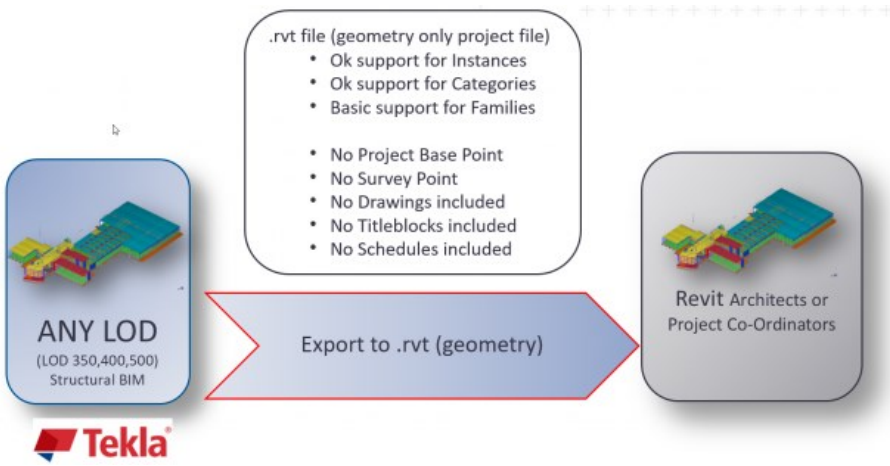


Figure 43: Tekla Structures and Revit BIM workflow .rvt geometry file exchange.

3.6.2 Tekla Structural Designer (TSD)

Tekla Structural Designer (TSD) software designs reinforced concrete and steel structures. It operates with tangible objects like beams, columns, and slabs. The physical information, such as geometry, section size, grade, and associated data, works with TSD. Experts can begin modelling in TSD or TS and then import/export in .cxl formats using BIM Integration commands. Information can be transferred rapidly between the software. In addition, the procedure can include either a partial or complete model, and for each update, it can read the project's modifications. It is possible to carry out imports/export many times and use the practical change management functionality.

TSD is a code-based modelling tool that enables structural engineers to create a code-compliant structure design and do calculations and schema design. All design/code information is stored in TSD. It analyses and designs structures to a range of International codes of practice. Furthermore, TSD enables the production and application of loads automatically. You can create data-rich models at rapid speeds. The physical model is used to build an analytical model without further change. The design and structural performance of the building are reviewed transparently. Early optimal designs allow for the production of concrete reinforcement for structural parts. In addition, more options can be investigated with less effort. Calculation reports are easily updatable and linked to the model. You can do a material take-off, create a design, and track documents containing steel quantities with a single click. Exporting data in numerous formats increases the software's compatibility. The physical information model functions and integrates nicely with TS and Autodesk Revit. As a result, the import process can identify and highlight all updates and modifications.

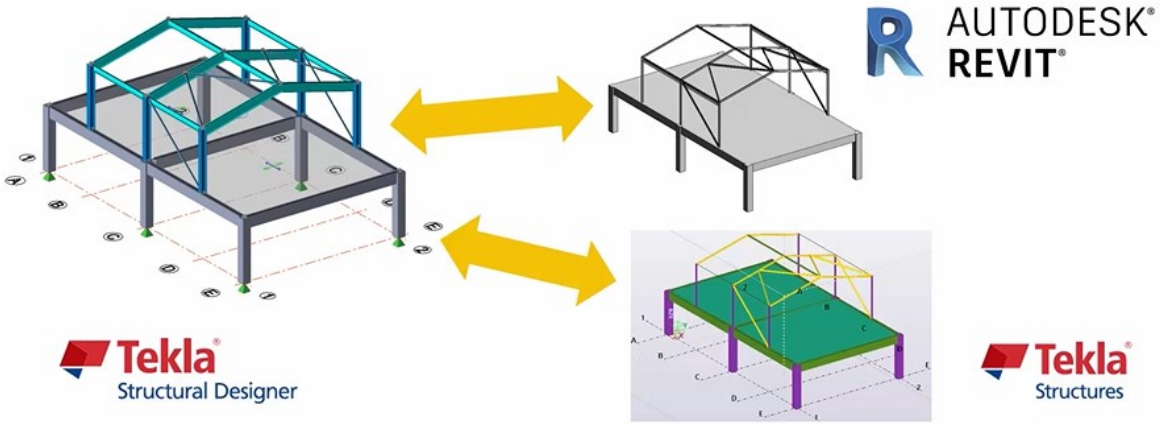


Figure 44: TSD Integration workflow of Analysis and Design model with BIM software

The feature of the Embodied Carbon Calculator introduced for TSD in 2021 has now been improved for the viewing, reporting, and sharing of carbon data. Using Tekla Structural Designer, structural engineers may optimise the design and materials to generate a low-carbon design by calculating the embodied

carbon of several alternative ideas during the early scheme-design phase. In addition, the software makes it simple to present relevant information using reports, graphics, and data export. By generating data and reports in both Tekla Structural Designer and Tekla Structures, you can monitor carbon emissions as the project progresses from design to manufacturing to on-site assembly.

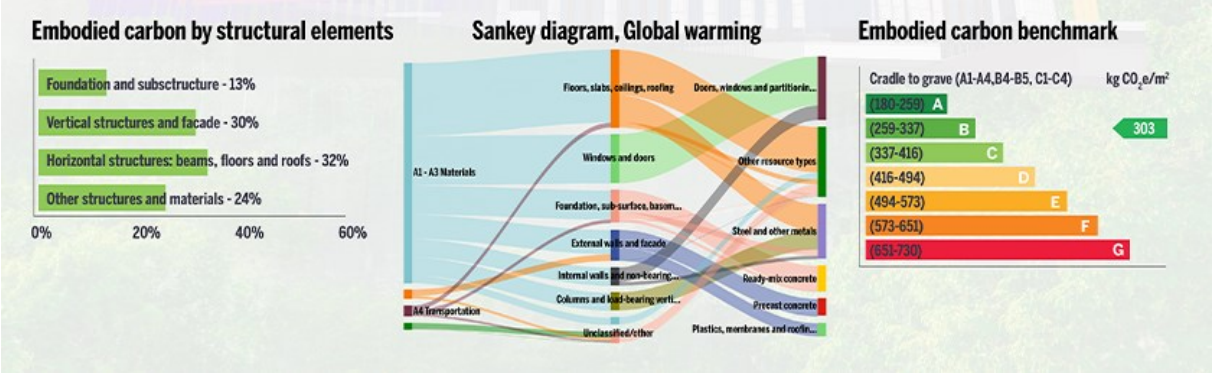


Figure 45: Embodied Carbon percentages of structural elements (Source: Tekla Structures)

Embodied carbon is the total life cycle carbon used in the collection, manufacture, transportation, assembly, maintenance, recycling and disposal of a given material or product. ***Operational carbon*** is the total carbon associated with the in-use operation of the building. This usually includes carbon emissions from heating, hot water, cooling, ventilation and lighting systems (regulated) and those associated with cooking, equipment and heat, which are unregulated (O P Gibbons and J J Orr, 2020).

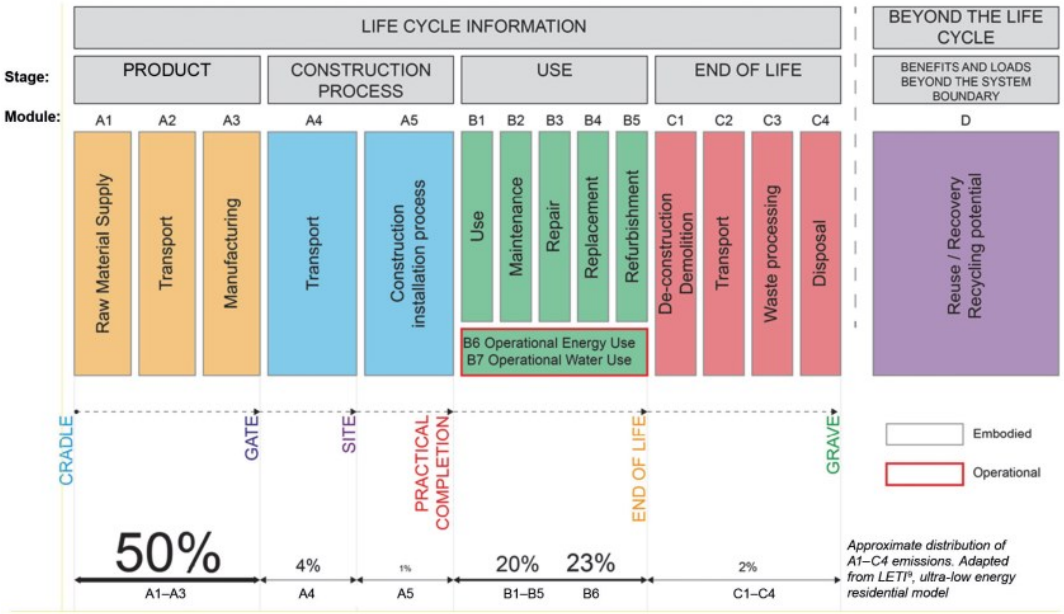


Figure 46: BS EN 15978[3] Life cycle stages for Embodied Carbon in Residential Building (O P Gibbons and J J Orr, 2020).

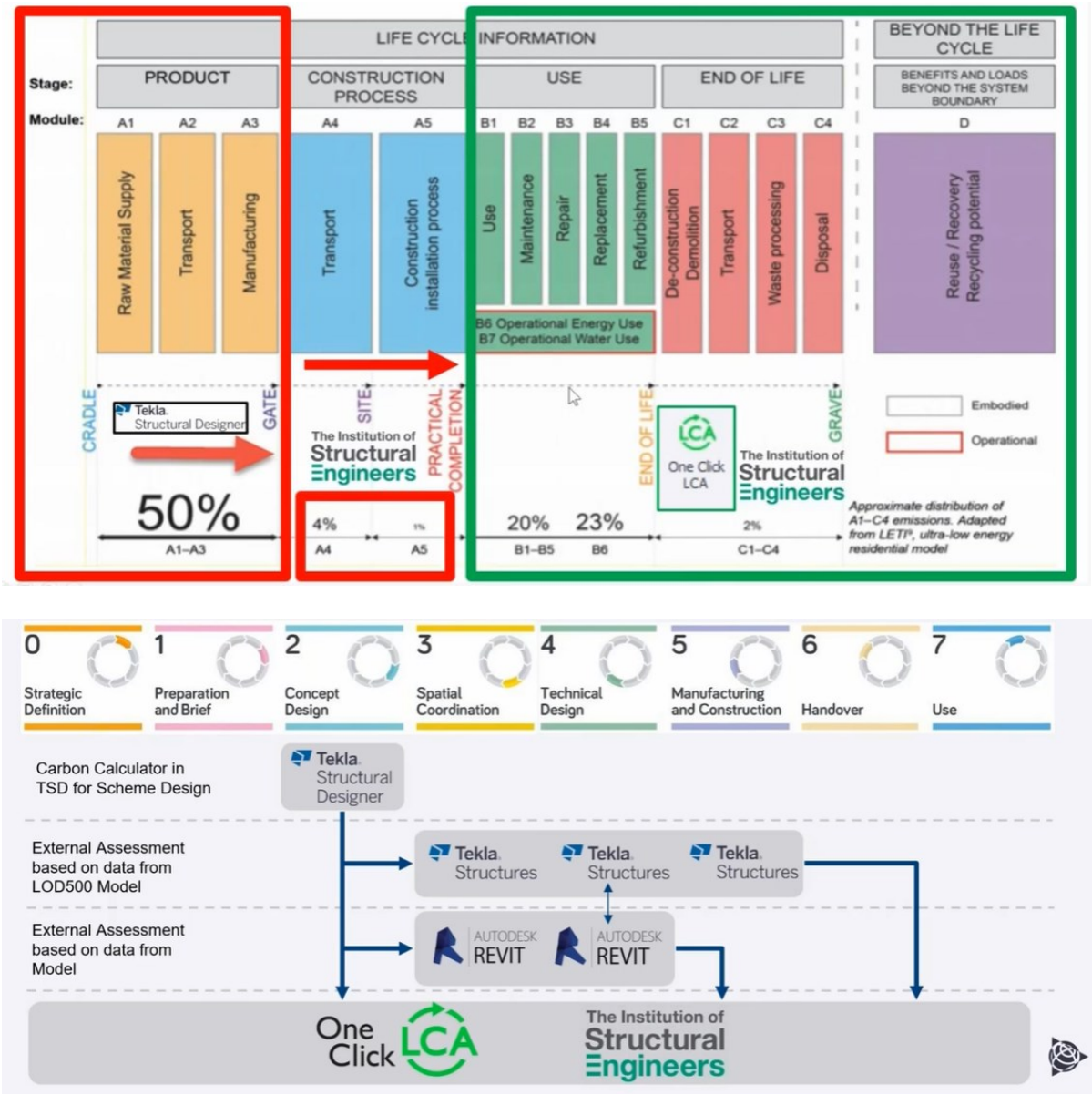


Figure 47: TSD and Revit interoperability workflow for lifecycle assessment and RIBA stages (Source: Trimble Tekla Structures).

3.6.3 Tekla Tedds (TT)

Tekla Tedds is a powerful software solution that automates repetitive structural calculations. Tekla Tedds offers seamless structural design information and documentation sharing via Trimble Connect to improve design-to-detail workflows. In addition, Tekla Tedds is an intuitive software that engineers can rely on for precise calculations. As a result, engineers may speed engineering design with Tekla Tedds, eliminate errors, and display output correctly. The current version features new and updated structural element design calculations.

Tekla Tedds Key features are as follows:

- Multiple material libraries of code of compliant calculations;
- Creating bespoke calculations;
- Easily compiled project reports;
- Vast list of international design codes and regions;
- 2D analysis tools.

3.6.4 IDEA StatiCa

Due to the need for BIM-based interoperability between engineering solutions and design teams, a toolkit is developed to link virtually any structural analysis or modelling solution to IDEA StatiCa quickly and efficiently. IDEA StatiCa cooperation between Autodesk, Trimble, HILTI, and NEMETSCHEK has led to the development and the best structural engineers' workflows. In addition, IDEA StatiCa integrates with many FEM/FEA programmes. As a result, their workflow reduces errors and repetitious effort, allowing structural engineers and designers to concentrate on more essential duties, such as correct analysis, design, and code-checking of connections, cross-sections, members, and details.

Figure 48: Integrated software partners with IDEA StatiCa

IDEA StatiCa Checkbot is a BIM workflow management programme that imports and synchronises connections and members. Checkbot provides structural engineers with:

- Total command over all imported connections and members,
- A complete list of all imported items, including their status (checked or unchecked),
- Imported members and loads are visualised in 3D,

- Material and cross-section conversion table,
- Load combination control.

The IDEA StatiCa Checkbot identifies a project in a third-party solution and generates a folder that includes all the connections and members.

- ***IDEA StatiCa BIM-Link***

The BIM links between structural computation FEA software and model detailing CAD software are widely established for Global structural geometry, boundary conditions, material and cross-section properties that can be imported from one software and used in the other. It is a dream come true for structural connections professionals! This form of semi-automatic workflow is advantageous, particularly for those responsible for connection design, assessment, and code-check calculations.

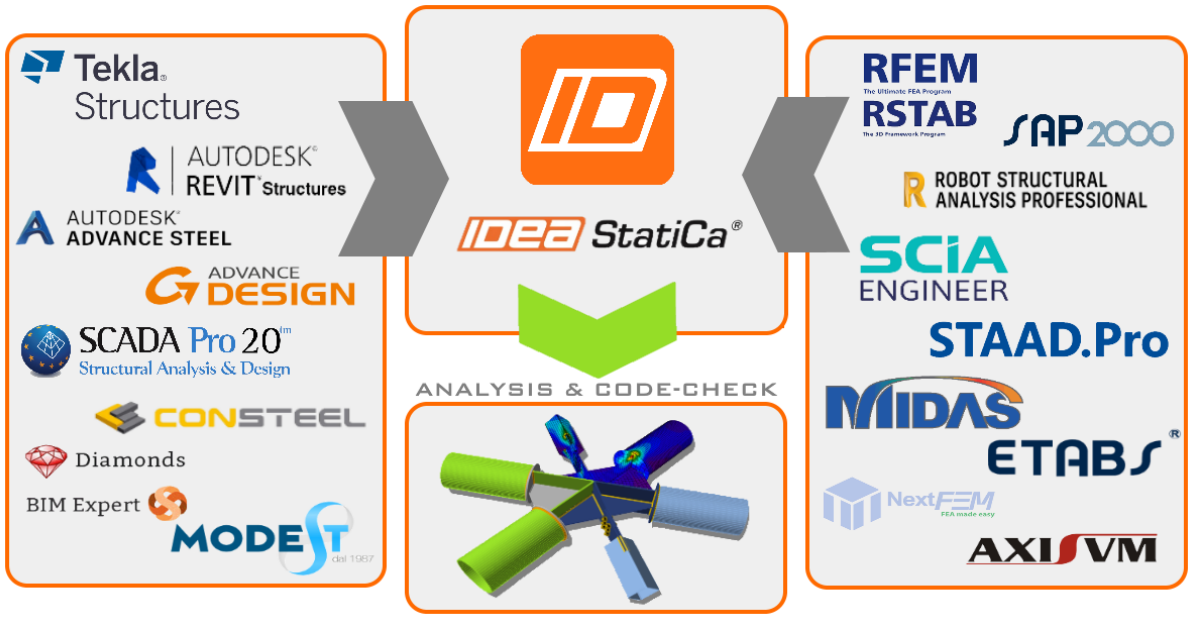


Figure 49: BIM-Link workflow for IDEA StatiCa - FEA/CAD software (Source: IDEA StatiCa).

- ***Tekla Structural Designer and IDEA StatiCa BIM-Link***

IDEA StatiCa is compatible with Tekla Structural Designer. Any number of steel connections and members can be exported from Tekla Structural Designer to IDEA StatiCa for structural design and code checking. Not only are all beams, cross-sections, and internal forces exported, but they are also synchronised if the Tekla Structural Designer model is modified. As a result, IDEA StatiCa and Tekla Structural Designer provide structural engineers with a workflow for structural steel design that saves time, reduces errors, and optimises.

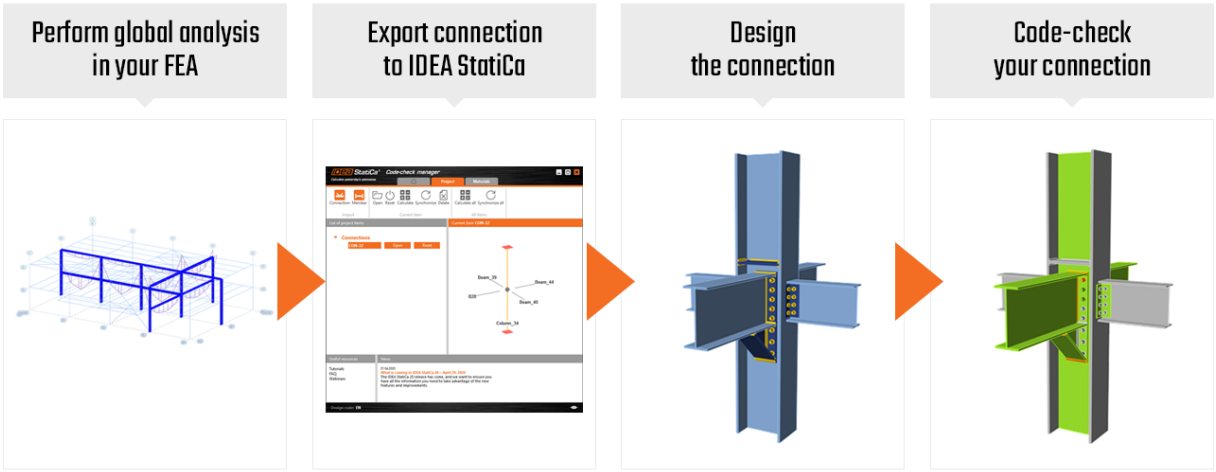


Figure 50: Tekla Structural Designer and IDEA StatiCa workflow (Source: IDEA StatiCa).

3.7 BIM Interoperability Workflow between the Software

In order to build practical BIM interoperability for implementation in Slovenian BIM structural design offices, the above-mentioned FEA/FEM and CADs software and plug-ins have been studied for integration within themselves to save repeat work and streamline the design team operations. Thus, a structural model created in one software can be exported and imported into another. In addition, the method assesses the information's coherence, dependability, and precision. Finally, the quality of the information exchange across the various models can be evaluated to determine their interoperability.

The analytical model must be exported and imported accurately between software applications. The objective is for a structural engineer to begin modelling in one application and finish analysis and design in another by sharing his structural and analytical model across the design team without remodelling from any parties. This occurs throughout the Revit/SCiA/TS workflow. Another case is the separation of the workflow into the analysis and design phase and the detailing phase (similar to the TSD/TS/IDEA StatiCa workflow). The TS Integrator Tool facilitates efficient information exchange between Revit and Tekla, mapping to native objects. SCiA Engineer has an add-in (Bi-directional link) that integrates with Revit and TS, using Revit's/TS native objects by utilising essential automatic relationships between structural sections.

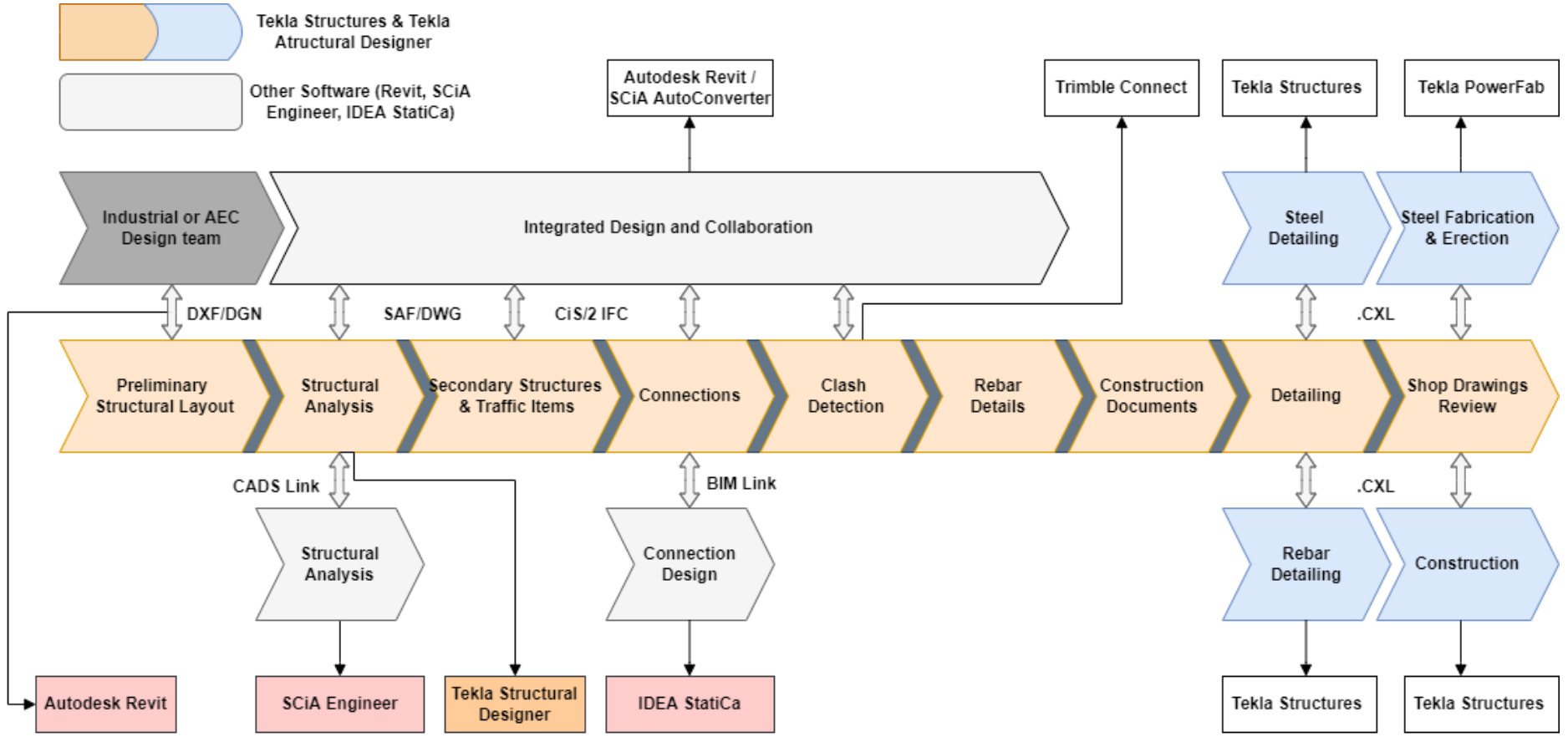


Figure 51: Project Team Workflow for Implementation in a Design Office (Author's Own)

4 CASE STUDY

This chapter will focus on case study implementations of the BIM workflow illustrated in Figure 51 for a simple, practical project. . Firstly, modelling, load applications, analysis, and structure design are initiated with structural modelling on TSD. Then, the workflow is applied for practical interoperability for model exchange between TS, Revit, external FEA software, and CAD/BIM links (SCiA Engineer and IDEA StatiCa). The conclusion of the case study scenarios is the adoption of BIM for structural design, which is our goal.

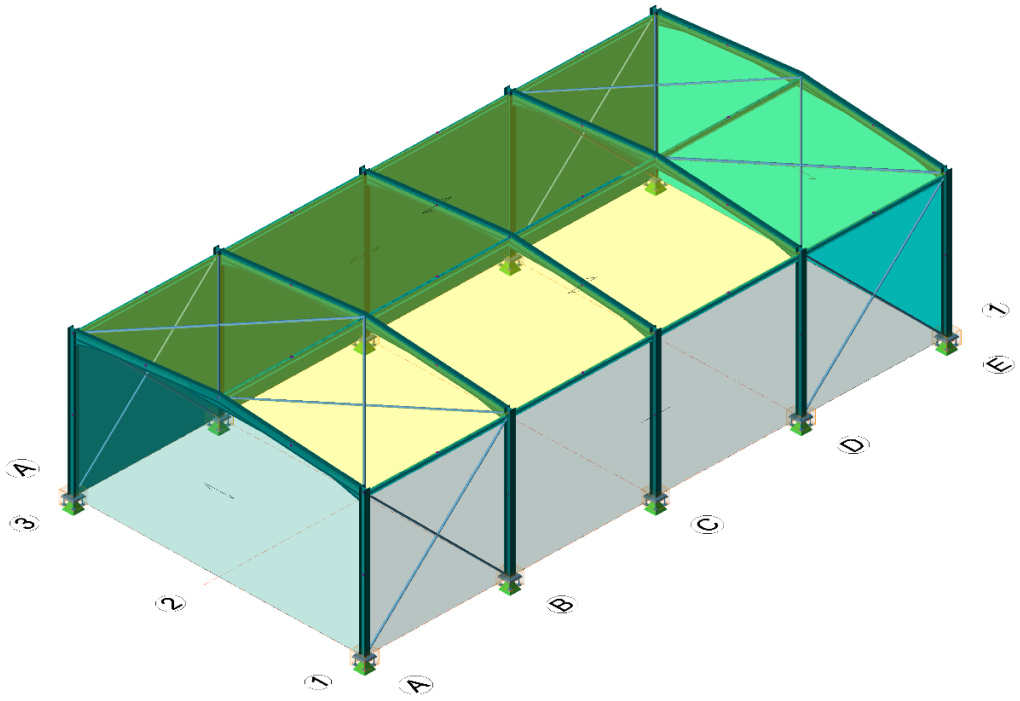


Figure 52: Isometric S-BIM Model for Casestudy (Source: Author's Own)

4.1 Case Study Parameters

4.1.1 Structural Details

Design Code = France (Eurocode)

- Warehouse (including roof) of 5.626m
- X direction bays = 4 x 5.0m
- Y direction bays = 2 x 5.0m
- 10 steel columns, orientation and height, as shown in figure 52.
  - ✓ Auto design using HEA section order file, S235JR
- Steel beams, as shown in figure 52.
  - ✓ Auto design using IPE section order file, S235JR

- Eaves level and above unrestrained.
- Steel-pitched roof rafters, as shown in figure 52.
  - ✓ Auto design using IPE section order file, S235JR
  - ✓ 2-panel divisions left and right, 5.62m height
- Steel bracings, as shown in figure 52.
  - ✓ Auto design using Angle bars L80*8 section order file, S235JR
- Portal Frames, as shown in figure 52.
- Pad foundation beneath column bases, C30/37 concrete

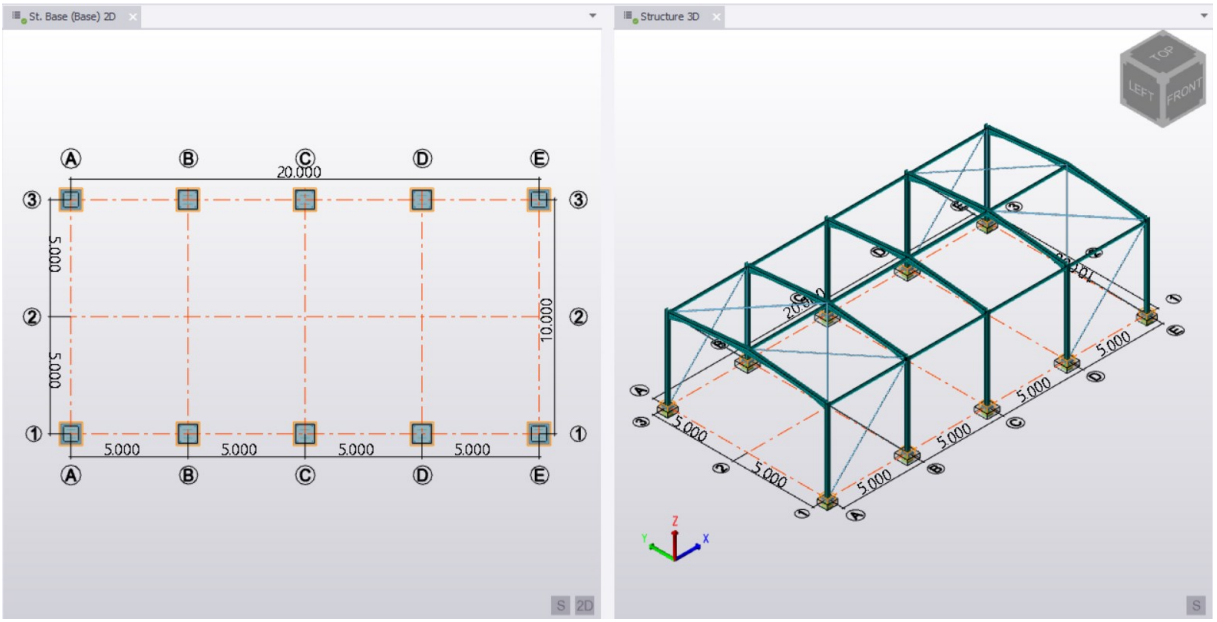


Figure 53: S-BIM TSD Model (Source: Author's Own)

4.1.2 Load Cases and Combinations

- Self-weight of frame = Automatically Applied
- Slab self-weight = Automatically Applied
- Dead load = 0.6 kN/m2 (Dead - Level load)
- Roof Imposed area load (snow load) = 1.0 kN/m2 (Roof Imposed - Area load)
- Wind load (Auto-generated by wind wizard)

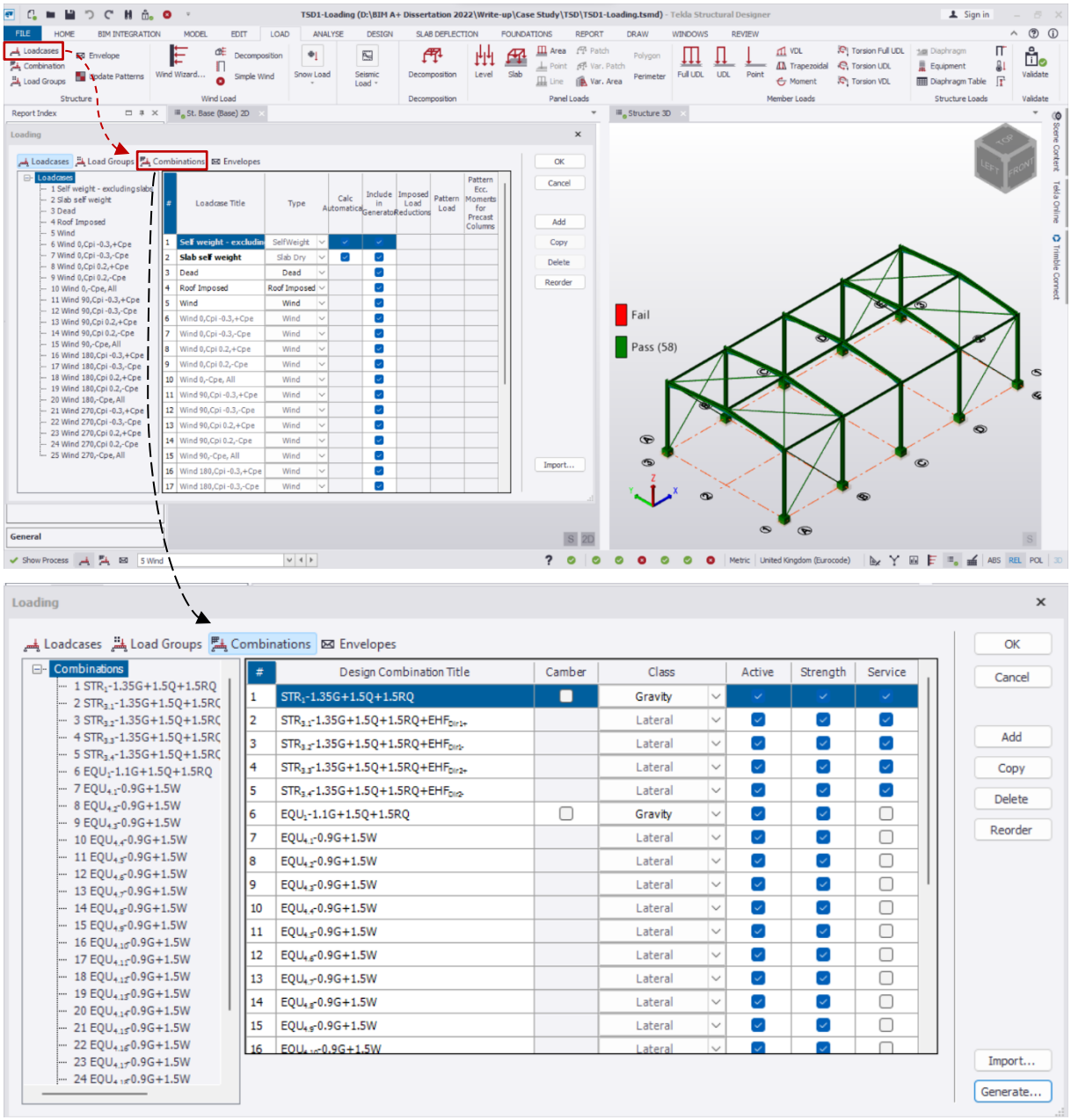


Figure 54: Load Cases and Combinations in TSD (Source: Author's Own)

4.2 S-BIM Model Interoperability Scenarios

4.2.1 S-BIM Model transfer between TSD and Revit

Autodesk Revit and TSD are BIM authoring tools mainly used by structural engineers to produce execution plans and shop drawings after S-BIM modelling, structural analysis, and design. The interoperable FEM tools used together to perform external structural analysis and design S-BIM models communicate through direct links. With TSD, the data and models are exchanged through the TSD integrator, a bi-directional link to share S-BIM analytical models with Revit and TS. Any changes in the tools used for modelling the S-BIM structure can be updated from the other software after materials and

cross-sectional members are mapped in either authoring software. In this case study application, the modelling is done in TSD, and the results are analysed and shared with other team members who use Revit and TS.

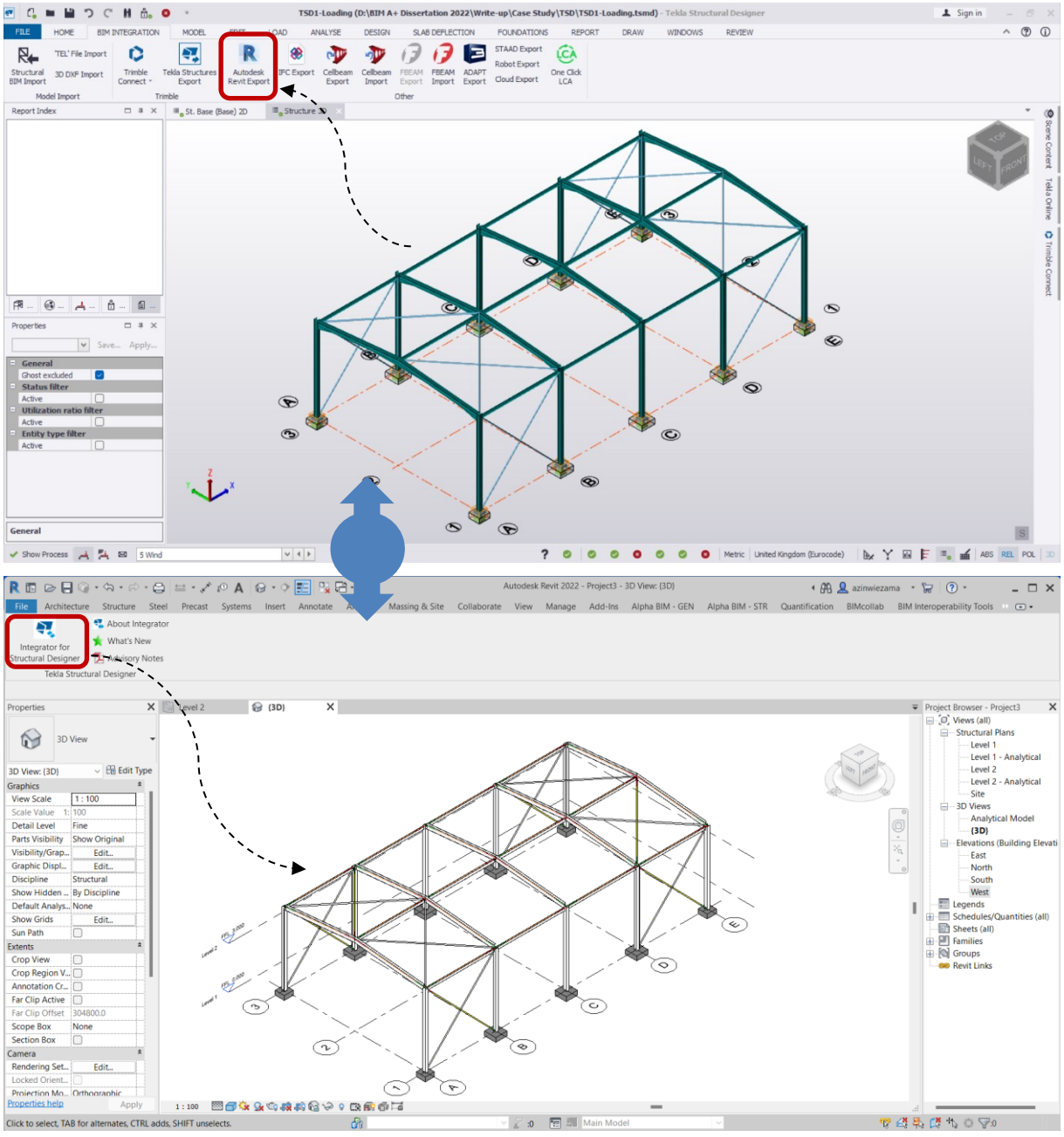


Figure 55: S-BIM Model Exchange between TSD – Revit (Source: Author's Own)

4.2.2 S-BIM Model transfer between TSD and TS

The S-BIM model exchange between TSD/TS is simple. The model can be initiated either in TSD or TS. In this case, the S-BIM model is built and exported from TSD integrated and saved to a .CXL format. Furthermore, the same .CXL file is imported into TS through the TSD integrator tool in TS. Any modifications carried on either tool can be updated to the other successfully. We observe that the principal structural elements are mostly successfully mapped and imported into TS as the secondary bracing elements are not present in the S-BIM model.

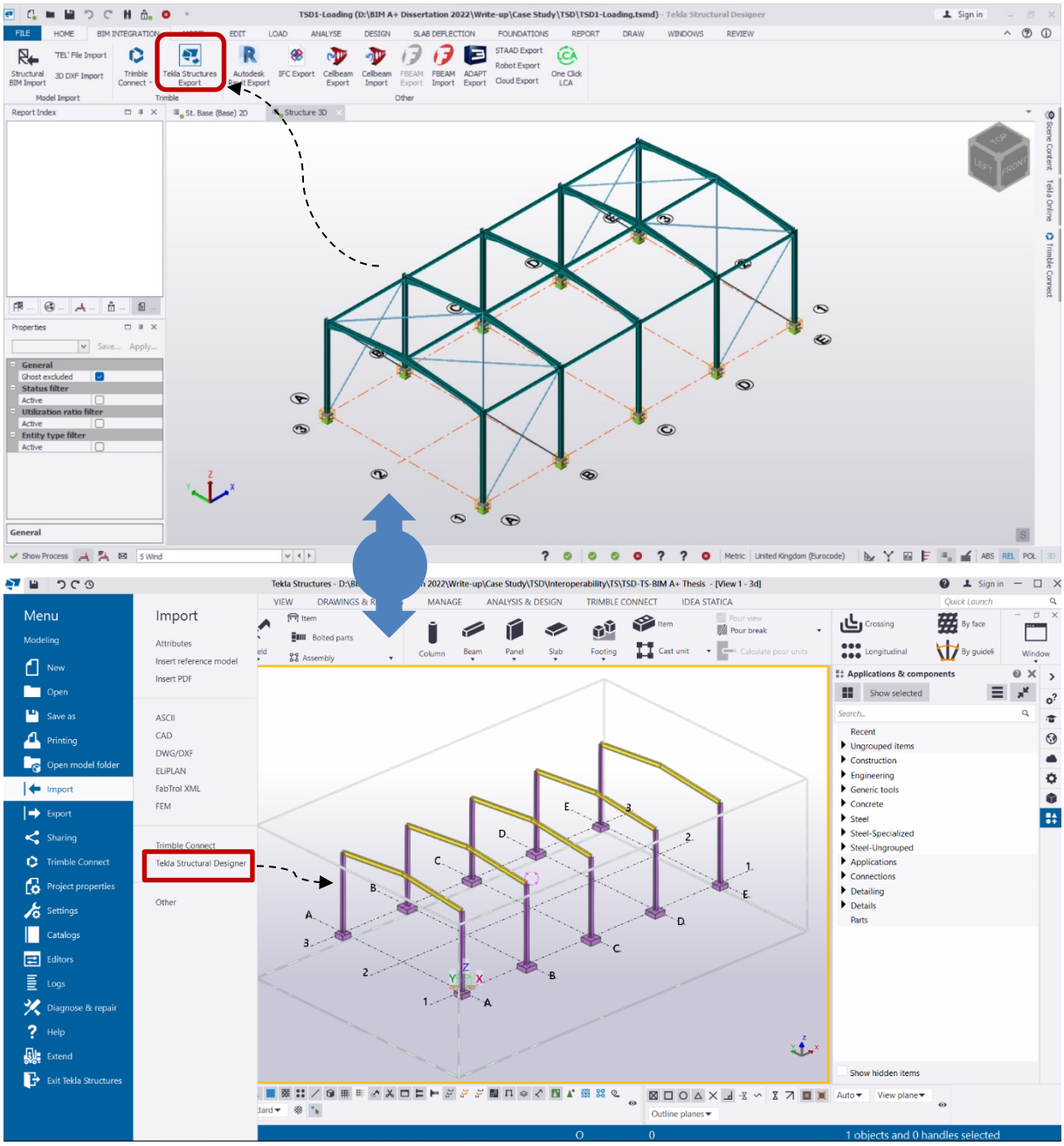


Figure 56: S-BIM Model Exchange between TSD – TS (Source: Author's Own)

4.2.3 S-BIM Model Shop Drawings in Tekla Structures

As seen in Figure 56 above, much background work has been done after receiving the S-BIM model from TSD through the Tekla Structure Designer integrator link. The structures' principal elements (columns-HEA 200, rafter-IPE 270) were successfully mapped into TS. The secondary elements (purlins, structural frames for side cladding, bracing elements) have been modelled in TS. The reverse bi-directional integrator link has been used to auto-update the S-BIM model in TSD to design the seconding structural elements for stability. Furthermore, the detailed steel design of the model has been carried to standard and required LOD of the project. In this case study, we have attended LOD 400 to maintain the accuracy and high quality of the steel detailing. In addition, all the connections have been designed and checked by IDEA StatiCa from TSD. The moddel of the connections are based on the design results from IDEA StatiCa. It should be noted that load cases and combinations are not imported/exported in the bi-directional and IFC information exchange between TSD/TS.

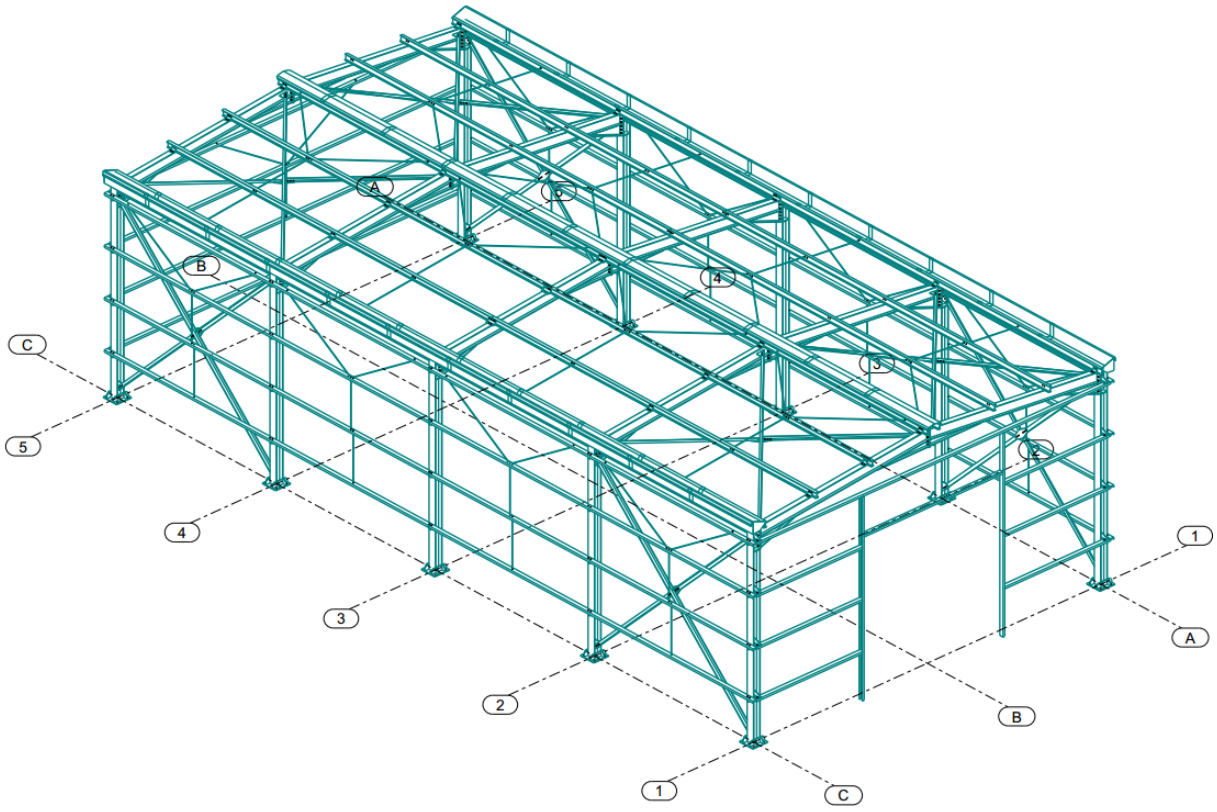


Figure 57: S-BIM Tekla Structures Model after Design (Author's Own)

The figure below shows general arrangement and shop drawings extracted from the Tekla Structural design model.

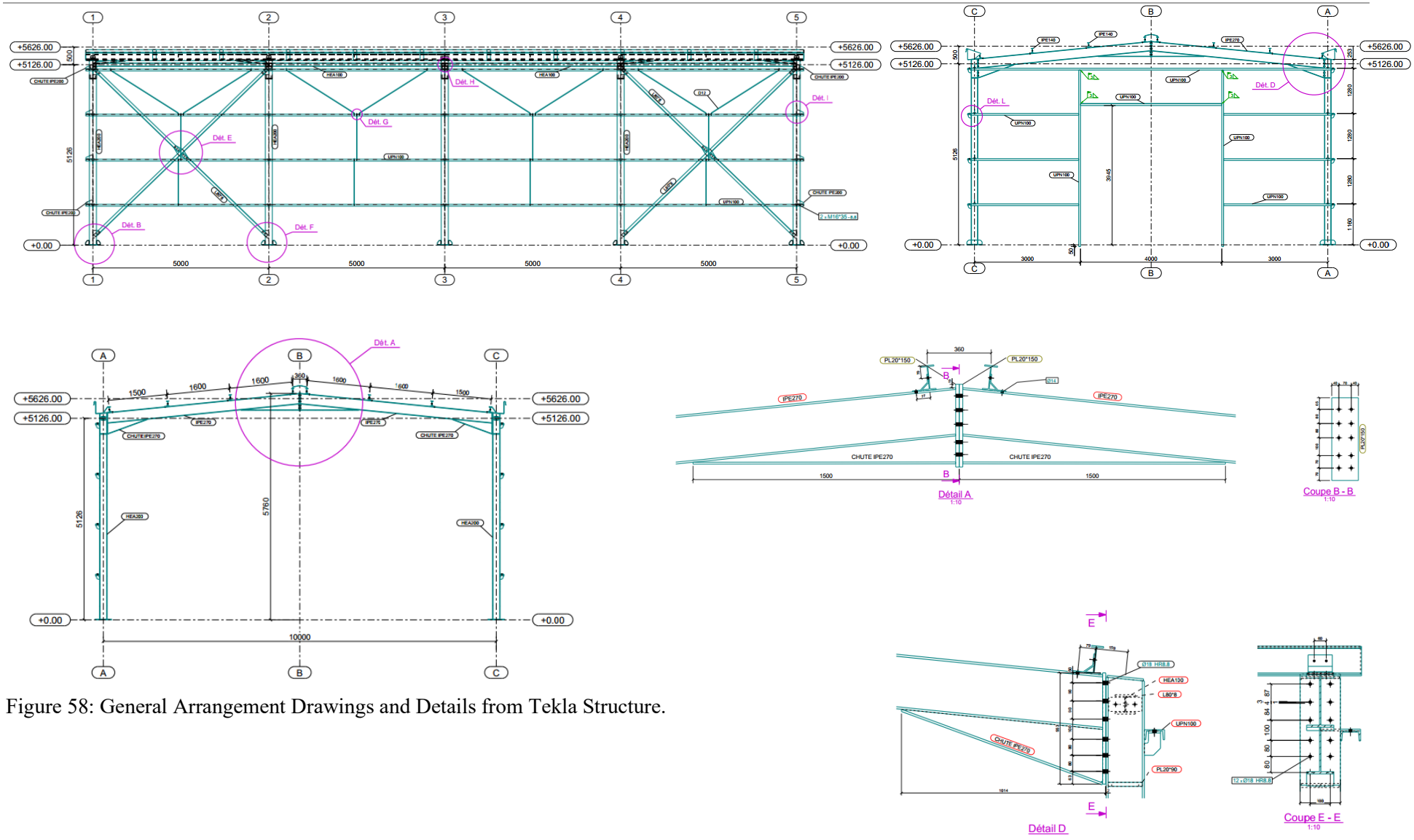


Figure 58: General Arrangement Drawings and Details from Tekla Structure.

5 CONCLUSION

Building Information Modelling (BIM) is the leading process for entirely digitalising the twenty-first century's architecture, engineering, and construction IT industry. Structural engineers may or may not have a standardised methodology for modelling, analysing, and designing S-BIM projects. Implementing a workflow ensures that all BIM model contributors have attained a particular degree of proficiency. Implementing the BIM methodology in many projects necessitates practical training and certification of specialists. Transitioning from CAD systems to the BIM environment enables the design team to optimise processes, decreasing time spent on repetitive tasks, costs, and mistakes.

In addition, the amount of time spent troubleshooting the model will be decreased since all parties will be familiar with the modelling techniques and data exchange between them. All stakeholders must be conversant with the same modelling procedures. Numerous design firms have already established modelling, analysis, and design workflows. Without the adequate implementation of interoperability between BIM and FEM and across design teams, they may not be specialised for structural engineering and FEM analysis. In this context, the necessity of model exchange plays a significant role. Structural engineers must be able to constantly exchange models without losing data to have a solid working foundation.

Moreover, structural analysis and design, the essential activities for a structural engineer, are carried out in a FEM environment, which is unique from the BIM environment. Implementing interoperability between these two worlds is crucial for this reason. In a few instances, it is also vital to have the ability to switch models within the same FEM programme, allowing other specialists to collaborate and review the models and results upon which the project is based.

This thesis aims to provide a workflow for a structural BIM design office that promotes BIM and FEM interoperability. This thesis has achieved its goal through brief, generalised studies incorporating workflows and modelling principles that could be implemented as a centralised methodology. Nevertheless, some issues could be considered regarding cross-disciplinary collaboration during the case study application. Interoperability across design teams is, however, conceivable. The workflow has been successfully tested between Trimble Tekla Structures, Tekla Structural Designer, Revit, and SCiA Engineer. Implementing this approach assures that all BIM model collaborators have attained a minimum competency level. Consequently, a BIM-related project can be launched with any S-BIM authoring tool, and engineers and architects can share data and S-BIM models freely and confidently. Finally, model exchanges between BIM, BIM-to-FEM, and FEM-to-FEM are possible.

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