Univerza *v Ljubljani*
Fakulteta *za gradbeništvo*
in geodezijo

SHEYANU ODEYEMI

BI-DIRECTIONAL INTEROPERABILITY BETWEEN

ARCHITECTURAL AND STRUCTURAL BIM

FOR EFFICIENT STRUCTURAL DESIGN AND ANALYSIS

MASTER THESIS

SECOND CYCLE MASTER STUDY PROGRAMME BUILDING

INFORMATION MODELLING – BIM A+

Ljubljana, 2023

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DVOSMERNA INTEROPERABILNOST MED ARHITEKTURNIM

IN KONSTRUKCIJSKIM BIM ZA UČINKOVITO

KONSTRUKCIJSKO PROJEKTIRANJE IN ANALIZO

BIM A+ European Master in Building Information Modelling

Master thesis No.:

Supervisor:
Assist. Prof. Tomo Cerovšek, Ph.D.

Ljubljana, 2023

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Ključne besede: informacijsko modeliranje zgradb (BIM), temeljni razredi za industrijo (IFC), dvosmerne povezave, Revit, Prota Structure

Izvleček:

Informacijsko modeliranje zgradb (BIM) je z digitalno predstavitvijo fizičnih elementov zgradb temeljito spremenilo gradbeno industrijo. Kljub transformativnemu potencialu so glavne ovire za boljše sodelovanje težave, ki so povezane z interoperabilnostjo med platformami za modeliranje arhitekture in gradbenih konstrukcij. Zato preučujemo interoperabilnost med okolji BIM s poudarkom na oceni učinkovitosti dvosmernih povezav, ki temeljijo na IFC (angl. Industry Foundation Classes).

Namen te raziskave je izdelati presojo interoperabilnosti med modeli arhitekture in gradbenih konstrukcij ter vpliv na učinkovitost projektiranja, modeliranja in analiz z uporabo BIM. Za doseganje teh ciljev smo uporabili metodologijo, ki vključuje podrobno analizo avtorskih okolij BIM in orodij za modeliranje končnih elementov (FEM) z razvojem in uporabo praktičnega delotoka na realnih projektih. Aplikativno preučujemo interoperabilnost med platformamo Autodesk Revit ter platformo za račun konstrukcij ProtaStructure z dodatkom ProtaBIM, ki omogoča dvosmerne povezave na osnovi IFC.

Z raziskavo želimo prispevati k boljšemu razumevanju interoperabilnosti in izboljšati sodelovanje med arhitekturno in gradbeno stroko ter povečati učinkovitost dela z BIM, ter ob tem zmanjšati obseg napak, zamud in stroškov, kar je pomembno za projektante in druge deležnike projektov. Rezultati raziskave prispevajo k analizi in razvoju IFC ter utirajo pot prihodnjim pobudam raziskovalcev in razvijalcev orodij BIM, ki želijo izboljšati interoperabilnost med okolji BIM.

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BIBLIOGRAPHIC– DOCUMENTALISTIC INFORMATION AND ABSTRACT

Abstract:

Building Information Modelling (BIM) has revolutionized the construction industry's digital representation of physical building elements. Despite the transformative potential, the main obstacles to better collaboration are issues related to interoperability between architectural and structural modelling platforms. Therefore, we study interoperability between BIM environments with an emphasis on the analysis of the effectiveness of bi-directional links based on IFC (Industry Foundation Classes).

The purpose of this research is to assess the interoperability between architectural and structural models and the related impact on the effectiveness of design, modelling, and analysis using BIM. To achieve these goals, the methodology used includes a detailed analysis of the capabilities of BIM environments and Finite Element Modelling (FEM) which are tested using practical workflow on real-life projects. The study evaluates the interoperability between the Autodesk Revit (BIM) and the ProtaStructure (FEM) platforms with the ProtaBIM add-on and IFC, which enables two-way connections.

This research contributes to a better understanding of interoperability and aims to improve the cooperation between the architectural and construction professions by increasing the efficiency of work with BIM, and at the same time, aiming to reduce the scope of errors, delays, and costs. The results are important for designers and other project stakeholders, as well as contribute to the analysis and development of IFC which pave the way to future initiatives by researchers and BIM software developers with the goal of improving interoperability between professions.

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1   INTRODUCTION

1.1   Background of Study

Building Information Modelling (BIM) involves the creation and management of digital representations of physical characteristics (such as size, shape, and location) and functional services (such as heating, ventilation, and lighting) of buildings.

Since the early 2000s, BIM has gained widespread adoption in various countries. The implementation of BIM has effectively addressed issues related to data collection and storage, thus generating significant interest from researchers and organizations seeking to evaluate its level of adoption (Van Berlo et al., 2012). It can combine geometric representations with diverse semantic information about buildings, bringing about a significant shift in the approach to documenting and exchanging information across various models in the AEC (Architecture, Engineering, and Construction) industry. As an innovative technology, BIM bridges the gap between two-dimensional drawings and three-dimensional models to integrate various stages of the building or infrastructure lifecycle (Ren and Zhang, 2021). One key aspect of BIM is interoperability, which refers to the ability of different software tools to exchange data seamlessly.

BIM interoperability is an important aspect of the AEC industry, which allows different software systems used by different disciplines to effectively exchange BIM data. In particular, the interoperability between architectural and structural engineering platforms is critical, as these two disciplines work closely together to model, analyze, and design buildings. However, owing to differences in software systems, file formats, and modelling approaches, BIM interoperability issues are common and can cause inefficiencies, errors, and project delays. Therefore, either an open data format or a bi-directional link is required to ensure data interoperability.

Industry Foundation Classes (IFC) is an open file format developed by buildingSMART International that allows BIM data to be exchanged between different software systems. It provides a standardized approach to data exchange, enabling different software systems to communicate with each other. According to a non-exhaustive survey, over 200 software tools have import or export capabilities for IFC data models (Lai and Deng, 2018).

Bi-directional links, on the other hand, are powerful technologies that enable seamless data exchange between different software applications. Building information Modelling (BIM) allows the integration of different BIM platforms, enabling project stakeholders to work collaboratively and in a more coordinated manner. It also facilitates the exchange of information between different BIM platforms in real-time, ensuring that changes made in one application are automatically reflected in the other, thus

providing a single source of truth for the project. This technology has significant potential to improve project outcomes by reducing errors, increasing efficiency, and improving communication between project stakeholders. Therefore, a comparison of the interoperability of BIM data using bi-directional link – ProtaBIM and IFC format can provide valuable insights into the effectiveness of these two file exchanges in facilitating BIM interoperability between architectural and structural engineering platforms. This can help identify any issues or challenges related to BIM interoperability between these two disciplines and inform the development of solutions to improve collaboration and communication in the AEC industry.

1.2 Problem Statement

The lack of seamless interoperability between architectural and structural engineering platforms in Building Information Modelling (BIM) is a significant challenge hindering effective collaboration and coordination in the AEC industry. Bi-directional links and Industry Foundation Classes (IFC) are potential solutions for structural modelling, analysis, and design in structural design offices, but their effectiveness remains uncertain.Moreover, the existing BIM-based workflow for structural modelling, analysis, and design may not be optimized for efficiency and accuracy. Therefore, there is a need to investigate and evaluate BIM interoperability using IFC and Bi-directional link, coupled with developing an improved BIM-based workflow for structural modelling, analysis, and design that can enhance collaboration and optimize project outcomes.

1.3 Aim

The aim of this study is to evaluate interoperability between architectural and structural BIM for structural modelling, analysis, and design using bi-directional link and IFC. To achieve this, the following objectives were considered.

1.4 Objectives

The objectives of this study are as follows:

1. Development of a BIM-based workflow for structural modelling, analysis, design, and identification of best practices for achieving effective BIM interoperability between architectural and structural engineering platforms.

2. Evaluate the Structural BIM model and data interoperability between architectural and structural engineering platforms using a bi-directional link for structural analysis and design.

3. Evaluate the Structural BIM model and data interoperability between architectural and structural engineering platforms using an IFC file exchange for structural analysis and design.

4. Assess and evaluate discrepancies observed in the interoperability of the Structural BIM model and data during file transfer between the two exchanges (Bi-directional link and IFC)

1.5 Scope of Study

This study covers the interoperability aspect of BIM data between different platforms (architectural and structural) for structural modelling, analysis, and design using IFC and Bi-directional exchanges. This study investigated two research approaches.

- The interoperability of the model and data between two different BIM platforms (Autodesk Revit and ProtaStructure) was performed based on a bi-directional link - ProtaBIM for structural analysis and design.
- The interoperability of the model and data between the two different BIM platforms (Autodesk Revit and ProtaStructure) was performed based on the IFC format.
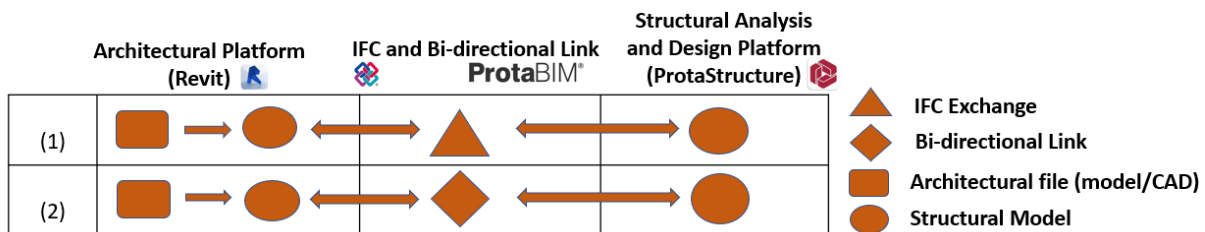
Figure 1: *Interoperability approach investigated in this study.*

1.6 Significance of Study

This study provides valuable insights into the interoperability of BIM models and data between the architectural and structural engineering platforms. This will help improve collaboration and communication between the two disciplines and optimize the BIM-based workflow for structural modelling, analysis, and design in a structural design office, which leads to better project outcomes. It also has practical implications such as reducing errors, minimizing project delays, and reducing costs. Additionally, it will provide clarity on the potential benefits of BIM interoperability for other engineering disciplines and stakeholders, such as MEP (mechanical, electrical, and plumbing) engineers, contractors, and owners. Finally, the results of this study will serve as a basis for future research and inform industry standards and guidelines for BIM interoperability.

1.7 Structure of Thesis

- **Chapter 1: Introduction**

Chapter one introduces the topic, providing an overview of the research focus and objectives. It outlines the main problem statement, emphasizing the need for bi-directional interoperability between architectural and structural BIM for efficient structural design and analysis. The chapter also

highlights the scope of the study and discusses the significance of addressing this issue in the field of structural engineering.

- **Chapter 2: Literature Review**

Chapter two presents an extensive literature review on structural BIM, focusing on key areas such as BIM interoperability, BIM workflow implementation, and relevant methods, tools, and supporting standards. It examines scientific papers and other resources to delve into the evolution of collaboration and design processes, including the transition from paper-based methods to computer-aided design and drafting (CADD) and ultimately to building information modelling (BIM). The chapter explores the concept of BIM, its maturity levels, global perspectives on BIM adoption, BIM Level of Development (LOD), and existing BIM standards and specifications. Furthermore, it explores the role of BIM in structural engineering processes, comparing traditional workflows with BIM-enabled workflows. The chapter also addresses the importance of BIM interoperability and the various types of interoperability, as well as the data transfer path involved. It also discusses the Industry Foundation Classes (IFC) and their versions, schema, and formats. Lastly, the chapter delves into the Structural Analysis Format (SAF), explaining its significance, SAF object and structure.

- **Chapter 3: Research Methodology**

Chapter three provides an overview of the research methodology employed in the study, focusing on the investigation of bi-directional interoperability between architectural and structural BIM for efficient structural design and analysis. It begins by evaluating prominent Building Information Modelling (BIM) and Finite Element Modelling (FEM) tools (Revit, SCIA, Robot Structural Analysis) that hold relevance within the domain of structural engineering, with a specific focus on their interoperability capabilities catering to both architects and engineers. Afterwards, it specifies BIM workflow utilized in the research, which involved the integration of software tools such as Autodesk Revit for BIM purposes, ProtaStructure for Finite Element Modelling (FEM), and ProtaBIM for establishing a bi-directional link between the architectural and structural BIM models. The chapter explains how these software tools were integrated to facilitate the seamless exchange of models and data between the architectural and structural domains. Additionally, the chapter emphasizes the importance of interoperability between ProtaBIM and the Industry Foundation Classes (IFC) format. It explores the process of exporting BIM models created in Autodesk Revit to the standardized IFC format and subsequently importing them into ProtaStructure for structural analysis and design purposes. This highlights the utilization of standardized data exchange formats as a means to achieve interoperability between different BIM platforms.

- **Chapter 4: Case Studies**

Chapter four presents detailed case studies that demonstrate the interoperability of the BIM models and data between different platforms. Specifically, it showcases two scenarios:

Interoperability via Bi-Directional Link: The case study involves the utilization of a bi-directional link between Autodesk Revit and ProtaStructure. It explains how the BIM models were seamlessly transferred from Revit to ProtaBIM, which enabled the structural analysis and design in ProtaStructure. This highlights the effectiveness of the bi-directional link in facilitating collaboration and data exchange between architectural and structural BIM models.

Interoperability via IFC Format: The case study demonstrates the interoperability achieved by exporting the BIM models from Autodesk Revit to the IFC format and subsequently importing them into ProtaStructure. It outlines the steps taken to ensure a successful data exchange, highlighting the advantages and limitations of utilizing the IFC format for interoperability purposes.

- **Chapter 5: Results and Discussion**

Chapter five presents the results obtained from the case studies and provides a comprehensive discussion of these results. It evaluates the effectiveness of the implemented interoperability methods, both through the bi-directional link and the IFC format.

- **Chapter 6: Conclusion and Recommendation**

Chapter six summarizes the key findings of the research and presents the conclusion drawn from the study. It discusses the contributions of the research in achieving bi-directional interoperability between architectural and structural BIM for efficient structural design and analysis. The chapter also provides recommendations for future research or improvements in the field of Structural BIM interoperability, based on the insights gained from the study.

- **References**

This section lists all the references cited throughout the thesis.

- **Appendices**

The appendices include any supplementary materials that support the research, such as calculation sheets, design repot and shop drawings..

2   LITERATURE REVIEW

The primary objective of this review is to thoroughly examine crucial discoveries and significant accomplishments that establish the groundwork for comprehending the necessary conditions and historical context for overall transformations in the realm of information technology within the building and construction sector. This review examines the various principles and frameworks utilized in the field to enable effective data exchange and collaboration. Moreover, understanding the emergence and evolution of structural BIM interoperability workflows requires an analysis of key events that have contributed to its development.

It also delves into the evolution of novel methodologies tailored specifically to structural Building Information Modelling (BIM) design and the exchange of data.

2.1   Evolution of Collaboration and Design Processes

The building and construction industry has undergone significant transformations in recent years, largely driven by advancements in information technology such as Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), and Building Information Modelling (BIM). These changes have revolutionized the way projects are designed, constructed, and managed. The key milestones in evolution involve Paper-Based Design Processes, Layered Production, Computer-Aided Design and Drafting (CADD), Building Information Modelling (BIM), and Structure Lifespan Management (future technology). A prominent innovation in this domain is Building Information Modelling (BIM), a digital representation of the physical and functional characteristics of a building. BIM has proven to be a powerful tool for enhancing collaboration, efficiency, and accuracy throughout the project life cycle.
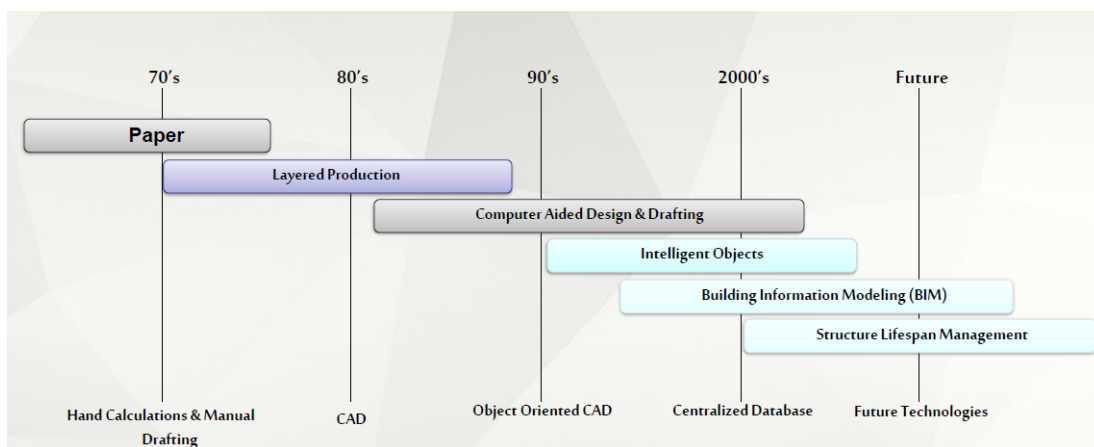
Figure 2: *Graphical Representation of Key Milestones in the Evolution Process* (Joseph Kubin, 2015)

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2.1.1 Paper-Based Design Processes

Historically, collaboration and design processes have relied heavily on paper-based methods. Hand-drafted print, sketching, and hand modelling were the standards for building designs before the advent of computer-aided design (CAD) systems. Nowadays, CAD systems are better understood, and their adoption has increased until 2D and 3D CAD systems and virtual reality systems have become the norm (Boukara and Naamane, 2015). Architects and engineers communicated their ideas through hand-drawn sketches, blueprints, and technical drawings. This approach limits collaboration to physical meetings and requires manual revisions, making it a time-consuming and iterative process.

2.1.2 Layered Production and Computer-Aided Design and Drafting (CADD)

The introduction of layered production and computer-aided design and drafting (CADD) led to a significant shift in design processes. CADD systems allow for the creation, modification, and visualization of designs using digital tools. Collaboration is improved through the ability to share digital files, enabling simultaneous work on different design aspects. The concept of layers facilitated the organization of complex designs and enhanced collaboration among multidisciplinary teams. In CADD, computers are used to generate drawings, which are the medium of communication and are only readable as graphics, so that information transfers for process activities such as structural analysis, bills of material, coordination between building systems, quality control, rebar fabrication, and piece production, must be done by people (Sacks et al., 2004). The traditional method of using CADD tools, based on digital drawings, requires a large volume of manual work and is susceptible to misunderstandings and irregularities. (Gomes et al., 2022)

2.2 Building Information Modelling (BIM)

BIM has emerged as a holistic approach for collaboration and design. BIM encompasses the creation and management of digital representations of the physical and functional characteristics of a building. BIM facilitates interdisciplinary collaboration by providing a shared platform for architects, engineers, contractors, and other stakeholders throughout the lifecycle of a structure. The collaborative nature of BIM streamlines communication, reduces errors, and improves project outcomes. The fundamental principle of BIM revolves around the creation of a centralized and accessible database that generates a digital three-dimensional (3D) model. This model incorporates comprehensive information pertaining to all project disciplines, facilitating effortless data-sharing among collaborators. Utilizing fully parametric 3D BIM systems to model buildings has many advantages, including enhanced productivity, capability to swiftly generate design alternatives at various levels, and a decrease in errors and discrepancies among design drawings (Goos et al., 2006)

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2.2.1 Concept of BIM

BIM is not limited to being just software; it represents a comprehensive concept that encompasses all stages of a building's lifecycle, including project planning, design, construction, operation, and eventual removal. The primary objective of BIM is to achieve complete digitization of the production and management processes involved in every aspect of the building's life cycle, ensuring an efficient approach (Li, 2014).
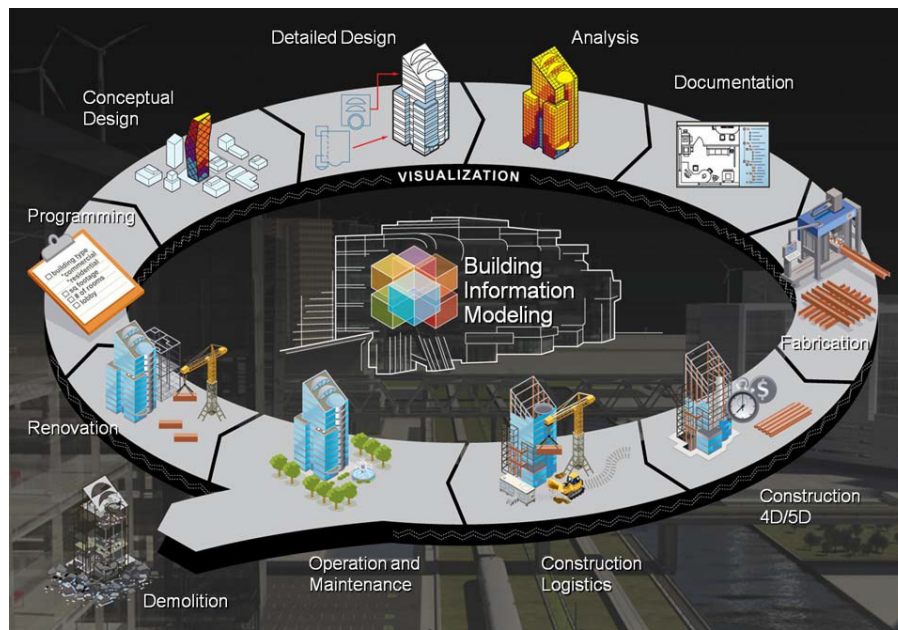
Figure 3: *BIM concept during the building lifecycle* (Taher, 2016)

BIM utilizes 3D modelling techniques to create a virtual representation of a project by incorporating architectural, structural, and MEP components. It integrates diverse sources of data, including design information, specifications, cost data, and scheduling information, thereby promoting interoperability and seamless exchange of information among stakeholders. Parametric modelling within BIM allows the creation of intelligent objects that dynamically respond to changes, facilitating design exploration, clash detection, and performance analysis. Collaboration and coordination are key aspects of BIM that enable multidisciplinary teams to work together effectively. It provides a shared platform for information-sharing, concurrent work, and conflict resolution. It serves as a central repository for project information and maintains a comprehensive database spanning the entire project lifecycle. This includes the design, construction, and facility management information. It also enables advanced analysis and simulation capabilities such as energy analysis, structural and thermal simulations, construction sequencing analysis, and facility operation and maintenance simulations. In addition, BIM enhances visualization and communication through photorealistic renderings, virtual walkthroughs, and augmented reality, facilitating design evaluation, client communication, and stakeholder engagement.

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2.2.2 BIM Maturity Levels

BIM maturity levels serve as a framework for assessing and measuring the extent to which BIM is integrated into an organization's processes, technology, and collaboration practices. The most widely recognized framework for BIM maturity levels is the BIM Maturity Model (BMM) developed by the Building Research Establishment (BRE) in the UK.
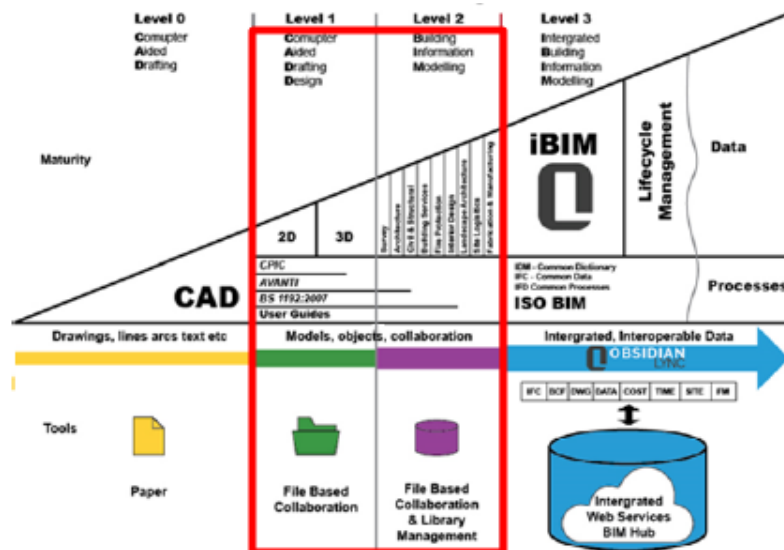
Figure 4: *BIM Maturity Model* (Prušková and Nývlt, 2017)

The BIM Maturity Model defines four levels of BIM maturity as follows:

- **Level 0: Unmanaged CAD**

This level represents traditional 2D computer-aided design (CAD) practices without collaboration or integration with other project stakeholders. Each organization or discipline works in isolation, using its own CAD tools.

- **Level 1: Managed CAD**

At this level, organizations begin to introduce the standardization and management of CAD data. Common file formats and data exchange protocols have been established; however, there is limited collaboration and information sharing between stakeholders.

- **Level 2: Managed 3D Environment**

Level 2 represents a significant leap in BIM adoption. This involves the creation and management of a collaborative 3D environment in which multiple disciplines and stakeholders work together on a shared project model. However, each discipline maintains its own specific model.

- **Level 3: Integrated Process and Lifecycle Collaboration**

Level 3 represents the highest BIM maturity level. It involves full integration and collaboration between all project participants throughout the project lifecycle. A centralized shared project model is used, which enables real-time collaboration and data exchange. Level 3 BIM promotes a collaborative approach by using open standards and shared data environments.

It is important to note that BIM maturity levels are not necessarily linear, and organizations may progress through the levels at different speeds or leap directly from one level to another, depending on their resources, capabilities, and project requirements. The aim of BIM maturity is to enable more efficient and effective collaboration, data exchange, and decision making throughout the construction project lifecycle.

Maturity levels 1 and 2 (Managed CAD and Managed 3D environment), highlighted in Figure 4, are important in the implementation of Structural BIM (S-BIM) practices, and most organizations are still working at these maturity levels.

2.2.3 Global Perspective on BIM Adoption: A Snapshot of Key Regions

BIM adoption has gained significant momentum globally and its extent varies by country, region, and industry. Governments, industry stakeholders, and professionals continue to promote and advocate BIM adoption to improve construction project outcomes, enhance collaboration, and drive innovation in built environments.
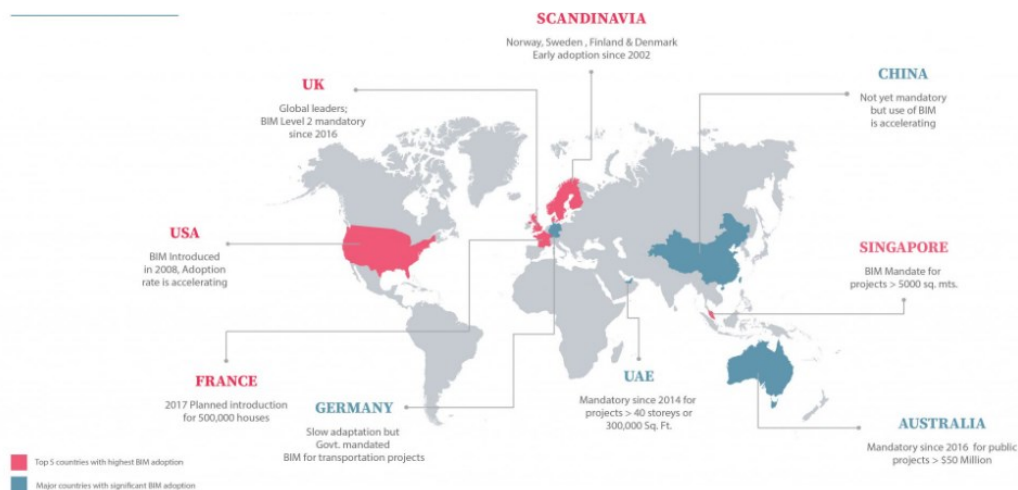
Figure 5: *Leading Countries with BIM Adoption* (Source: Google Image)

The following is an overview of BIM adoption from a global perspective.

- **Europe:** BIM adoption varies by country, with some leading the way in implementation. Countries such as Finland, Norway, and Sweden have extensively embraced BIM and have seen significant benefits in terms of cost savings and improved project outcomes. According

to Sampaio (2021), in Europe, the main entities and professionals using BIM in 2015 were, to a significant degree, architects (47%) and engineers (38%), because the technological potential for modelling design support was evident, and, to a smaller extent, contractors (24%), smaller because this group is made up of diverse professionals, individual, dispersed, and heterogeneous, and rooted in traditional working practices.

- **United States of America:** The United States has been at the forefront of BIM adoption, with widespread implementation in both public and private sectors. BIM is commonly used in large-scale projects and is increasingly becoming a requirement for government-funded projects. Porwal and Hewage (2013) reviewed the McGraw Hill Report on BIM adoption in the United States and noted that almost 39% of the construction industry currently uses BIM for significant projects with different designs and construction procurement processes.

- **United Kingdom:** The UK has been a global leader in BIM adoption, with estimates suggesting adoption rates of approximately 70-80% across the construction industry. It has also mandated BIM Level 2 for public sector projects since 2016 to enhance collaboration and efficiency. According to (Sampaio, 2021), To aid institutions in project submissions, a data structure has been devised by the Construction Operations Building Information Exchange (COBie). This structure delivers coherent and structured information on valuable assets, thereby enabling owners and operators to make informed decisions. It provides easy accessibility and control, as specified by COBie guidelines.

- **Asia:** Singapore is a leader in BIM adoption in Asia, with adoption rates estimated to be approximately 70-80%. South Korea also has a high adoption rate, likely in the range of 60-70%. Other Asian countries generally have adoption rates ranging from 20-50%.

- **Latin America:** BIM adoption rates in Latin America vary by country. Brazil is estimated to have a relatively high adoption rate of approximately 50-60%. Mexico and Chile have adoption rates ranging from 30-50%. The other countries in this region generally have lower adoption rates.

- **Africa:** BIM adoption in Africa is still in its early stages. South Africa has a relatively higher adoption rate of around 30-40%, while other countries in Africa generally have lower adoption rates.

2.2.4   BIM Standard and Specifications

BIM standards and specifications are established guidelines, protocols, and requirements that define how Building Information Modelling (BIM) should be implemented and used in construction projects. These standards ensure consistency, interoperability, and effective collaboration among the project stakeholders. Some commonly recognized BIM standards and specifications are as follows:

ISO 19650

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ISO 19650 is an international standard that provides guidelines and requirements for managing information throughout the life cycle of a built asset using Building Information Modelling (BIM). It is a successor to the earlier standard BS 1192 and PAS 1192 series developed in the United Kingdom. The ISO 19650 was published in two parts.

- **ISO 19650-1: Concepts and Principles**

  ISO 19650-1 sets out fundamental concepts, principles, and requirements for effective information management using BIM. It establishes a framework for information management processes and procedures throughout the life cycle of a built asset.

- **ISO 19650-2: Delivery Phase of the Assets**

  ISO 19650-2 focuses on the requirements and guidance for the delivery phase of built assets. It outlines the processes and information management activities that should be conducted during the design, construction, and handover stages.

National BIM Standards

National BIM standards are guidelines and specifications developed by individual countries to promote the implementation of Building Information Modelling (BIM) practices within the Architecture, Engineering, and Construction (AEC) industry. These standards provide a framework for consistent BIM adoption, interoperability, and collaboration between various project stakeholders. The goal of NBIMS is to enhance the entire life cycle of a facility, whether it is newly built or existing, by employing a standardized, machine-readable information model. This model encompasses all relevant information related to the facility, generated or collected, in a format that can be utilized throughout its lifespan. (NBIMS, 2007)
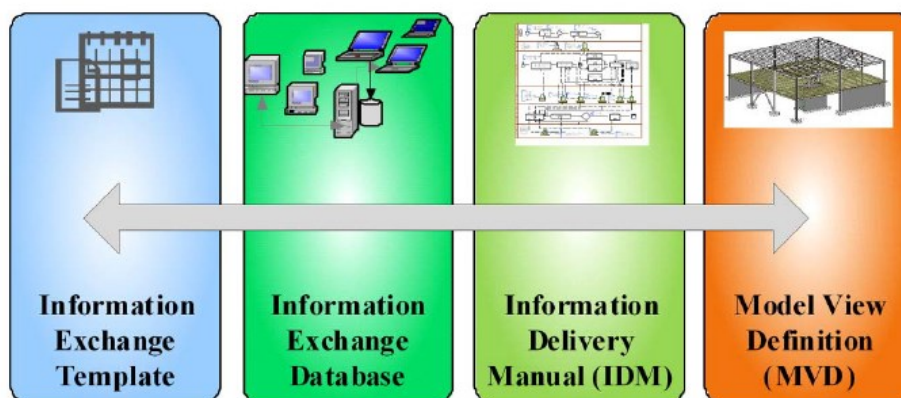
Figure 6: *NBIMS main components* (Nawari, 2012)

BuildingSMART

BuildingSMART, formerly known as the International Alliance for Interoperability (IAI), is a global industrial organization that promotes and supports the use of open BIM standards and methodologies.

It is an international community of professionals, organizations, and government agencies working together to advance the implementation of Building Information Modelling (BIM) and improve the built environment through interoperability. They are dedicated to improving the construction industry through open and neutral information-exchange standards. Their standards, such as the Industry Foundation Classes (IFC) and BIM Collaboration Format (BCF), focus on interoperability, data exchange, and collaboration across different software platforms and stakeholders.

2.3   BIM in Structural Engineering (S-BIM)

Building Information Modelling (BIM) is a collaborative and data-driven process that revolutionizes the planning, design, construction, and maintenance of projects. Within the field of structural engineering, the application of BIM, known as Structural BIM (S-BIM), offers specific advantages and enhancements to the structural engineering processes. S-BIM integrates various aspects of structural design, analysis, coordination, and documentation, thereby enabling more efficient and accurate project delivery.

2.3.1   Overview of S-BIM and its Role in Structural Engineering Processes

S-BIM plays a significant role in enhancing structural engineering processes by leveraging the power of digital modelling and data integration. It enables better visualization, integrated design and analysis, clash detection, accurate quantification, improved construction and fabrication management, and streamlined maintenance and facility management. By adopting S-BIM, structural engineers can optimize project outcomes, reduce errors, enhance collaboration, and ultimately deliver high-quality, cost-effective, and sustainable structures. S-BIM represents the future of structural engineering, empowering professionals to meet the challenges of the built environment more efficiently.
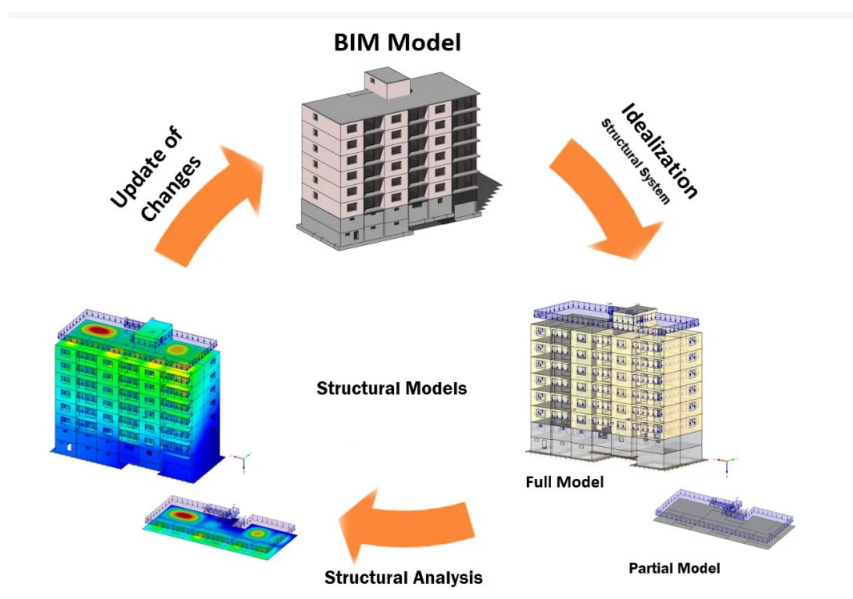
Figure 7: *Typical Data Exchange Scenario for BIM in Structural Engineering* (Source: Google Image)

In BIM, structural design plays a crucial role in ensuring the safety and stability of buildings. However, the successful implementation of BIM for structural design relies heavily on the interoperability of data and seamless exchange of information between different software platforms and disciplines. This is where the concept of structural BIM interoperability workflows comes into play.

2.3.2   Structural Engineering Workflow

The structural engineering workflow involves a series of steps and processes followed by structural engineers to design and analyze structures. The specific workflow may vary depending on the project and organization. This involves the traditional (general) workflow for structural design and BIM-enabled (using Structural BIM software) workflow for structural design.

1.   Traditional Workflow for Structural Design

The traditional design workflow encompasses various stages and processes involved in developing a structural design, from conceptual design to site construction.
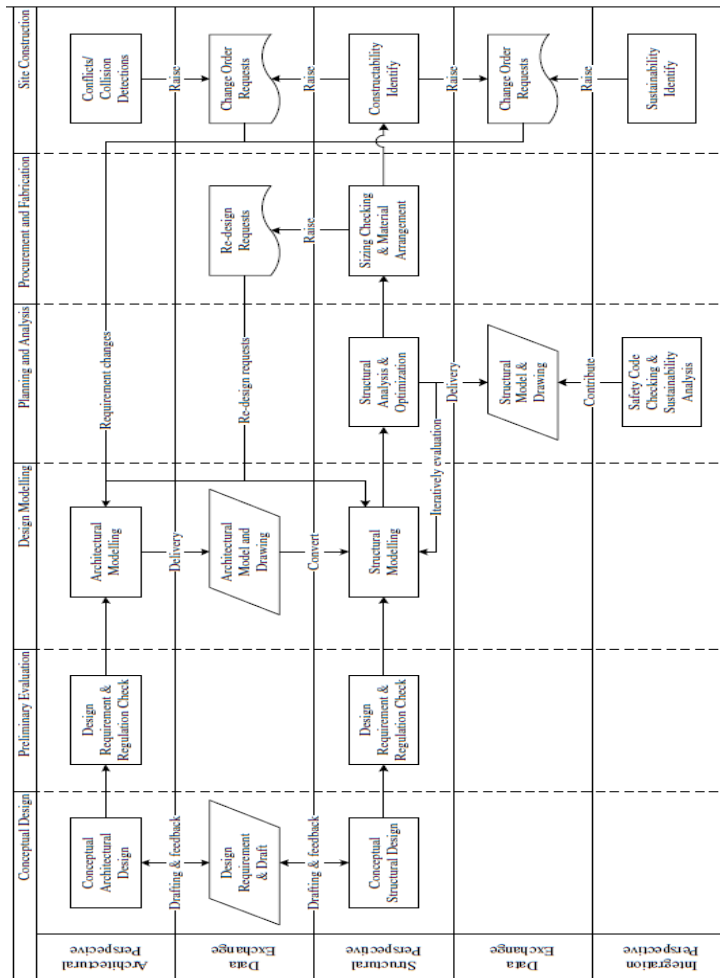
Figure 8: *Cross-functional flowchart for a traditional workflow in structural design process* (Chi et al., 2015)

The traditional workflow of the current structural design is illustrated in Fig. 9. The workflow for building design ranges from conceptual design to site construction.

- **Conceptual Design**

Conceptual Architectural Design: In this phase, architects develop a high-level vision and concept of the project. They consider functional requirements, aesthetics, and design intent to create an initial architectural design that aligns with project objectives.

Design Requirement and Draft: Architects establish design requirements by defining the desired functionality, spatial needs, and constraints. They create preliminary design sketches or diagrams to visualize the initial concepts, providing a starting point for further development.

Conceptual Structural Design: Concurrently, structural engineers work alongside architects to develop an initial structural framework that supports architectural design. They determine the load-bearing elements, material choices, and preliminary sizing to ensure the structural integrity of the building.

- **Preliminary Evaluation**

Design Requirements and Requirement Checks: The project team reviews the design requirements established in the conceptual phase to ensure that they are feasible, compliant with codes and regulations, and aligned with the project objectives. This evaluation helps to identify any potential issues or conflicts early on, ensuring that the design is realistic and achievable.

- **Design Modelling**

Architectural Modelling: Architects create detailed 3D models of architectural design using specialized software. This helps to visualize the spatial layout, elements, and overall appearance of the structure.

Architectural Model and Drawing: Architects generate architectural drawings based on 3D models, such as floor plans, elevations, and sections. These drawings serve as a basis for communication and collaboration between the architectural and structural teams.

Structural Modelling: Structural engineers develop a detailed 3D model of the structural system and integrate it with the architectural model. This includes accurately representing load paths, connections, and supports.

- **Planning and Analysis**

Structural Analysis and Optimization: Structural engineers perform structural analysis using engineering software to determine the structural behavior under different load conditions. This ensures that the design meets the safety requirements and identifies areas that require optimization.

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Structural Model and Drawing: Structural engineers create structural drawings, such as framing plans, details, and specifications, based on analysis results. These drawings provide essential information for construction.

Safety Code Checking: The design is reviewed to verify compliance with relevant safety codes and regulations, ensuring that the structure meets minimum standards for structural integrity and occupant safety.

Sustainability Analysis: The project team assesses the environmental impact of the structure and identifies opportunities for energy efficiency, sustainable materials, and the integration of renewable technologies.

- **Procurement and Fabrication**

Redesign Requests: Any design modifications or adjustments requested by the client, regulatory authorities, or other stakeholders are addressed. This may involve revisiting the structural analysis and making necessary changes.

Sizing Checking and Material Arrangement: Structural engineers verify that the selected structural elements, such as beams, columns, and foundations, are appropriately sized and aligned with the design intent. They coordinate with suppliers and manufacturers for the procurement and fabrication of materials.

- **Site Construction**

Conflicts/Collision Detections: During construction, clashes or conflicts between architectural and structural elements are identified and resolved. This may involve coordination with contractors and making necessary modifications to ensure a smooth construction process.

Change Order Request: Modifications or alterations requested during the construction phase that affect the structural design are managed. The implications are evaluated, necessary adjustments are made, and the documentation is updated accordingly.

Constructability Identification: The feasibility of constructing the structure based on the design documentation is assessed. The project team identifies constructability issues or challenges and develops solutions to overcome them, ensuring that the construction process can be conducted effectively and efficiently.

Sustainability Identification: The sustainability goals identified during the planning and analysis phases are implemented during construction. The project team incorporates sustainable construction practices, uses eco-friendly materials, and monitors the environmental impact to ensure that the structure aligns with the sustainability objectives.

2. **BIM-Enabled Workflow for Structural Design**

The BIM-enabled workflow encompasses the same stages and processes involved in developing a structural design as the traditional workflow, from conceptual design to site construction, but also includes BIM database integration.
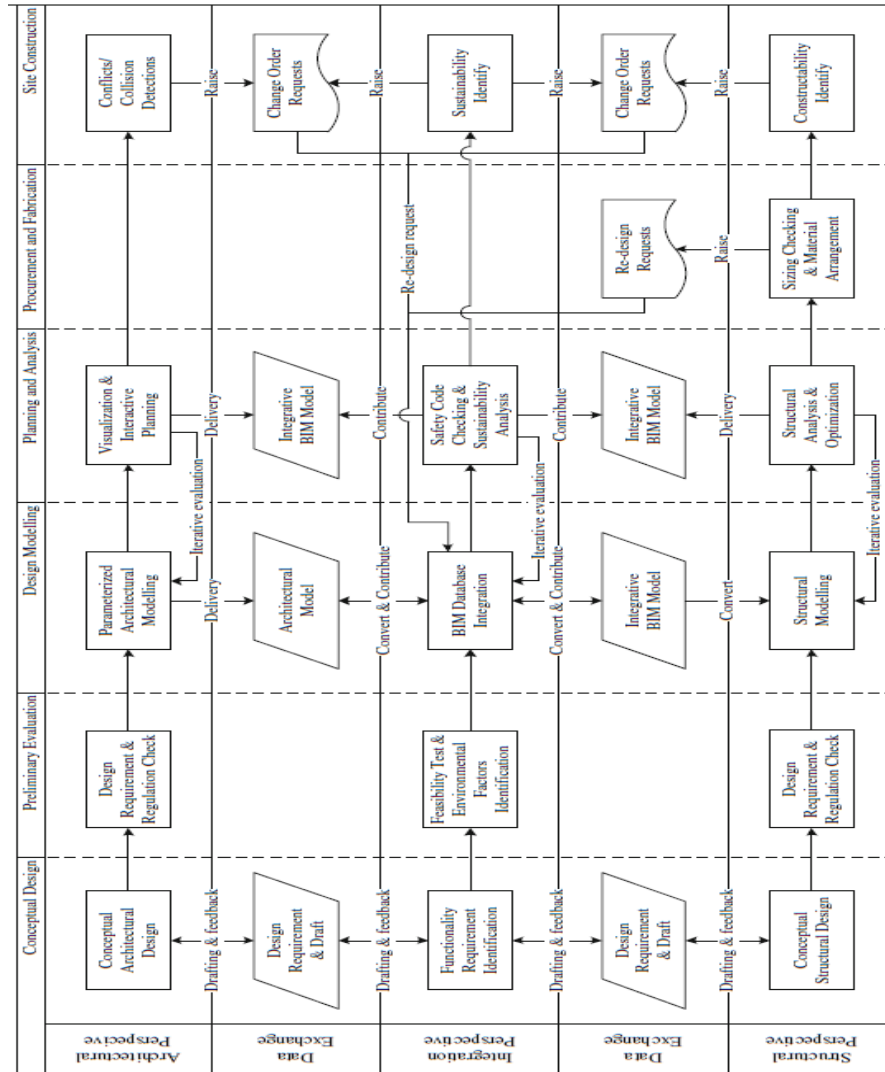
Figure 9: *Cross-functional flowchart for a BIM-enabled workflow in structural design process* (Chi et al., 2015)

- **Conceptual Design**

Conceptual Architectural Design: Architects create the initial vision and concept for the project by considering aesthetics, functionality, and design intent.

Design Requirement and Draft: Architects establish design requirements including functionality and spatial needs while creating preliminary design sketches or diagrams.

Functionality Requirement Identification (integration perspective): Architects collaborate with other disciplines, including structural engineers, to identify functional requirements that impact both the architectural and structural aspects of design.

Conceptual Structural Design: Structural engineers work with architects to develop the initial design concept and framework for the structural system, considering load paths, materials, and overall structural stability.

The link between conceptual structural design and design requirements and draft follows the Design Requirement and Draft phase within the Conceptual Design stage. Once architects have established the design requirements and produced initial drafts outlining the project scope, the Conceptual Structural Design phase begins. It builds upon the design requirements and draft phase, where architects collaborate with structural engineers to develop the initial design concept and framework for the structural system. This collaboration ensures that the structural design aligns with the overall project objectives and architectural vision defined in the design requirements and drafting phases.

- **Preliminary Evaluation**

Design Requirements and Requirement Checks: The project team reviews design requirements to ensure that they are complete and feasible. Both the architectural and structural aspects are evaluated for compliance and practicality.

Feasibility Test & Environmental Factors Identification: The team assesses the feasibility of the design by considering factors such as constructability, cost, and environmental impact. The integration perspective is crucial for evaluating how architectural and structural aspects align with these factors.

- **Design Modelling**

Parameterized Architectural Modelling: Architects create detailed 3D models of the architectural design using parametric modelling techniques, enabling efficient modifications and updates.

Architectural Model and BIM Database Integration: The architectural model is integrated with a Building Information Modelling (BIM) database, facilitating data exchange and coordination between architectural and structural perspectives (centralized repository for project information). The BIM database stores and manages various data related to architectural design such as component properties, specifications, and relationships.

Integrative BIM Model: The BIM model combines architectural and integration perspectives, allowing seamless data exchange and collaboration. The integrative BIM serves as a collaborative environment in which architects and other stakeholders can share and exchange information. Data from the architectural model, including spatial requirements, building components, and design intent, is integrated into the BIM model for coordination with structural design.

Structural Modelling: Structural engineers create a detailed 3D model of the structural system by incorporating elements such as beams, columns, slabs, and connections. The structural model represents the physical properties and behavior of the structural elements, considering the load paths,

support conditions, and construction methods. The model includes information regarding the structural components, material properties, and design parameters.

The design modelling phase plays a crucial role in the BIM-enabled workflow, as it enables the coordination, visualization, and analysis of architectural and structural designs. Detailed digital models provide a comprehensive representation of the project, allowing stakeholders to better understand the design intent, identify clashes or conflicts between architectural and structural elements, and assess the feasibility and constructability of the design. By working in a collaborative BIM environment, architects and structural engineers can seamlessly exchange data, make informed design decisions, and improve the overall efficiency and quality of the structural design process.

- **Planning and Analysis**

Visualization and Interactive Planning: The BIM model is used to visualize and plan architectural and structural designs, facilitating interactive decision-making.

Integrative BIM Model (Data exchange between architectural and integration perspectives): The BIM model enables data exchange between the architectural and integration perspectives, ensuring coordination and alignment of design elements.

Safety Code Checking and Sustainability Analysis: The integrated BIM model enables the integration of safety code checking and sustainability analysis into the design process. Safety code checking involves evaluating structural design against relevant building codes and regulations to ensure compliance with safety standards. Sustainability analysis focuses on assessing the environmental impact and energy performance of a structure, considering factors such as energy efficiency, material selection, and life-cycle assessment. The BIM model provides the necessary information to perform these analyses, such as the properties, connections, and material specifications of the structural elements. By integrating safety code checking and sustainability analysis within the BIM model, designers can evaluate a design's compliance with safety requirements and identify opportunities for sustainable design practices. Any non-compliance or sustainability concerns can be identified and addressed early in the design process, minimizing the risk of costly revisions or rework during construction.

Integrative BIM Model (data exchange between integration and structural perspectives): The BIM model allows data exchange between the integration and structural perspectives, ensuring accurate representation and integration of the structural design.

Structural Analysis and Optimization: Structural engineers utilize the BIM model to perform a detailed analysis and optimization of the structural design. The model provides essential geometric and physical information regarding structural elements, such as dimensions, material properties, and connection details. Engineers use specialized structural analysis software to simulate the behavior of a

structure under different load conditions, such as gravity, wind, or seismic loads. The results of the analysis, such as the stress distribution, deflection, and load-bearing capacities, are obtained and analyzed to ensure the structural integrity, safety, and efficiency of the design. Engineers can then make design modifications and optimizations based on the analysis results, thereby refining the structural system for improved performance.

The Integrative BIM Model serves as a central repository in which data from structural analysis and optimization, safety code checking, and sustainability analysis are exchanged, shared, and coordinated. This integration ensures that the structural analysis results and design modifications are considered when evaluating design compliance with safety codes and sustainability goals. By leveraging the BIM model for data exchange between these perspectives, the design team can collaborate more effectively, make informed decisions, and achieve optimized and sustainable structural design.

- **Procurement and Evaluation**

Redesign Requests: If design modifications are requested during procurement and evaluation, the BIM model is used to assess the impact on both architectural and structural designs and to make necessary adjustments.

Sizing Checking and Material Arrangement: Structural engineers verify the sizing of structural elements and coordinate with suppliers for material procurement by utilizing the BIM model for accurate information exchange.

- **Site Construction**

Conflicts/Collision Detections: The BIM model is employed for clash detection and collision identification between architectural and structural elements, enabling the early detection and resolution of conflicts.

Change Order Request: If design changes or modifications are required during construction, the BIM model is updated to reflect these changes and facilitate effective communication between the architectural and structural teams.

Constructability Identification: The BIM model aids in identifying and addressing constructability issues, ensuring smooth construction processes and coordination between architectural and structural elements.

Sustainability Identification: The BIM model is used to evaluate and identify opportunities for sustainable construction practices, aligning with the project's sustainability goals.

2.4   BIM Interoperability

According to European Commission (2004), Interoperability means the ability of information and communication technology (ICT) systems and of the business processes they support to exchange data and enable the sharing of information and knowledge. This definition of the European Interoperability Framework is readily applicable to the AEC domain. To exploit the vast number of benefits of BIM implementation completely, it is necessary to first provide a complete and proficient interoperability level (Jordi Somaini, 2021). Users from various disciplines select diverse software tools for their own business tasks, and then collaborate with other users for interoperability. Interoperability in practical projects involves many aspects. Chen et al., (2008) classified interoperability concerns into four areas: data, services, processes, and business. Data interoperability refers to the data sharing and exchange between heterogeneous BIM software, and it provides a basis for facilitating the interoperability of other concerns. However, the issues of data interoperability are still common in the AEC/FM industry (Lai and Deng, 2018)

Traditional data interoperability involves the exchange of data between different software systems, typically using common file formats, such as CSV or XML, and is applicable across various industries and domains. It focuses on facilitating data exchange and compatibility between systems, without deep integration. In this approach, the emphasis is on ensuring that data can be effectively shared and utilized in different applications.

By contrast, BIM-based data interoperability is specifically tailored to the construction industry and revolves around the exchange and integration of complex Building Information Modelling (BIM) data. BIM is a digital representation of a building or infrastructure project, encompassing its physical and functional characteristics. It extends beyond simple data exchange and incorporates industry-specific standards and workflows. It also involves the exchange of comprehensive BIM models that contain detailed information regarding building elements, properties, relationships, and attributes. The goal is to enable seamless collaboration and information sharing among the various stakeholders involved in the design, construction, and management of a building. It includes architects, engineers, contractors, facility managers, and other professionals.

Industry-standard formats, such as Industry Foundation Classes (IFC) and Construction Operations Building Information Exchange (COBie), are commonly used to achieve effective BIM-based data interoperability. These standards ensure consistent data exchange and compatibility between different BIM software platforms. The focus is not only on the geometric and visual aspects of the building, but also on the semantic information embedded within BIM models.

2.4.1   Types of BIM Interoperability

Horizontal interoperability refers to the ability of different systems or software applications to exchange data and collaborate within the same level or domain (between two architectural BIM

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software - CAD to CAD path). This involves integrating and sharing data between similar types of systems or applications that operate at the same level in a particular workflow or process.

Vertical interoperability refers to the ability of different systems or software applications to exchange data and collaborate across different levels or domains of a workflow or process (between architectural and structural software – CAD to CAE path). It involves the integration and data sharing between systems that operate at different stages or levels within a particular workflow or process (Bernardino et al., 2015)

2.4.2   Data Transfer Path

According to Gerbino et al. (2021), two main types of data transfer paths between two design environments exist depending on the way the information is exchanged:

➤ **Direct (Bi-directional) link (DL)**

A link that facilitates bi-directional communication, and establishes an automated connection between two distinct software environments using a specially designed plug-in. This enables seamless mapping of data from the sending environment onto data within the receiving environment. As a result, there is no requirement for an external intermediary data translator, making the exchange process highly efficient despite its reliance on proprietary formats.

➤ **Neutral link (NL)**

The implementation of a neutral link (NL) involves the utilization of an autonomous exchange format, which is considered the most suitable approach within a BIM-focused methodology and serves as a crucial milestone for the BIM environment. Most data pertaining to building descriptions, various building disciplines, and the different stages of the building lifecycle are gathered and administered through this neutral format. The primary aim of neutral formats is to guarantee sustained accessibility to data and eliminate any ambiguity concerning legal rights or technical specifications.
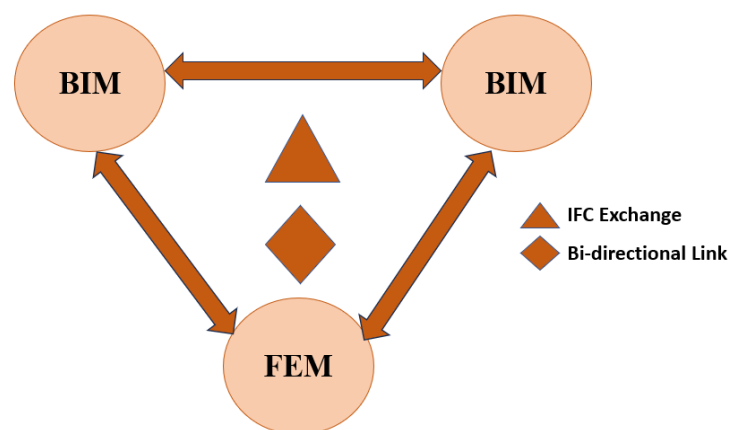
Figure 10: *Horizontal interoperability and vertical interoperability showing Bi-directional and IFC exchange*

Industry Foundation Classes (IFC), created by buildingSMART, are widely recognized as the predominant open and neutral format utilized in Building Information Modelling (BIM).

2.4.3   Importance of BIM Interoperability

BIM interoperability is particularly important in the context of the Architecture, Engineering, and Construction (AEC) industry, considering historical productivity trends and the impact of digitalization. The AEC industry has long been recognized as a significant and influential sector in every culture and country. Over the centuries, productivity has consistently grown, often matching the pace of the manufacturing industry. However, with the advent of digitalization in the 1970s, the manufacturing industry experienced a remarkable boost in productivity, more than doubling its output. By contrast, the productivity of on-site construction work remains relatively unchanged.
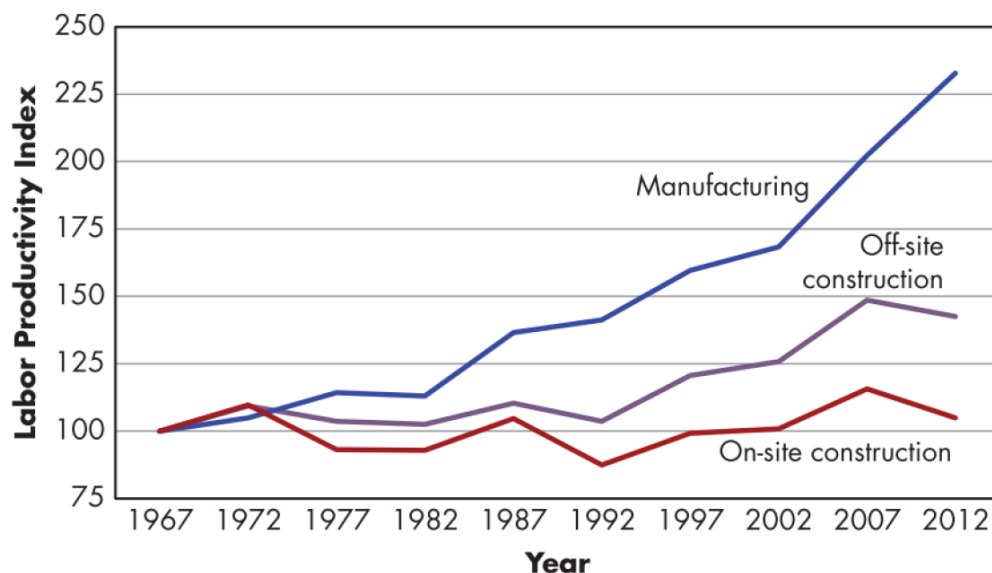
Figure 11: *Productivity trend in manufacturing and construction industries* (Jordi Somaini, 2021)

Thus, BIM interoperability is crucial. By facilitating seamless data exchange and collaboration between different stakeholders, BIM interoperability addresses the productivity gap between AEC and manufacturing industries. This enables the integration of diverse software tools, systems, and disciplines involved in the construction process. Through BIM interoperability, architects, engineers, contractors, and other professionals can share and exchange information, models, and data effectively. This enhances coordination, reduces errors, and improves decision-making throughout the project life cycle. This enables stakeholders to work collaboratively, leveraging the benefits of digital technologies and streamlining workflows.

BIM interoperability also promotes efficiency by minimizing redundant tasks, eliminating manual data entries, and reducing the need for data conversion. It enables seamless communication and coordination among different project phases and disciplines, optimizes resource allocation, and avoids costly rework. According to Jordi Somaini (2021), the McGraw Hill Construction report stated that the

value/difficulty ratio for engineering analysis using BIM is very low. This ratio for structural analysis is even negative, which means that a structural engineer is better off creating a structural analysis model from scratch than reusing the BIM model generated from the corresponding architectural design process. Generally, it bridges the productivity gap and drives positive changes in the AEC industry. It enhances collaboration, increases efficiency, and helps unlock the full potential of digitalization to transform and advance construction practices.

2.4.4 Industry Foundation Classes (IFC)

The purpose of IFC is to enable the exchange of data and information related to a building project between different software applications without losing critical information. It defines a structured and standardized data model that represents various elements of a building project, such as walls, floors, doors, windows, structural components, etc. This data model captures not only the geometry and physical properties of these elements but also their relationships, classifications, and other relevant information. IFC supports a wide range of information beyond geometric data, including spatial relationships, construction schedules, quantities, costs, material specifications, and more. This comprehensive representation allows for effective collaboration, coordination, and integration of different software tools used by various stakeholders involved in building project design, construction, and management.
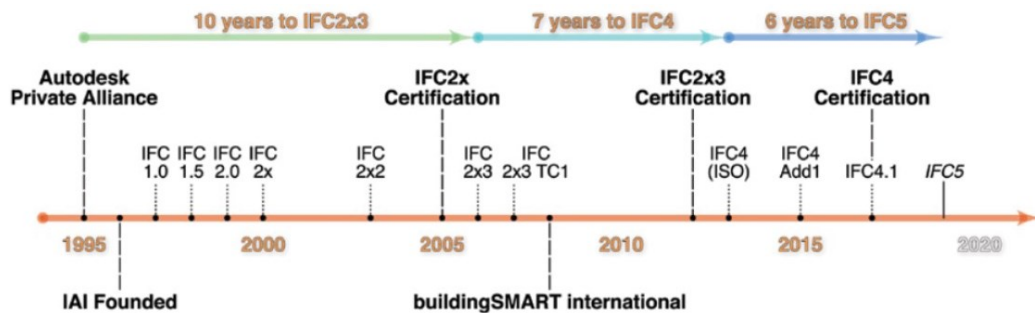
Figure 12: *IFC Historical Timelines* (Source: Google Image)

The IFC standard has evolved through multiple versions since its inception, with each iteration bringing enhancements, improvements, and new features to the data model. Figure 15 illustrates the historical timeline of IFC from its creation till date. According to Gerbino et al. (2021), The release of IFC 2x3 in 2006 witnessed widespread adoption and promotion by software providers, often accompanied by certification of conformity from buildingSMART. This version introduced significant advancements to the data model, aimed at enhancing various aspects. Notably, it brought improvements in supporting construction sequencing, refining the representation of building systems, and facilitating seamless data exchange with other industry standards. Every IFC version has a corresponding set of authorized 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

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BuildingSMART. The CV 2.0 schema is thorough and includes information on CAD and CAE workflows (Azinwie Zama, 2022).
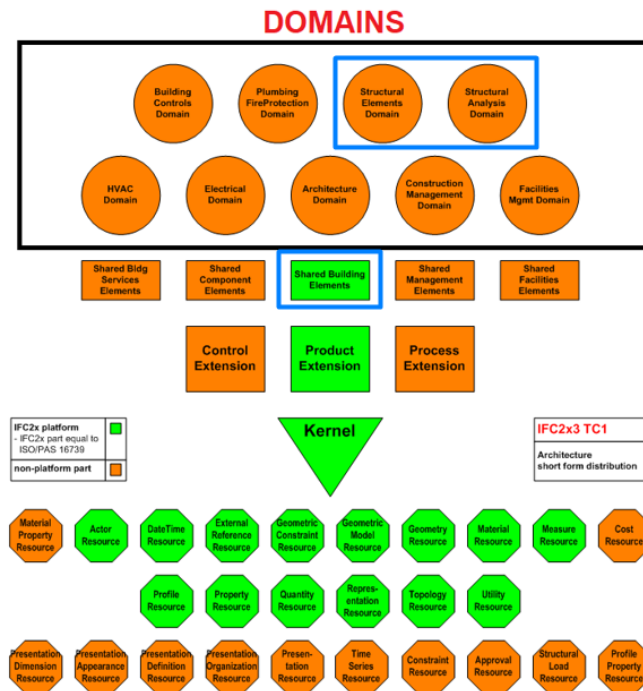
Figure 13: *IFC 2X3 Data Schema relevant to Structural Engineering highlighted in blue* (Source: BuildingSMART)

There are two main formats commonly used: IFC-SPF (Standard Data Exchange Format) and IFC-XML (XML-based format). IFC-SPF is a text-based format that was the original and widely adopted format for IFC files. It represents the information in a structured manner using plain text. On the other hand, IFC-XML is an XML-based format that provides a more human-readable and extensible representation of IFC data. Both formats adhere to the IFC schema and can be used for importing and exporting data between software applications. The choice of format depends on the specific requirements and capabilities of the software tools being used.

Numerous plug-ins currently exist to establish a direct connection between Revit and FEM-software. Alternatively, users have the option to export the model using IFC, which proves beneficial in situations where the specific FEM-software is uncertain or when direct program integration is not feasible. Table 1 shows which format can be used to enable a link between an architectural program and FEM-software

Available links						
from\ to	RSA	SCIA Engineer	Staad.Pro	ETABS	RFEM	FEM-design
Revit	Direct	Direct/ IFC2x3	ISM	CSI/ IFC4	IFC2x3	StruXML
ArchiCAD	IFC2x3	IFC2x3	IFC2x3	IFC2x3/ IFC4	IFC2x3	IFC2x3
AECOsim	IFC2x3	IFC2x3	ISM	IFC2x3/ IFC4	ISM	IFC2x3
Tekla Structures	IFC2x3	IFC2x3	IFC2x3 trough ISM	IFC2x3	IFC2x3	IFC2x3
Vectorworks	IFC2x3	IFC2x3	IFC2x3 trough ISM	IFC2x3/ IFC4	IFC2x3	IFC2x3

Table 1: *Summary links from BIM to FEM* (Beirnaert and Lippens, 2018)

2.4.5   IFC Structural Analysis Model

The *IfcStructuralAnalysisModel* class is an integral part of the Industry Foundation Classes (IFC) schema, a standardized framework used to digitally represent various aspects of building and construction projects. Within this overarching schema, IfcStructuralAnalysisModel plays a crucial role in capturing the intricate details associated with structural analysis.

IfcStructuralAnalysisModel serves as a standardized conduit for sharing essential structural analysis information across different software applications and tools. This ensures that critical details, such as load distributions, element behaviors, and support conditions, can be accurately communicated and interpreted throughout the project's lifecycle. As a result, potential discrepancies and errors arising from manual data transfer or inconsistent representations are minimized, enhancing the overall accuracy and efficiency of the construction process.

```
IfcRoot
  └ IfcObjectDefinition
      └ IfcObject
          └ IfcGroup
              └ IfcSystem
                  └ IfcStructuralAnalysisModel
```
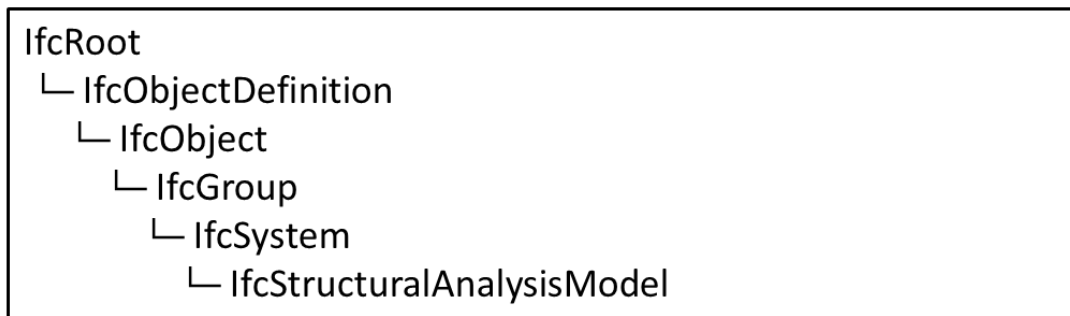
Figure 14: *Positioning IfcStructuralAnalysisModel in the Inheritance Graph* (Source: BuildingSMART)

- **IfcRoot:** As the foundation of the IFC schema, *IfcRoot* introduces two pivotal attributes: GlobalId represented by *IfcGloballyUniqueId,* which assigns a unique identification to every entity, ensuring distinctiveness across the schema. Additionally, OwnerHistory represented by *IfcOwnerHistory* encapsulates historical context, containing creation and modification information, vital for maintaining data integrity and traceability. These attributes collectively establish a robust groundwork for consistent data representation and effective exchange within the IFC framework.

- **IfcObject:** This serves as a versatile representation of tangible or conceptual elements within a construction project. This entity can encompass diverse items such as physical components or abstract entities. A notable aspect of *IfcObject* is its ability to be decomposed into smaller parts, and this hierarchy is established through the *IsDecomposedBy* attribute. This attribute is linked to the *IfcRelNests* relationship, enabling the definition of close relationships between objects and their constituent elements.

- **IfcGroup:** This can be associated with instances of *IfcRelAssignsToGroup,* which serves as a bridge between the grouping entity and the individual elements being grouped. This implies that elements belonging to a specific structural analysis model can be logically grouped using

IfcGroup. This grouping can encompass both *IfcStructuralMember* instances and *IfcStructuralConnection* instances that pertain to the same analysis context. While the *IsGroupedBy* attribute within *IfcGroup* is a powerful mechanism for grouping elements, it is essential to note that loads and results in the context of structural analysis follow distinct relationship patterns. Loads are assigned through the *LoadedBy* attribute using load groups, and results are assigned via the *HasResults* attribute using result groups. These mechanisms ensure that loads and results are accurately associated with the relevant structural components, contributing to a comprehensive and organized representation of the structural analysis model.

- **IfcSystem:** inherits the capacity to create relationships with one or more *IfcBuildings* as required by the project. This relationship acts as a bridge, allowing the analytical model captured using *IfcStructuralAnalysisModel* to be correlated with the tangible aspects of the building.

- **IfcStructuralAnalysisModel:** This class signifies a specialized type of structural activity group, dedicated to defining comprehensive structural analysis models. It encompasses essential attributes like PredefinedType (categorized by *IfcAnalysisModelTypeEnum*) that provides predefined analysis classifications. Crucially, this class captures key details about structural elements, applied loads, support conditions, and other pertinent data necessary for a thorough analysis of a building's structural behavior. In essence, it serves as a crucial tool in ensuring the structural integrity and safety of the building.

The *IfcStructuralAnalysisModel* class inherits its properties and attributes from various parent classes in the IFC schema hierarchy. It is a specialized class that represents the structural analysis model of a building or structure within the broader context of IFC's data representation standards.

2.5   Structural Analysis Format (SAF)

A significant challenge in openBIM lies in the absence of an effective and standardized format to handle structural analysis models.. While the widely adopted IFC standard facilitates building information exchange, it lacks comprehensive support for detailed structural analysis data. Structural analysis involves intricate calculations and simulations to evaluate structure behavior under various loads and conditions, necessitating specialized formats capable of accurately representing these complex analysis models. Existing openBIM formats' limitations in this regard create difficulties in seamless data exchange between software applications. As a result, engineers often resort to manual workarounds or proprietary formats, leading to data loss, inconsistencies, and inefficiencies. To address this issue, the field of structural engineering has adopted the Structural Analysis Format (SAF).

SAF is a standardized data format designed specifically for representing and exchanging structural analysis data. It provides a structured and consistent approach for storing and communicating

information related to structural models, loads, boundary conditions, analysis results, and other pertinent data. SAF is an open-source project and it is being developed under the Nemetschek Group, coordinated by SCIA Engineer.

An analysis of the subsidiaries associated with the Nemetschek Group reveals that incorporating the SAF format into their product offerings enhances the efficiency of BIM-based structural design and fosters improved communication between different software programs. Notably, well-known CAD companies such as Allplan, Graphisoft (Archicad), ProtaStructure and Vectorworks, along with esteemed analysis software manufacturers like SCIA, Risa, and FRILO Software, are part of this endeavor. These companies provide open BIM-based data exchange capabilities, supporting both IFC and SAF file formats.

For example, Graphisoft's CAD-BIM program, Archicad, allows the generation of an analysis model that can be exported in SAF format. Additionally, some CAD manufacturers utilize the Bimplus collaboration platform, which is also supported by Nemetschek, and integrate SCIA AutoConverter into their workflows. This approach offers architects and structural engineers flexibility by enabling them to work with both IFC and SAF data interchangeably. By adopting this strategic approach, the Nemetschek company aims to cater to a wide range of specialist planners, providing them with a diverse array of software solutions. This allows them to compete on a global scale with other construction software manufacturers and deliver an optimal workflow for their clients (Dlubal Daniel, 2021).
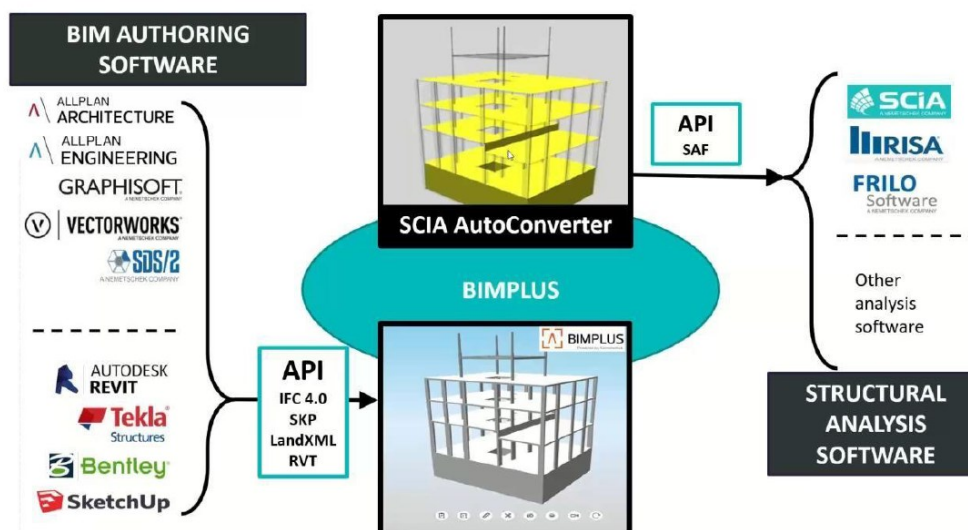
Figure 15: *Options for communication between BIM authoring and structural analysis programs primarily developed within the Nemetschek Group.*(Dlubal Daniel, 2021)

The first SAF version was released in the year 2019 and since then has been constantly developed. SAF is basically excel based format with sheets dedicated to structural analysis objects (materials, nodes, beams, slabs, loads, supports and hinges etc.). Properties are stored in excel cells, in rows are

defined objects and columns represent specific attributes. Every excel sheet represents set of similar analysis elements. Format is readable even in the excel itself and can be easily adjusted also outside of the structural analysis application, that is capable of reading and interpreting the SAF file. SAF can be also inspected in free SAF viewer web application, which is part of the SCIA Auto-Converter (Šonka, 2020).

2.5.1   SAF Objects

SAF offers a total of 40 objects that are grouped into 5 primary categories: General Information, Analysis Elements, Supports and Hinges, Loads, and Results. You can refer to Table below for a comprehensive list of all these objects and their respective classifications. The object names are self-explanatory, designed to reflect their intended purposes. Notably, the first column of the table presents both General Information and Results, each containing only two objects within their respective categories.

General Info and Results	Analysis Elements	Supports and Hinges	Loads
Project	StructuralMaterial	StructuralPointSupport	StructuralLoadGroup
Model	StructuralCrossSection	StructuralSurfaceConnection	StructuralLoadCase
	CompositeShapeDef	StructuralCurveConnection	StructuralLoadCombination
ResultInternalForce1D	StructuralPointConnection	StructuralEdgeConnection	StructuralPointAction
ResultInternalForce2DEdge*	StructuralCurveEdge	RelConnectsStructuralMember	StructuralPointMoment
	StructuralCurveMember	RelConnectsSurfaceEdge	StructuralCurveAction
	StructuralCurveMemberVarying	RelConnectsRigidCross	StructuralCurveMoment
	StructuralCurveMemberRib	RelConnectsRigidLink	StructuralSurfaceAction
	StructuralSurfaceMember	RelConnectsRigidMember	StructuralSurfaceActionThermal
	StructuralSurfaceMemberOpening		StructuralCurveActionThermal
	StructuralSurfaceMemberRegion		StructuralPoinActionFree
	StructuralStorey		StructuralCurveActionFree
	StructuralProxyElement		StructuralSurfaceActionFree
			StructuralSurfaceActionDistri

Table 2: *SAF Objects Review and Classification* (Šonka, 2020)

2.5.2   SAF Structure

The SAF format, presented in tabular form, functions as a **relational database**, and is stored as an Excel file denoted by the extension **"*.xlsx."** This relational database relies on table-based relationships, enabling the linkage of various objects within the format.

Excel Structure

A SAF file in Excel can be divided into four basic components:

- Sheet → Object Element
- Column → Attribute
- Row (Row) → Instance
- Cell (Cell) → Value

In a SAF format, each object type is stored in a sheet or a list (sheet). Each sheet consists of rows, columns and cells. Each line represents a new instance or a new entry, e.g. e.g. node, member, support, etc. (Dlubal Daniel, 2021)

Object Database

Utilizing a relational database allows for seamless linking of multiple object types, resulting in a clear and comprehensible representation of both structural and load data. Accurate designations play a crucial role in facilitating references between the different elements of the objects. For instance, let's consider the object type *"StructuralMaterial."* This type comprises two materials, C25/30 and S235, which serve as components for other object types, such as *"StructuralCrossSection"* (cross section) and *"StructuralSurface"* (area).
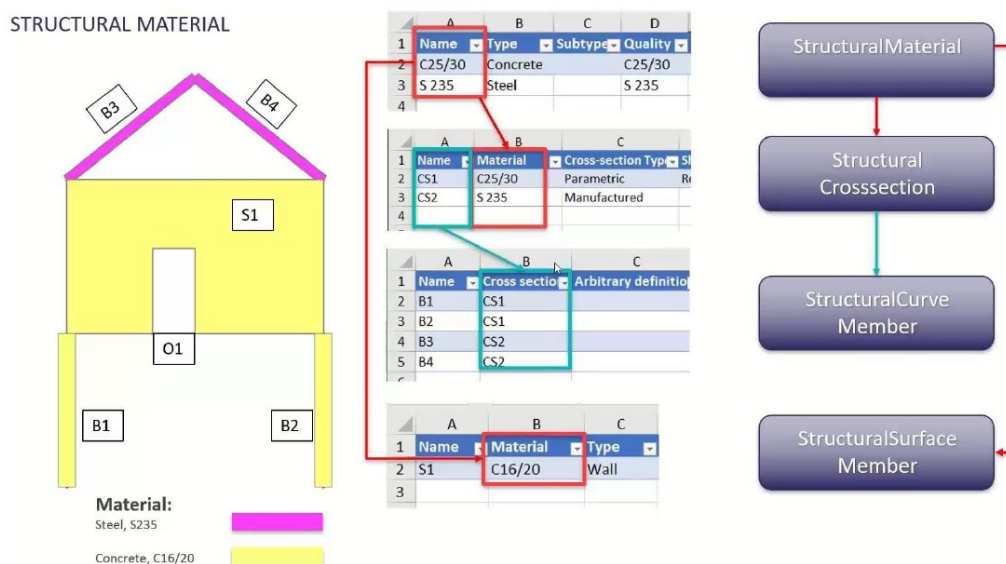
Figure 16: *SAF object relation for the object type StructuralMaterial* (Dlubal Daniel, 2021)

Unique ID's

The SAF format also provides the capability of including Unique IDs. These IDs consist of unique and randomly generated numbers assigned to each object. This feature facilitates round trips during data exchange with other software tools that support the SAF format. When the IDs remain unchanged, the corresponding object elements are recognized, and new creations are avoided, only adjustments are made. It's worth noting that filling out the cells with IDs is not obligatory for the exchange format (Dlubal Daniel, 2021).

Figure 17: *Unique IDs in SAF format*

3   RESEARCH METHODOLOGY

This research aims to explore and highlight the significant advantages and limitations of employing BIM-based technologies in the construction of structural BIM projects, leading to enhanced performance. The study evaluates two methods of data transfer: Bi-directional link and the IFC standard. By developing a specialized procedure for structural engineers and retaining key insights, the research investigates the creation, exchange, and validation of structural BIM models at different project stages.

The methodology encompasses several essential stages aimed at achieving bi-directional interoperability between architectural and structural BIM for efficient structural design and analysis. The key steps involve carefully selecting and applying BIM-based technologies, along with identifying and preparing data for utilization in modelling, analysis, and design phases. Following each data transfer, a thorough check is conducted to ensure data analysis consistency, and necessary adjustments are made to enhance accuracy.

The study findings demonstrate a range of benefits, focusing on addressing current limitations and proposing an actionable plan to implement BIM workflows effectively within engineering offices for structural design. Structural engineers play a pivotal role in AEC projects, engaging in the conception, analysis, and design of the structural framework. Collaboration with architects, MEP engineers, and cost managers is critical, and leveraging CAD technologies streamlines the structural engineering process, replacing time-consuming hand drafting. BIM's capabilities have the potential to overcome traditional challenges, including outdated drawings and manual clash detection, ultimately leading to improved overall efficiency.

During the collaborative process between architects and structural engineers, essential details like 2D drawings, dimensions, and section sizes are provided by the architect. Utilizing this data, the structural engineer creates a sturctural/analytical model in Structural BIM software, incorporating load applications, section properties and materials. Nonetheless, the manual updating of the analytical model becomes arduous and time-consuming whenever modifications to the architectural design are made. Consequently, the capability to seamlessly import or export models between architectural and structural BIM software becomes crucial, leading to a significant reduction in the time required for creating a new model from scratch.

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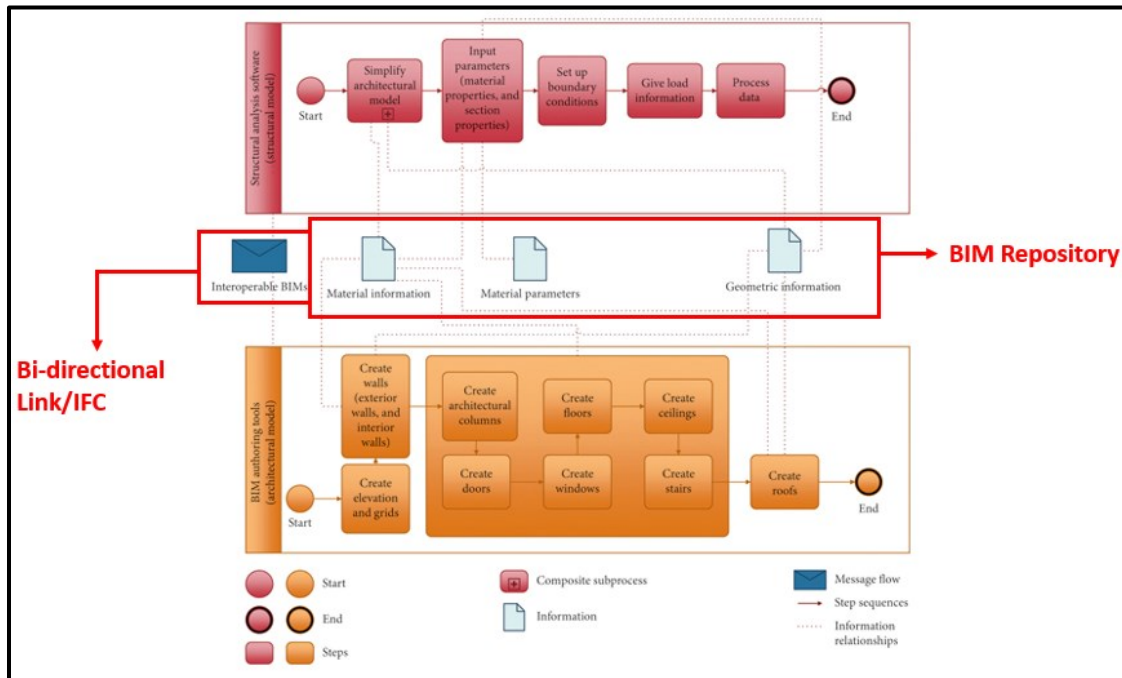
Figure 18: *Interoperability between Architect and Strucutral Engineer using BIM* (Ren & Zhang, 2021)
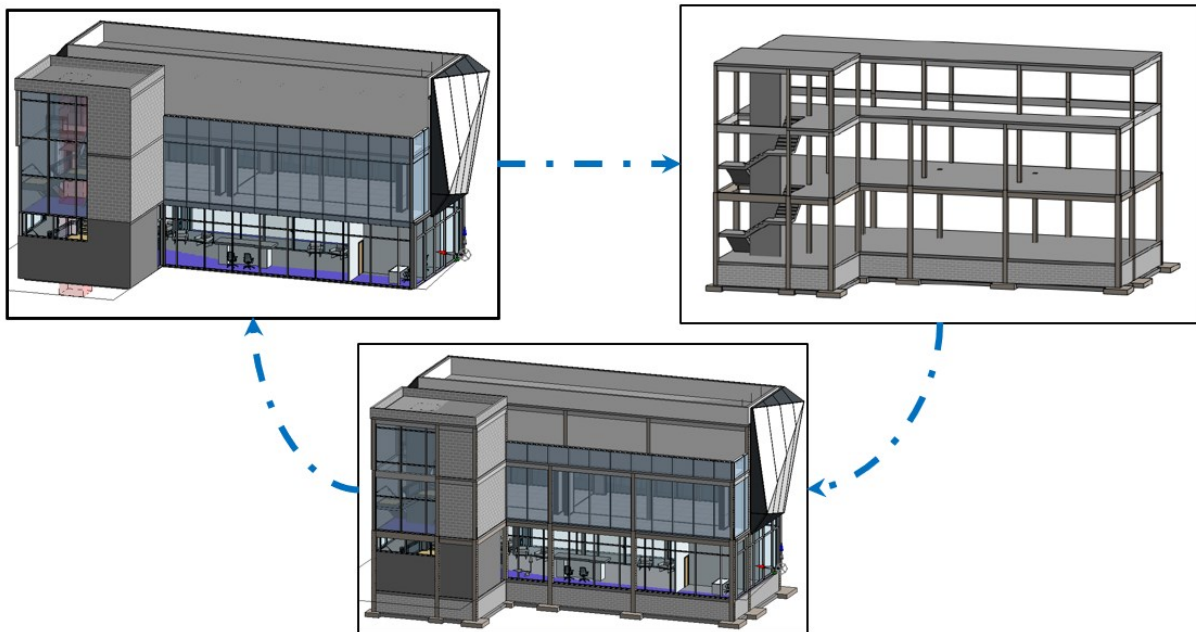
Figure 19: *Process workflow between Architect and Strucutral Engineer using BIM*

3.1 Structural BIM Workflow

Structural Building Information Modelling (BIM) has revolutionized the way structural engineers approach the design and construction of building structures. The workflow begins with the creation of the BIM structural model using specialized software. This 3D digital representation incorporates the building's structural elements such as columns, beams, slabs, and foundations. From this model, a detailed version is developed, capturing specific dimensions, material properties, and connections of

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structural elements. The detailed model becomes the basis for further analysis and is linked directly (plug-ins or add-ons) or indirectly (IFC) to Finite Element Modelling (FEM) or Finite Element Analysis (FEA) software. This seamless connection transfers geometrical and material data to create an analytical model for in-depth structural analysis under various loads and conditions. Engineers optimize the design based on analysis results, adjusting member sizes, structural elements, and material selection for improved efficiency and safety. The changes made during the FEM analysis are updated in the detailed model, ensuring accurate representation. Clash detection is performed to identify conflicts between structural elements and other building systems, facilitating coordination among stakeholders. The BIM structural model serves as the foundation for generating construction documentation, including detailed drawings, schedules, and specifications. Throughout construction, the BIM model remains valuable for construction management, aiding in progress tracking and decision-making. This collaborative approach enhances precision, reduces errors, and streamlines project delivery, resulting in superior structural performance and successful construction projects.
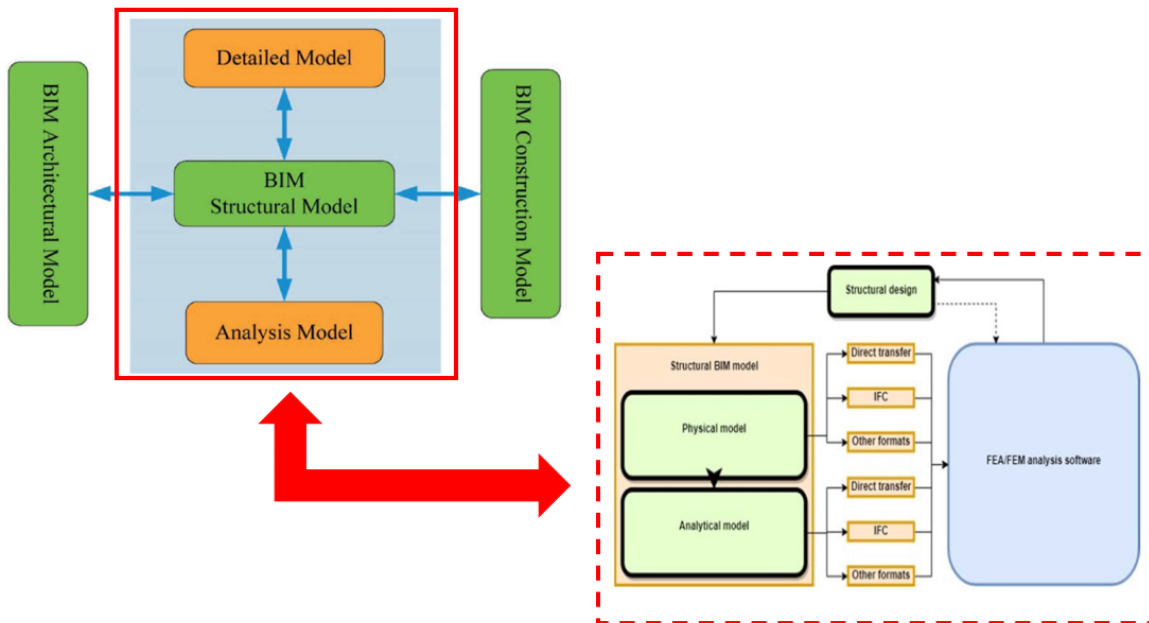
Figure 20: *Typical Structural BIM workflow*

3.1.1 BIM Workflow: Structural Analysis, Design and Shop Drawings

The BIM workflow for structural analysis and design begins with obtaining the architectural model and other essential data, such as soil data and load data. The architectural model serves as the basis for the structural engineer's work, providing valuable information about the building's layout, spatial arrangements, and other architectural elements. With the architectural model in hand, the structural engineer proceeds to generate the structural layout. This involves developing a preliminary plan for the placement of structural elements such as columns, beams, slabs, and foundations. The engineer

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considers the building's intended use, load-bearing requirements, and architectural constraints while creating the layout.

Once the structural layout is established, the structural engineer proceeds to develop the structural model, which serves as the draft of the structural design. The structural model involves detailing the specific dimensions, materials, and connections of the structural elements. During this stage, the engineer defines the cross-sectional properties of the elements and their interactions. The next step is to export it to a structural analysis application. This application, typically Finite Element Analysis (FEA) or Finite Element Modelling (FEM) software, allows the structural engineer to perform in-depth structural analysis. The structural model, once imported into the FEM/FEA software, is used to simulate the behavior of the structure under various loads and conditions.

The structural analysis helps the engineer verify the structural integrity, identify areas of stress concentration, and assess the building's overall stability. It aids in determining whether the design can withstand the anticipated loads and ensures compliance with safety standards and building codes. After the structural analysis is completed, the structural engineer reviews the results to determine if the structural analysis model (FEM) is satisfactory. If the analysis model meets the engineering requirements and exhibits desired structural performance, the engineer proceeds to export the model back to the structural design application. The structural design application allows the engineer to perform additional design optimizations and updates based on the results of the analysis. This step helps refine the structural design to achieve the desired performance and safety. The engineer can make necessary adjustments to member sizes, modify structural elements, and select appropriate materials to enhance structural efficiency.

The iterative process of exporting the structural model to the analysis application and updating the design model as depicted in Figure 24 continues until the structural engineer is satisfied with the design's performance and safety. The collaborative approach between the structural analysis application and the design application ensures that the final structural design is well-optimized and meets all engineering requirements.
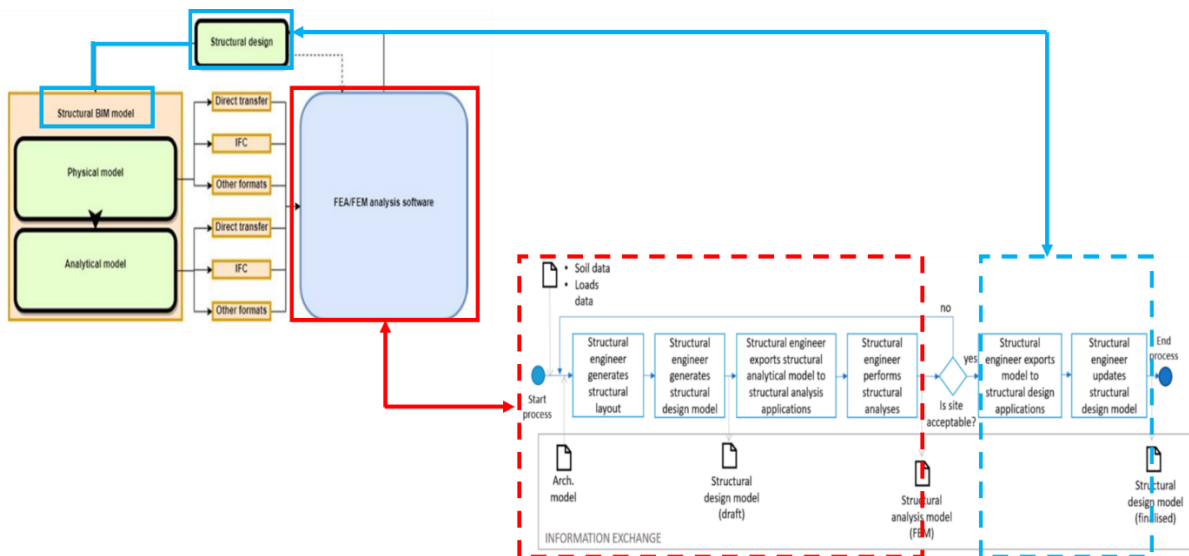
Figure 21: *BIM workflow for Structural Analysis and Design*

The BIM workflow for structural analysis and design is a multi-step process that involves obtaining the architectural model, generating the structural layout, developing the detailed structural model, performing structural analysis using FEM software, and refining the structural design based on analysis results. This iterative workflow ensures that the structural design is precise, efficient, and safe, leading to successful construction projects that meet engineering standards and regulations.

The creation of shop drawings is a critical phase in the structural engineering process, following the development or updating of the structural design model after structural analysis. The BIM workflow reference method for manufacturing them is shown in Figure 25. This process will be applied in diverse simulations by professionals working in a design office engaged in advanced practices for BIM design projects. This approach is now known as "*BIM Sustainable Integrated Design."* A comprehensive implementation procedure is created to serve as a reference for the design team's utilization.

During this stage, coordination activities are essential to ensure that the design is well-integrated with other building systems, and clash detection is used to identify any potential collisions or conflicts. Once the structural engineer has finalized the structural design model after the structural analysis, coordination activities come into play. This involves collaborating with other stakeholders, such as architects, MEP (Mechanical, Electrical, Plumbing) engineers, and contractors, to review the design and address any potential clashes between the structural elements and other building systems. The goal is to ensure that the design is well-coordinated and fits seamlessly with the overall building design.

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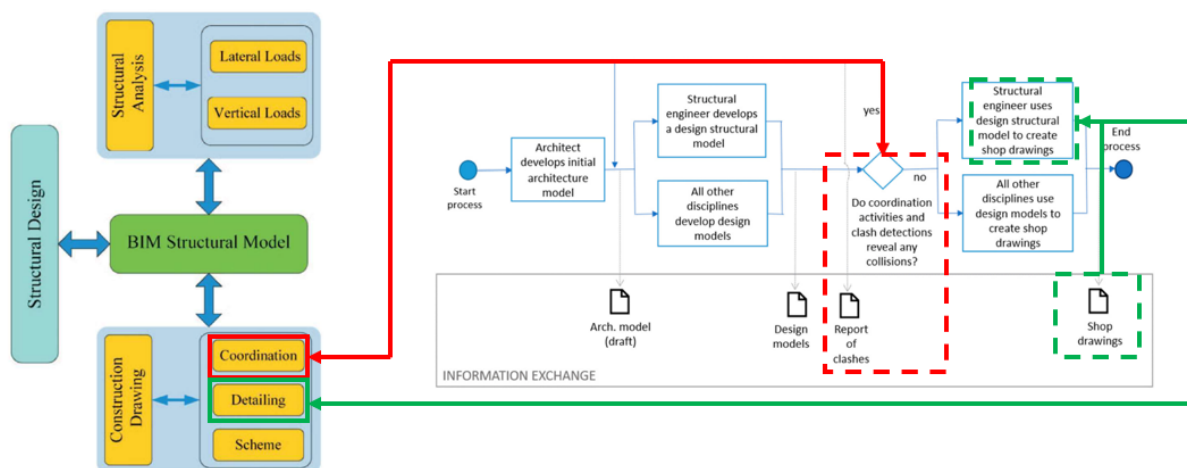
Figure 22: *BIM workflow for production of shop drawings*

Clash detection tools are utilized to identify any conflicts between the structural elements and other building components, such as ductwork, pipes, or electrical conduits. If clashes are detected, the structural engineer must go back to the structural model to make the necessary adjustments. This iterative process shown in figure 25 continues until all clashes are resolved, and the design is conflict-free.

Once the coordination phase is completed, and any clashes are resolved, the structural engineer proceeds to create shop drawings. Shop drawings are detailed drawings that provide precise information for the fabrication and installation of structural components. These drawings are used by contractors, fabricators, and construction teams to execute the construction accurately and efficiently. Using the design structural model as a basis, the structural engineer generates shop drawings that include essential details, such as dimensions, reinforcement requirements, connection details, and material specifications. The shop drawings represent a more detailed and accurate version of the structural design, tailored for the construction and fabrication processes.

Shop drawings play a vital role in the construction phase, ensuring that the structural elements are correctly manufactured and installed as per the design intent. They serve as a communication tool between the design team and the construction team, reducing errors and improving the overall construction process.

3.2 Utilization of Prominent Software for Structural BIM workflow

The interoperability between BIM platforms and analysis/design software depicted in Figure 26 has revolutionized modern construction practices, enhancing the efficiency and effectiveness of design, analysis, and execution. A vital aspect of this integrated approach lies in the seamless connection between BIM and Finite Element Analysis (FEA) or Finite Element Modelling (FEM) software. By merging BIM's architectural and engineering data with FEM's analytical capabilities, engineers can simulate and evaluate complex structural behaviors accurately. This interoperability enables the direct

transfer of critical model information, such as geometry, material properties, and loads, from BIM to FEM analysis tools. Consequently, the design workflow becomes streamlined, fostering collaboration, data consistency, and informed decision-making. The synergistic relationship between BIM and FEM empowers structural engineers to optimize designs, anticipate challenges early on, and create cutting-edge, resilient structures with utmost precision and confidence.
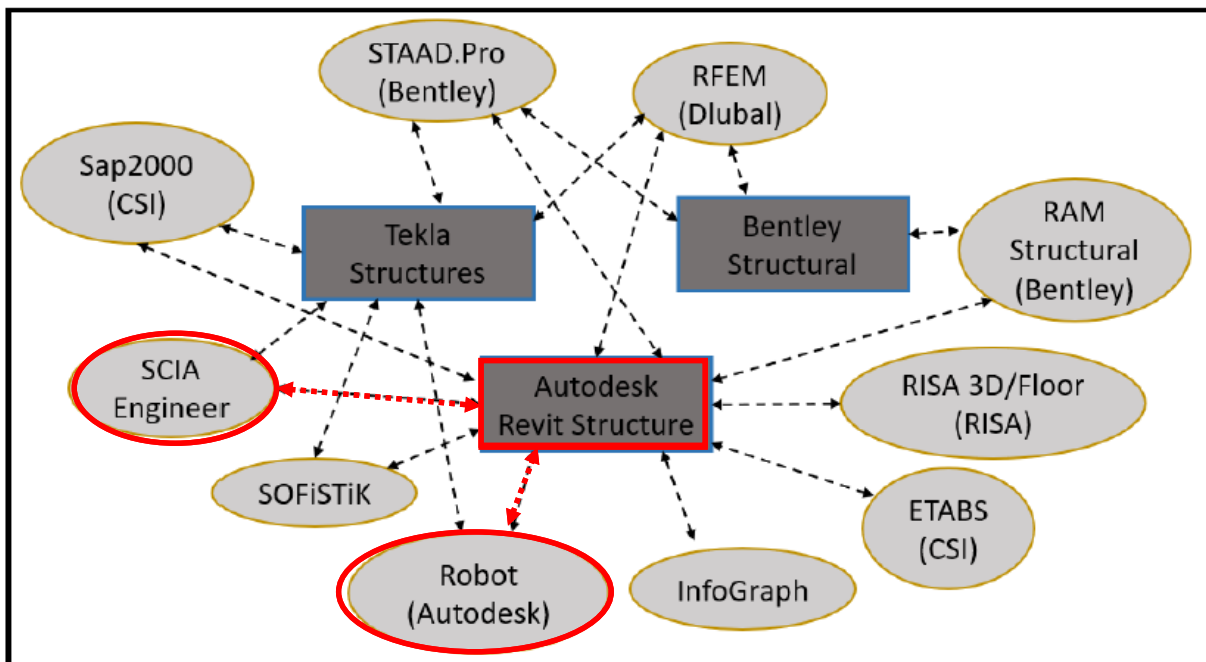
Figure 23: *Prominient Interoperability Solutions for BIM Platforms and Analysis & Design Software*
(Nyei Muniru, 2021)

The exposition of the highlighted interoperability solutions and workflow for BIM Platforms (specifically, the connection between Revit and Robot Structural Analysis, as well as the linkage from Revit to SCIA Engineer) is provided in the subsequent description related to Figure 26.

3.2.1   Autodesk Revit and Robot Structural Analysis

Facilitating a seamless information interchange between Autodesk Revit and Autodesk Robot Structural Analysis (RSA), both dynamic software offerings from Autodesk, is a sophisticated direct link mechanism. This direct link establishes a dynamic two-way conduit, allowing data to flow fluidly between the two platforms. This exchange is a vital component of the collaborative workflow, fostering efficient coordination between the design and analysis stages of a project.

The focus of this interoperability lies in its ability to infuse the Revit model with analysis-focused insights while also enabling the Revit model to be enriched with subsequent analysis results. When crafting the digital representation within Revit, not only is the physical model constructed but also a parallel analytical model is meticulously created. This analytical counterpart contains essential elements such as boundary conditions and load definitions that are essential for precise structural analysis. Thus, the inherent architectural and analytical aspects converge within Revit. Empowering

structural engineers, this interconnected ecosystem facilitates the seamless linkage of these models to Autodesk Robot Structural Analysis. This synergy accelerates the design process, saving valuable time by minimizing manual redundancies. The culmination of this harmonious synergy is observed after the analysis, where refinements or adjustments may be needed. These changes seamlessly travel back to Revit, showcasing the circular nature of this information exchange as seen in Figure 28

A defining characteristic of this integration is the iterative approach it offers. The design-iterate-analyze-refine cycle persists in an unwavering pursuit of an optimal and satisfactory solution. As this cycle continues, the digital constructs evolve in harmony, resulting in a progressively refined and cohesive architectural vision.

Workflow for Autodesk Revit and Robot Structural Analysis Direct Link

The two-way connection connecting Revit and Robot significantly enhances the transfer of structural analysis data. This connection empowers organizations to incorporate analysis-specific details into the Revit model, employ this model (and its details) directly for analysis in Robot Structural Analysis Professional, and subsequently revise the Revit model according to the analysis findings.
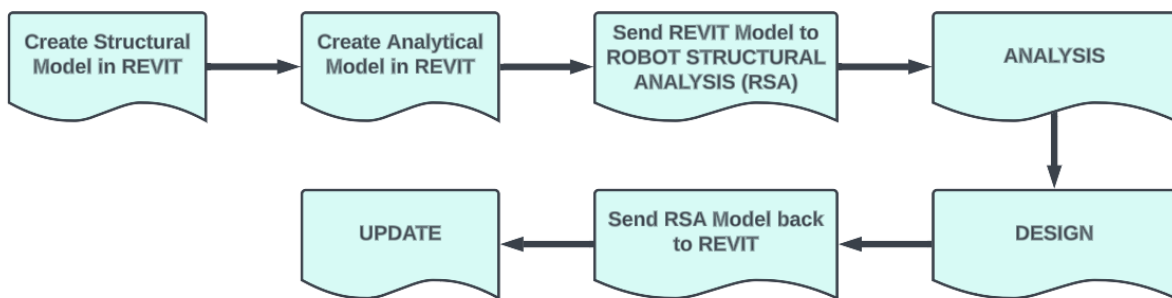
Figure 24: *Revit to Robot Structural Analysis Direct Link Workflow*
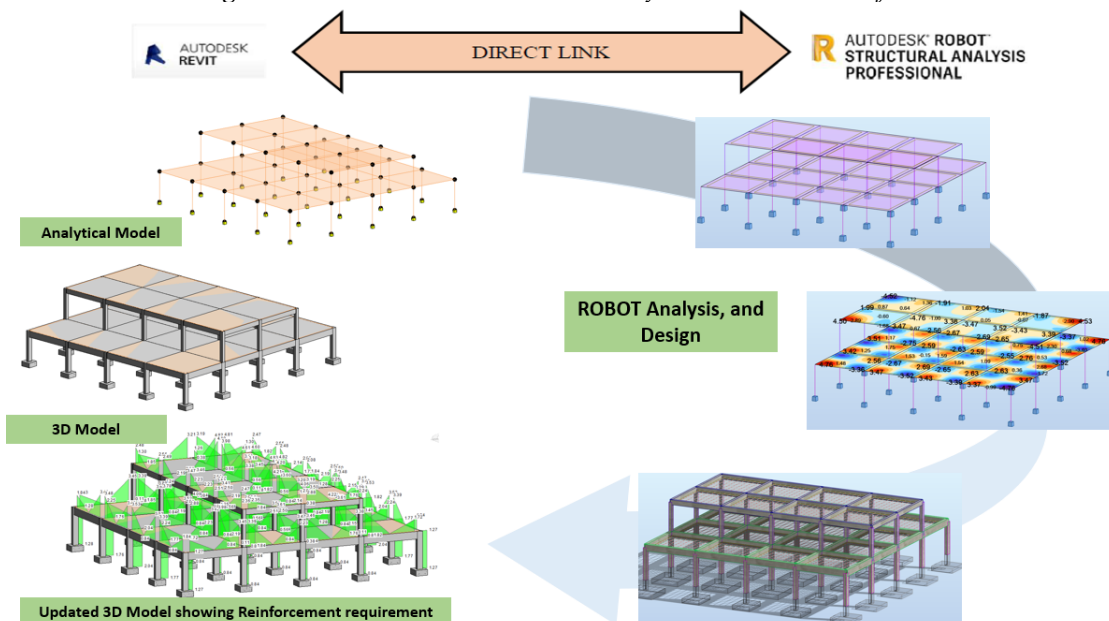
Figure 25: *Revit to Robot Structural Analysis (RSA) Interoperability Workflow*

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According to Autodesk (2015), Below outlines a recommended procedure for simultaneous structural documentation, design, and analysis:

- A CAD specialist develops a structural model derived from an existing architectural model or existing 2D architectural layouts.

- The structural designer refines material and profile specifications, and fine-tunes the analytical model proposed by Revit. Autodesk suggests utilizing the Content Generator Extension to aid in crafting appropriate material definitions and sections based on regional catalogues encompassing crucial structural properties for in-depth analysis and code validation.

- The designer establishes loads and load combinations suitable for analysis in Robot, along with preliminary or load assessment analysis facilitated by Revit Extensions. This data can also be integrated into design and code validation tools, such as the Composite Design Extension for composite steel framing.

- Subsequently, the designer transfers the Revit model to Robot Structural Analysis Professional. This leverages the software solutions' compatibility, utilizing the Revit analytical model and Robot software to conduct comprehensive structural analyses.

- Following the analysis outcomes, the engineer may reach decisions necessitating coordination with the designer (and potentially involving the architect as well). Within Robot, the engineer updates the analytical model with recommended modifications and informs the designer.

- Using Revit, the designer assesses the engineer's suggested adjustments to the analytical model. Through collaborative efforts with the engineer, the designer accepts or rejects the proposed alterations to the analytical model, prompting Revit to automatically adapt the physical model accordingly.

- This iterative teamwork between the designer and engineer continues as needed.

- Additionally, the designer may modify section dimensions and properties based on insights received from Robot Structural Analysis Professional or other code validation applications linked with Revit.

The Robot Structural Link in Revit is typically located within the software's interface where users can access various tools and features. In Revit, you can find the Robot Structural Link in the "Analyze" tab or menu as seen in Figure 29. This location may vary slightly depending on the version of Revit.
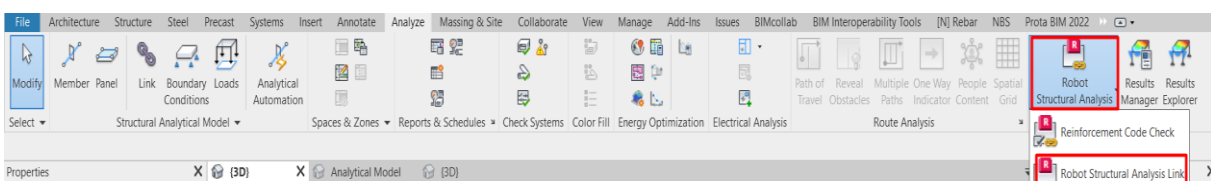
Figure 26: *Direct link RSA in analyze tab Revit highlighted in red*

In cases where Revit and RSA are installed on different computers, Revit users should consider selecting the "Use Autodesk Robot Structural Analysis RTD file" option. The RTD file is RSA's native file format, enabling engineers to conduct analyses in Robot while designers continue their work in Revit. Should this option not be accessible, the model can be saved in the .smxx file format. Although the transfer remains feasible, it necessitates more coordination between the two parties (Beirnaert & Lippens, 2018). This connection also allows Revit users to transmit their models to an intermediary file format called .smxx, and subsequently update the Revit model using the .smxx file. It's important to note that certain options, such as "Use plan views as backgrounds," "Reinforcement projects," and "Steel connections," are unavailable in this form of data transfer. Additionally, the outcomes of analyses cannot be conveyed using the .smxx file. This alternative proves beneficial in scenarios where Robot and Revit are installed on separate machines (Autodesk, 2015).

On the contrary, when both software tools are installed on the same computer, users need not concern themselves with the RTD option. Additional commands integrated into the user interface model seamlessly establish a connection between the programs. As a result, the model will be automatically transmitted from Revit to RSA, streamlining the process.

Baseed on the practical wrokflow for Revit to Robot Structural Analysis (RSA) direct link, the following were noted:

Import/Export of Structural Elements:

- Slabs, floors, beams, and columns in concrete can be seamlessly imported/exported between Revit and RSA.
- The preservation of complex geometries maintains the integrity of the design during the analysis phase.

Analytical Elements Exchange:

- Supports, boundary conditions, load cases, and load combinations are smoothly transferred between Revit and RSA.
- Consistency maintained between structural model in Revit and analytical requirements in RSA.

Export of Analysis Results to Revit:

- Deflections, moments, stresses, and shear forces obtained from RSA can be exported back into Revit.
- Architects gain insights for informed design decisions, promoting iterative optimization.

Reinforcement Data Transfer:

- Area of required and provided reinforcement is exportable through the direct link.

- Facilitates communication between design and analysis teams for code-compliant and structurally sound designs.

3.2.2   Autodesk Revit and SCIA Engineer

The collaboration between Autodesk Revit and SCIA Engineer in the field of structural engineering is empowered by a direct link, enhancing seamless data exchange and synchronization. This connection serves as a dynamic channel for the interchange of information between design and structural analysis.

There are various kinds of options, we can divide them into two categories - Open and Closed BIM. Open BIM utilizes the IFC format to share data broadly, while Closed BIM relies on exclusive connections with other software. Revit link serves as a clear instance of Closed BIM, enabling the transfer of 3D models between Revit and SCIA Engineer.
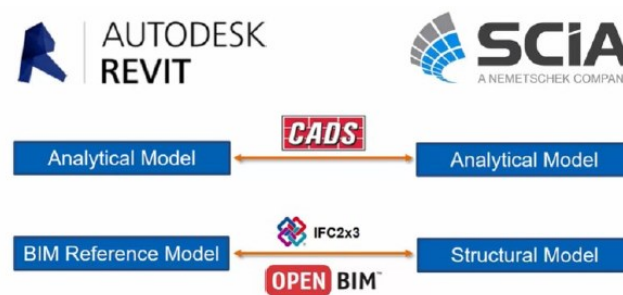
Figure 27: *SCIA Engineer Data Exchange Scenarios*

The data communication between Revit and SCIA Engineer is facilitated by the CADS Revit SCIA Engineer link. This dedicated tool ensures a two-way exchange of structural engineering data between these software applications, managing both the export and import configurations. The process involves sending a Revit structural model to SCIA Engineer via the direct link. After analysis and design activities are conducted within SCIA, the updated model is then transmitted back to Revit, completing the seamless cycle of information flow. This direct transfer enables simultaneous work between Revit and SCIA Engineer, facilitating real-time updates. Conversely, file export allows sharing with colleagues well-versed in the alternate application.

On the other hand, The IFC format, among several that SCIA Engineer accommodates, serves as a fundamental cornerstone for facilitating Open BIM. SCIA Engineer holds the distinction of being the inaugural structural analysis software to be certified for both importing and exporting IFC 2x3 formats. The software incorporates an exclusive BIM toolbox designed to enhance the efficiency of the Open BIM workflow for structural analysis. It is important to highlight that this process can be further streamlined with the aid of SCIA Autoconverter.

Workflow for Autodesk Revit and SCIA Engineer CADS Link

The Workflow for Autodesk Revit and SCIA Engineer CADS Link encompasses a systematic and collaborative process that harmonizes architectural design and structural analysis. This integrated approach leverages the CADS Link extension to facilitate seamless data exchange between Autodesk Revit and SCIA Engineer, optimizing the design and analysis phases of a construction project. The CADS Link acts as a conduit, ensuring that structural data harmoniously traverse between Autodesk Revit and SCIA Engineer.

According to Azinwie Zama (2022), The link offers extensive capabilities, encompassing:

- The ability to seamlessly import and export a wide range of structural elements, such as slabs, floors, walls, shells, beams, columns, and bracing, each crafted from diverse materials like steel, concrete, and timber. This also includes the intricate mapping of various geometries and construction styles.

- A comprehensive import/export function for analytical elements, including supports, hinges, and intricate load configurations, ensuring a holistic transfer of vital structural data.

- Empowering the export of analysis results back into Revit, encompassing essential metrics like deflections, stresses, and beam end reactions, facilitating a unified understanding of structural performance.

- A robust Change Management feature that diligently tracks and accentuates alterations, providing engineers with a clear visual representation of edits originating from the alternate software, thereby enhancing collaboration and clarity.

- The seamless export of reinforcement details, reinforcing the connection between the two realms and streamlining the integration of detailed structural elements.
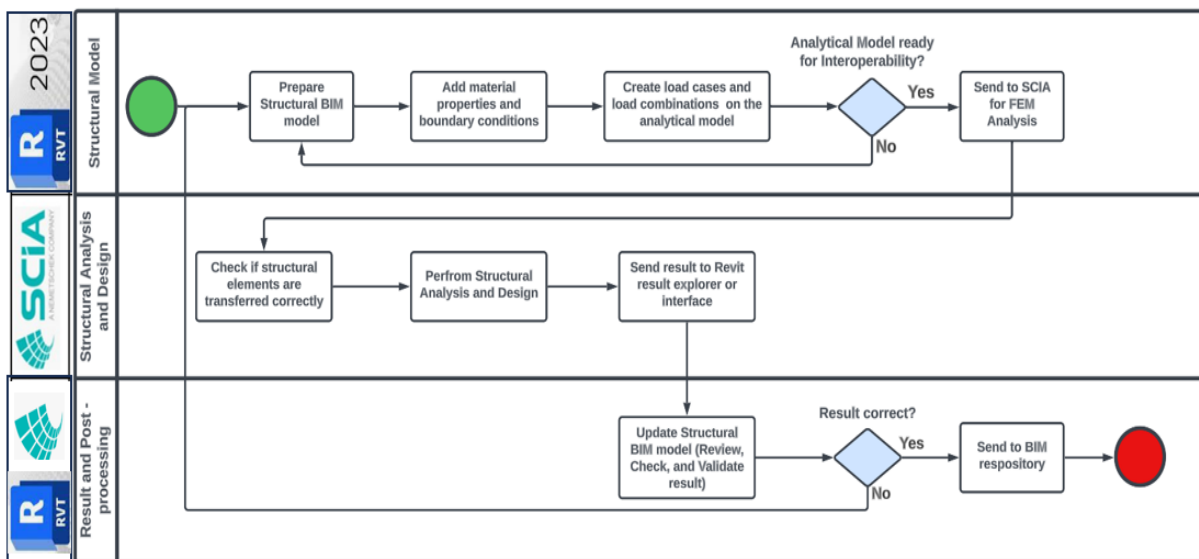
Figure 28: *Revit to SCIA Engineer Workflow Diagram for the Direct Link Exchange Scenerio*

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Once the BIM model is prepared, a simple click on the add-on link (indicated by a green marker) initiates the unveiling of a ribbon brimming with a collection of commands (refer to Figure 32 for visual reference). Below, a concise overview of these commands is presented:
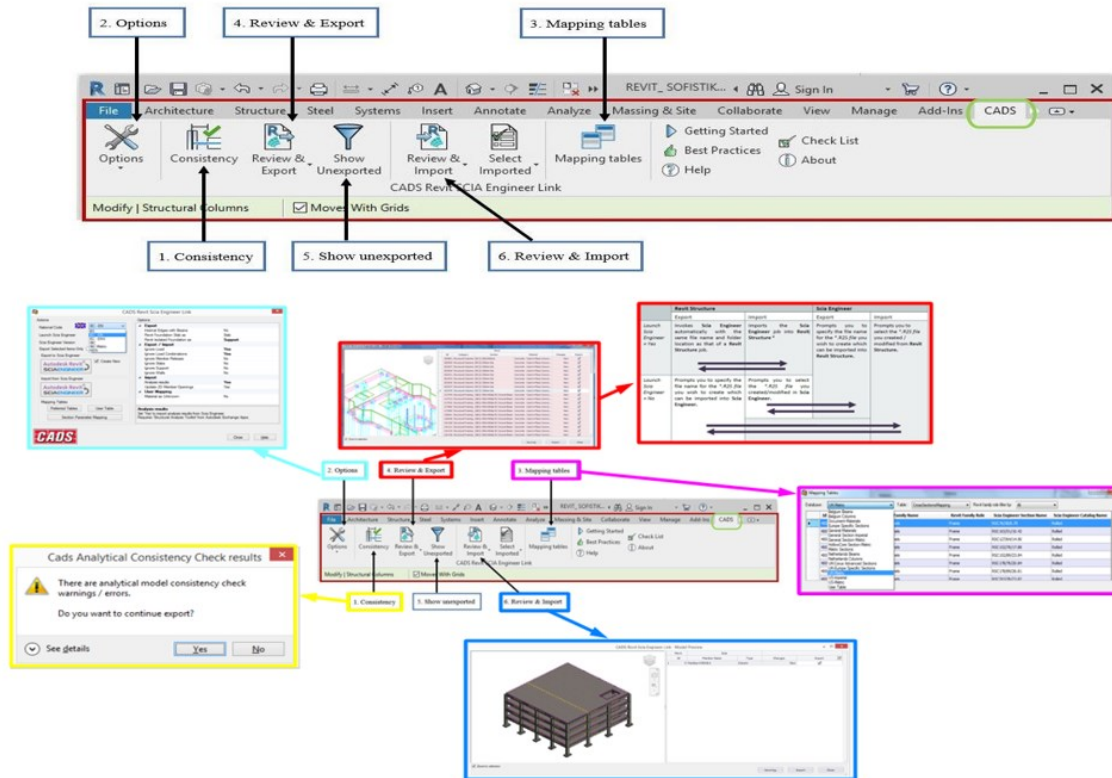
Figure 29: *Revit- SCIA Engineer direct link user interface and command panel in Autodesk Revit*

1. **Consistency:** This command undertakes a thorough examination of model coherence, a prerequisite before delving into calculations. It scans for potential discrepancies encompassing mapping failures, overlaps, support issues, and misalignments of structural elements and properties as indicated in yellow.

2. **Options:** Opting for this command navigates you to a dialogue box showcased in Figure 32. The key selections come into play, including the designation of a national code, the preferred export mode (either direct or via file exchange), and the specific SCIA Engineer version. This versatile dialogue box also governs the intricacies of both export and import functionalities.

3. **Mapping Tables:** Recognizing that Revit and SCIA Engineer feature distinct cross-sections and material properties, the mapping table within the Revit-SCIA Engineer interface becomes an invaluable resource. This table empowers users to align user-defined parameters or properties between the two programs, ensuring a seamless transition during model export and import maneuvers.

4. **Review & Export:** This command extends the opportunity for users to meticulously scrutinize the model before committing to the export process.

5. **Show unexported (Spotlight on Unexported Elements):** After export process, certain structural components might remain unexported due to geometric incongruities within the Revit model. The "Show unexported" command acts as a spotlight, revealing these elements that necessitate attention.

6. **Review & Import:** Similar to its export counterpart, the "Review & Import" command empowers users to conduct a thorough assessment of the model when importing model from SCIA Engineer to Revit before proceeding with the import phase.
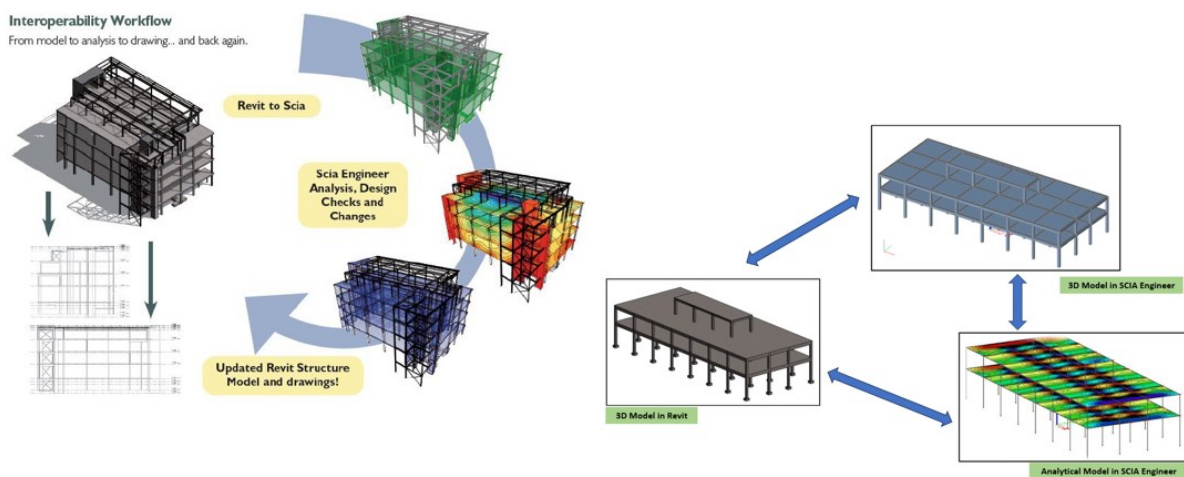
Figure 30: *3D representation of Model in Revit through to the Analytical Model in SCIA Engineer*

Figure 33 shows the 3D implementation of the workflow highlighted in Figure 31 (Revit to SCIA Engineer Workflow Diagram for the Direct Link Exchange Scenerio)

Baseed on practical wrokflow from Revit to SCIA using CADS link, the following were noted:

1. All elements of the model, such as beams, columns, and slabs, were effectively exchanged between the two software platforms without any encountered complications. To ensure a smooth transfer into SCIA Engineer, it is advisable to preselect the appropriate building Code or standard, streamlining the model's development.

2. The process of transferring boundary conditions between Revit and SCIA Engineer was executed seamlessly, with no identified issues in either direction. The exchange of boundary conditions proved to be a robust and functional scenario. This successful interaction underscores the efficacy of the transfer mechanism.

3. Transferring loads to SCIA Engineer presented certain challenges due to the utilization of an externally sourced CAD program for the bi-directional exchange, which is based on a distinct software platform. Exporting loads and load cases encountered complications due to this software disparity. Despite this, the transfer of load combinations from Revit to SCIA Engineer was notably successful, showcasing a proficient interchange between the two platforms.

4. The libraries within Revit and SCIA Engineer vary in their naming conventions to some extent. To address this disparity, the CADS Revit SCIA Engineer link incorporates a material mapping table, offering a solution to this challenge. Consequently, for the effective transfer of my case study model to SCIA Engineer, a manual process was required to align Revit's material families with their corresponding materials/sections in SCIA Engineer.

3.3   BIM Interoperability and Software Utilization: Insights on Case Studies

This thesis strategically adopts two primary methodologies to address its underlying objectives. Firstly, it entails an extensive evaluation of Building Information Modelling (BIM) and Finite Element Modelling (FEM) tools (Revit, SCIA, Robot Structural Analysis) that hold relevance within the domain of structural engineering, with a specific focus on their interoperability capabilities catering to both architects and engineers. Secondly, it embarks on the deveolpment of a practical workflow for structural BIM (as stated in the objective), exemplified through an experimental application of BIM interoperability within the case study. This practical demonstration is executed utilizing a designated early-stage performance tool (Autodesk Revit), known for its integration with other BIM tools (FEM software – ProtaStructure) using different exchange formats, employed by structural design teams.

The practical application is intended to unearth potential challenges in implementing a structural BIM interoperability workflow from BIM to FEM softwares using Bi-directional link, comparing and evaluting discrepancies observed against the IFC file exchange format. Among the notable hurdles encountered during the practical case study was the absence of an established and validated methodology for data interoperability and design implementation, as well as a standardized workflow governing the holistic modelling and analysis processes

Figure 34 shows the holistic approach for both case studies (**Case Study 1** - BIM to FEM using Bi-directional link, **Case Study 2** - BIM to FEM using IFC format). This process also consist of two milestones which are:

Trip 1: Exporting the Structural Model from Autodesk Revit to ProtaStructure using both Bi-directional Link (ProtaBIM) and IFC 2X3, while Comparing the model exported to the initial Revit Structural Model and identifing interoperability pros and cons after export.

Trip 2: Importing the Structural Model from ProtaStructure to Autodesk Revit using both Bi-directional Link (ProtaBIM) and IFC 2X3, while Comparing the model imported to the Protastructure designed Structural Model and identifing interoperability pros and cons after import.
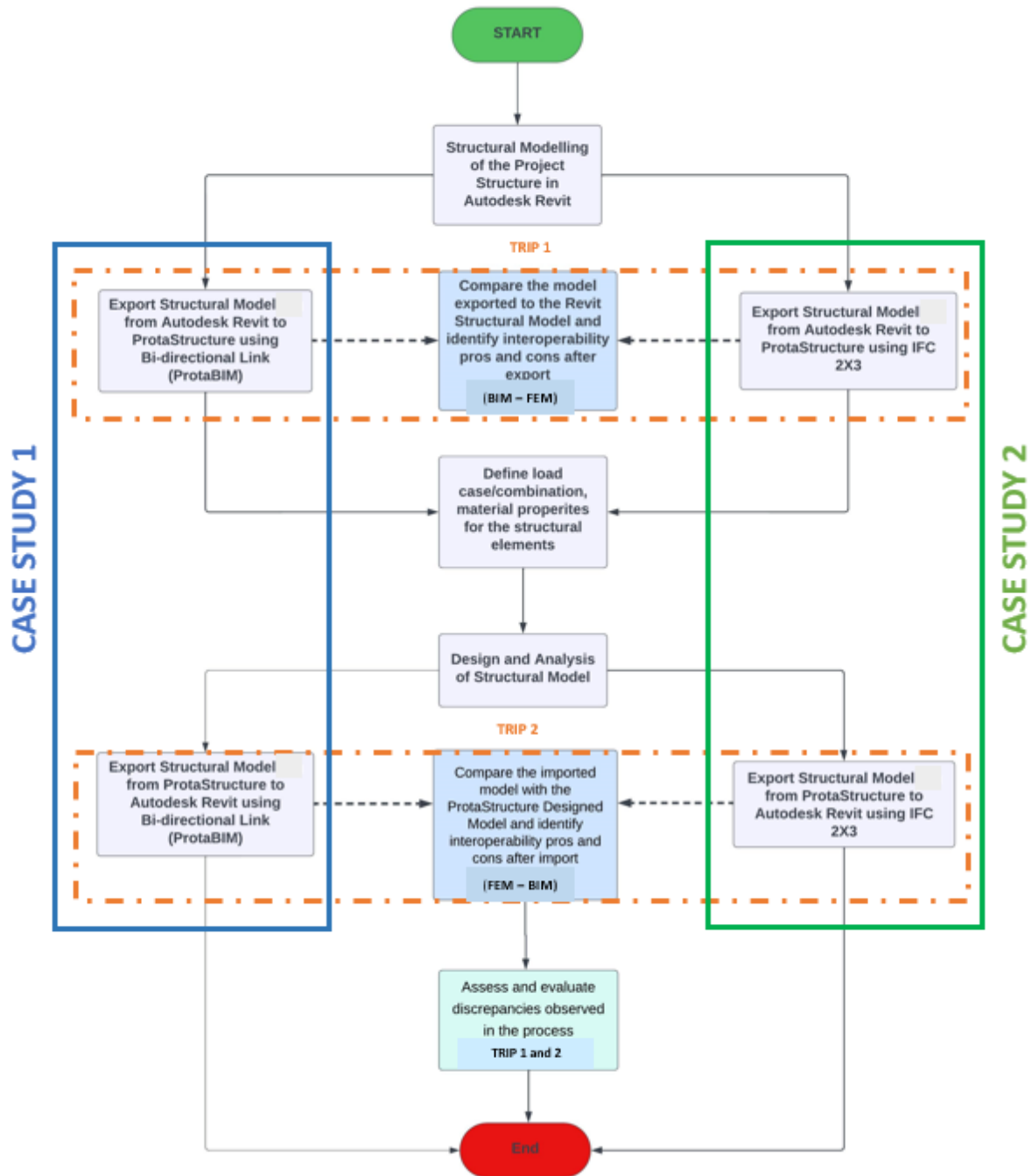
Figure 31: *Holistic BIM interoperability workflow for the Case Studies*

3.4   Autodesk Revit

Autodesk Revit plays a vital role in the context of Building Information Modelling (BIM), serving architects, engineers, and construction experts as a robust tool for designing and managing complex building models. Through its parametric modelling capabilities, Revit not only enables the creation of detailed 3D building representations but also ensures that changes made are consistently applied throughout the model, maintaining accuracy and uniformity. The concept of "families" within Revit empowers users to design custom components that mirrors real-world building elements, enhancing the fidelity of the virtual construction.

The significance of Revit's structural modelling prowess is magnified by its capacity to comprehensively address the complexities of structural design. Its robust toolkit empowers engineers to model a building's structural framework, incorporating beams, columns, foundations, and intricate detailing. The software's parametric capabilities ensure that modifications to one element automatically propagate throughout the model, maintaining accuracy and consistency across the structural design.

Among the array of supported formats, Revit ensures compatibility with well-established industry standards such as IFC and DWG, fostering seamless communication between different software ecosystems. This connectivity extends to formats like DWF/DWFx, gbXML, HTML, DXF, DGN, SAT, ADSK, and FBX, enabling effective information sharing and coordination among project stakeholders.

It also excels in constructing and seamlessly connecting structural models through both direct and indirect links, making it particularly well-suited for robust 3D structural design. The software's capabilities extend beyond design, encompassing formal structural analysis. This analytical prowess spans material properties, load simulations, combinations of loads, and defining boundary conditions across the myriad elements of the model. Such capabilities empower designers to delve into the structural intricacies and optimize their creations.

3.5   ProtaStructure

Protastructure stands as a fundamental cornerstone in modern structural engineering, seamlessly blending innovation, and efficiency to shape the methods by which we conceive and construct buildings. This comprehensive software solution transcends the limitations of traditional design, empowering engineers, architects, and construction professionals with a suite of tools that profoundly transform the entire building lifecycle. It embodies an integrated approach that spans from the initial concept to the final realization, harmonizing creative vision with technical precision. Its user-friendly platform facilitates the creation of intricate structural models, enabling professionals to bring their architectural aspirations to life while ensuring the utmost standards of safety and functionality.

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The heart of Protastructure resides in its robust structural analysis capabilities. Engineers have the capability to simulate a diverse array of scenarios, assessing how a building reacts under various loads and conditions. This empowers them to refine their designs meticulously, guaranteeing the preservation of structural integrity and adherence to regulatory standards. Its influence goes beyond analysis, seamlessly transitioning into the domain of design. The software generates optimized designs based on analysis outcomes, translating abstract calculations into tangible, efficient, and visually striking structures. Detailed drawings, reports, and specifications are effortlessly produced, streamlining the journey from conception to construction.

A defining characteristic of Protastructure is its seamless integration with Building Information Modelling (BIM), a digital framework that unifies project data and promotes collaborative communication. Through this integration, Protastructure becomes an essential participant in the BIM environment, contributing its structural expertise to the collective pool of knowledge. The outcome is a harmonious convergence of architectural vision, structural analysis, and collaborative ingenuity.
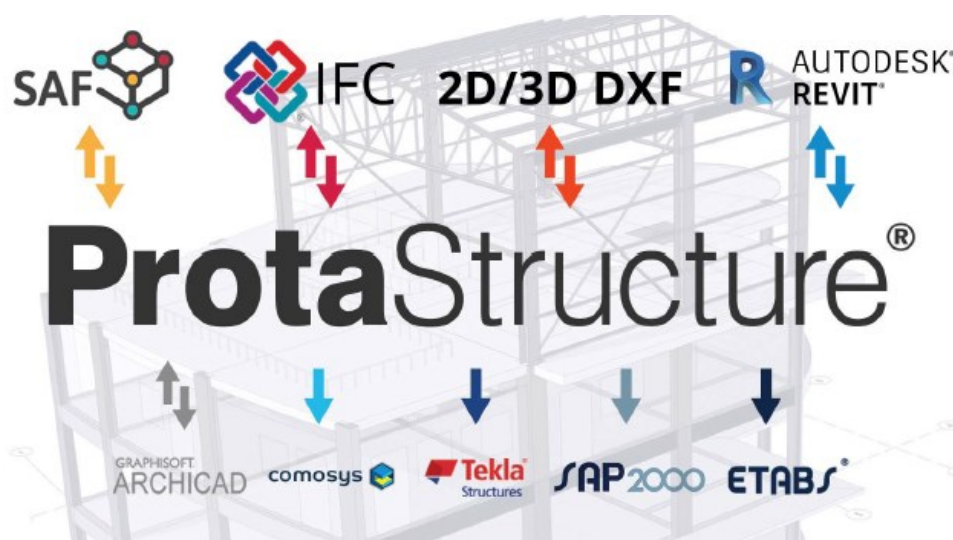
Figure 32: *ProtaStructure Interoperability with other BIM Software using different file formats* (Prota, 2022)

Due to this integration, Protastructure not only elevates the design and construction stages but also extends its impact to the domain of facility management. The lasting digital footprints it produces persist beyond the completion of construction, evolving into a priceless resource throughout the ongoing lifecycle of the building.

According to Prota (2022), the following are some advantages of using Protastructure software:

1. **Support for BIM Industry Standards**

   ProtaStructure facilitates the interchange of models through the import and export of various file formats such as IFC, 2D/3D DXF, and SAF. This feature enables seamless collaboration between ProtaStructure and prominent BIM platforms like Autodesk Revit, ArchiCAD, and

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AllPlan, allowing professionals to easily share their work across different software environments.

2. **Autodesk Revit Bi-directional Integration**

Prota Software has crafted specialized integration for Autodesk Revit, enabling a direct and smooth coordination of models. This integration offers features for seamless roundtrip synchronization of changes in real-time. Users can navigate revisions with color-coded visual aids and interactive change logs. Additionally, the newly introduced family mapping functionality provides a customized experience aligned with specific BIM workflows and standards.
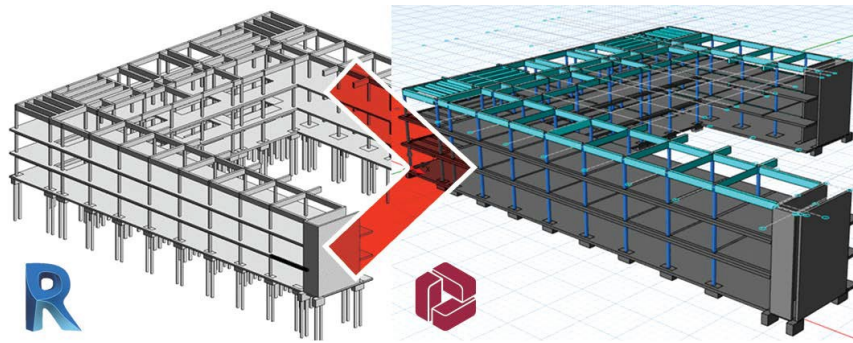
Figure 33: *Bi-directional Interoperability with Autodesk Revit* (Prota, 2022)

3. **Analysis Model Collaboration**

Acknowledging the variety of tools employed by engineering offices for analysis and design tasks, it is also common for firms and regulatory bodies to mandate structural engineers to verify and validate analysis outcomes against established platforms. ProtaStructure provides a seamless solution through accessible intelligent model links to OpenSees, ETABS™, SAP2000™, LUSAS™, SAF integration, and other compatible options, making it effortless to achieve this verification process.

4. **Output Reports and Drawings to Industry Standard Formats**

- Generates and shares personalized, visually compelling calculation reports that can be exported as Microsoft Office documents or PDF.

- Comprehensive drawings adhere to the widely recognized DXF and DWG formats, aligning with industry formats. Every drawing within ProtaStructure adheres to top-notch drafting standards and offers complete customization in terms of layers, styles, and scaling.

- Tailored templates, crafted to match your company's drafting preferences, can be readily set up and reused across projects. Furthermore, a variety of formats including 3D DXF, STL, and image files, are readily accessible.

3.5.1   ProtaBIM

ProtaBIM represents a pioneering concept in the domain of collaborative construction, bringing to the forefront a seamless integration between ProtaStructure and Autodesk Revit. At its core, ProtaBIM serves as a powerful bridge, connecting the analytical precision of ProtaStructure with the collaborative environment of Autodesk Revit. This integration enables architects, engineers, and construction professionals to work harmoniously within a shared digital ecosystem, thereby redefining the collaborative construction landscape.

Figure 34: *BIM Interoperability between Autodesk Revit and Protastructure using ProtaBIM*

By facilitating bi-directional communication between ProtaStructure and Autodesk Revit, ProtaBIM establishes a dynamic and fluid interchange of data. This real-time link empowers design modifications in one platform to instantly translate into the other, eliminating manual data transfers and enhancing project coordination. This integration is not just a technical feat; it embodies a transformative approach to design and analysis, where stakeholders can seamlessly toggle between tasks without compromising accuracy or efficiency.

ProtaBIM's true power lies in its ability to provide architects and engineers with immediate access to structural analysis insights within the Autodesk Revit environment. This real-time feedback loop informs design decisions, enabling professionals to iterate and refine their creations while ensuring structural integrity. This iterative process, grounded in analytical precision, empowers the creation of buildings that marry aesthetic vision with sound engineering principles.

3.5.2   ProtaDetails

ProtaDetails emerges as an advanced and comprehensive software solution for structural drawings and detailing, streamlining the creation and organization of concrete detail drawings with unparalleled efficiency. By automating the process, it enables the extraction and arrangement of structural design, draft, and detail elements directly from ProtaStructure onto designated company drawing sheets, translating into significant time savings in drafting.

Figure 35: *Production of Shop Drawings through ProtaDetails*

This innovative tool offers specialized CAD drawing, editing, and detailing functionalities tailored to the field of structural engineering, allowing for precise customization and refinement of drawing production. The software's capabilities extend further, facilitating well-informed design decisions through comprehensive quantities extraction, thereby enabling value engineering and enhancing design services provided to clients. It also ensures seamless adaptation to changes by effortlessly incorporating project design updates from ProtaStructure, a robust structural analysis and design software. This integration enhances the efficiency of handling modifications and underscores the software's role as a cohesive and indispensable component in the construction and engineering workflow.

ProtaDetails automates the creation of reinforced concrete (RC) detail drawings, facilitates efficient sheet management, empowers manual drafting, provides steadfast DWG support, and boasts an ever-expanding engineering macro library. This transformative software emerges as a beacon of efficiency, rendering the traditional drafting process more efficient, accurate, and time effective. By seamlessly extracting and meticulously detailing all designed elements directly from ProtaStructure, it mitigates the need for laborious manual drafting, potentially saving thousands of man hours in the architectural and engineering domains.

3.6   BIM Interoperability Workflow Using Bi-directional Link and IFC: Autodesk Revit and ProtaStructure

In order to enhance BIM interoperability within BIM-focused structural design firms, a comprehensive analysis has been undertaken to facilitate seamless collaboration between architectural and structural engineering domains. This involves a meticulous exploration of FEM/FEA and BIM software, specifically Protastructure and Autodesk Revit, alongside the bi-directional plug-in ProtaBIM and IFC. The ultimate goal is to refine and optimize the BIM-driven workflow for structural modelling, analysis, and design within a structural design office. The results are anticipated to yield improved project outcomes through enhanced communication and synchronization between disciplines.

Accurate export and import of the structural model across software platforms via ProtaBIM and IFC is of paramount importance. The aim is to evaluate potential outcomes by initiating structural modelling in Autodesk Revit and culminating in analysis and design using Protastructure through the established link, facilitating smooth return of the finalized model. Moreover, this approach serves to uncover best practices for seamless transfer of the designed structural model among the design team, eradicating the necessity for any party to redo modelling when utilizing the software tools mentioned above.

Figure 39 and 40 shows the workflow developed for this research for seamless interoperability of a structural model for analysis and design between Autodesk Revit (CAD software) and Protastructure (FEM software).
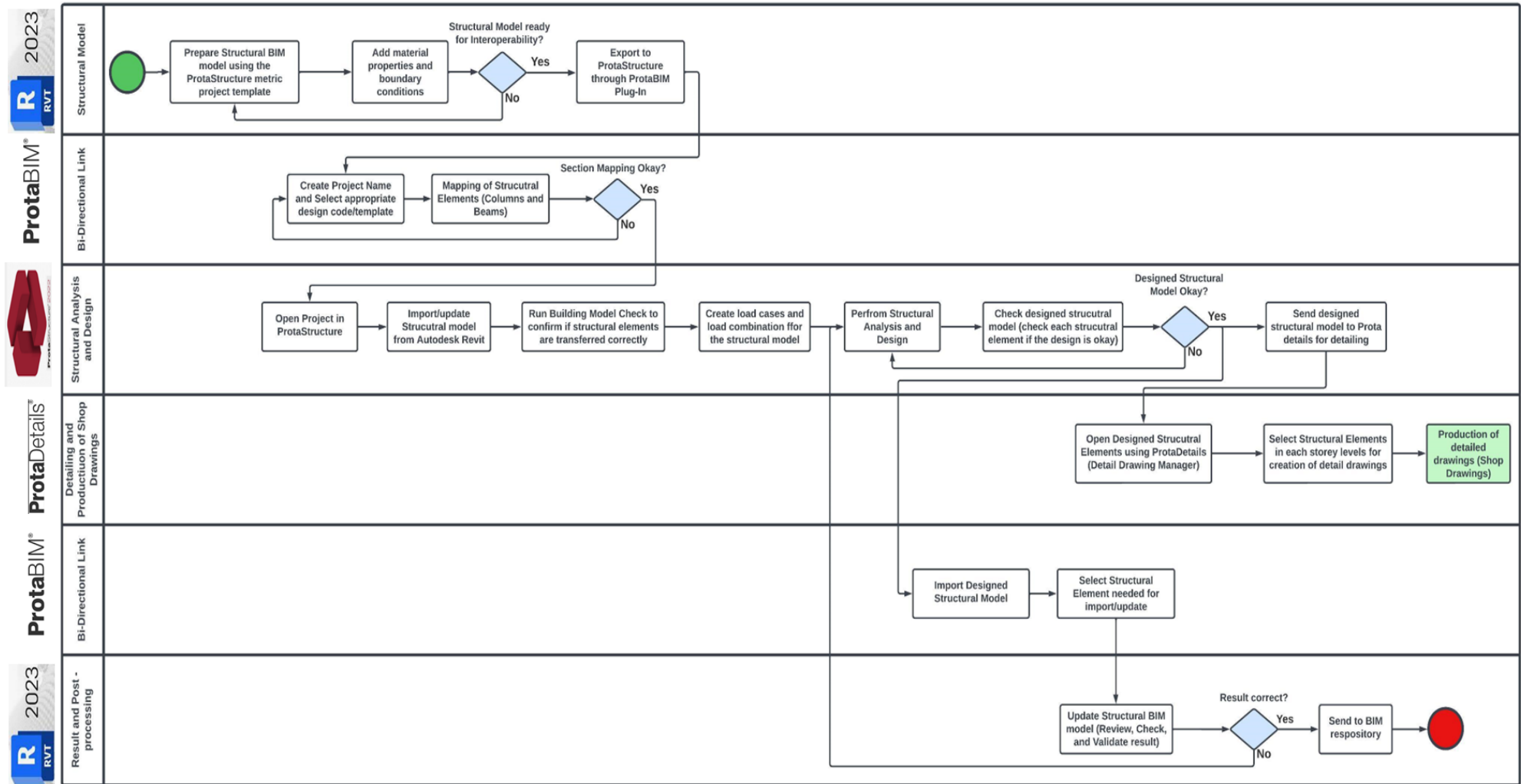
Figure 36: *BIM Interoperability Workflow between Autodesk Revit and ProtaStructure Using ProtaBIM (Bi-directional link)*

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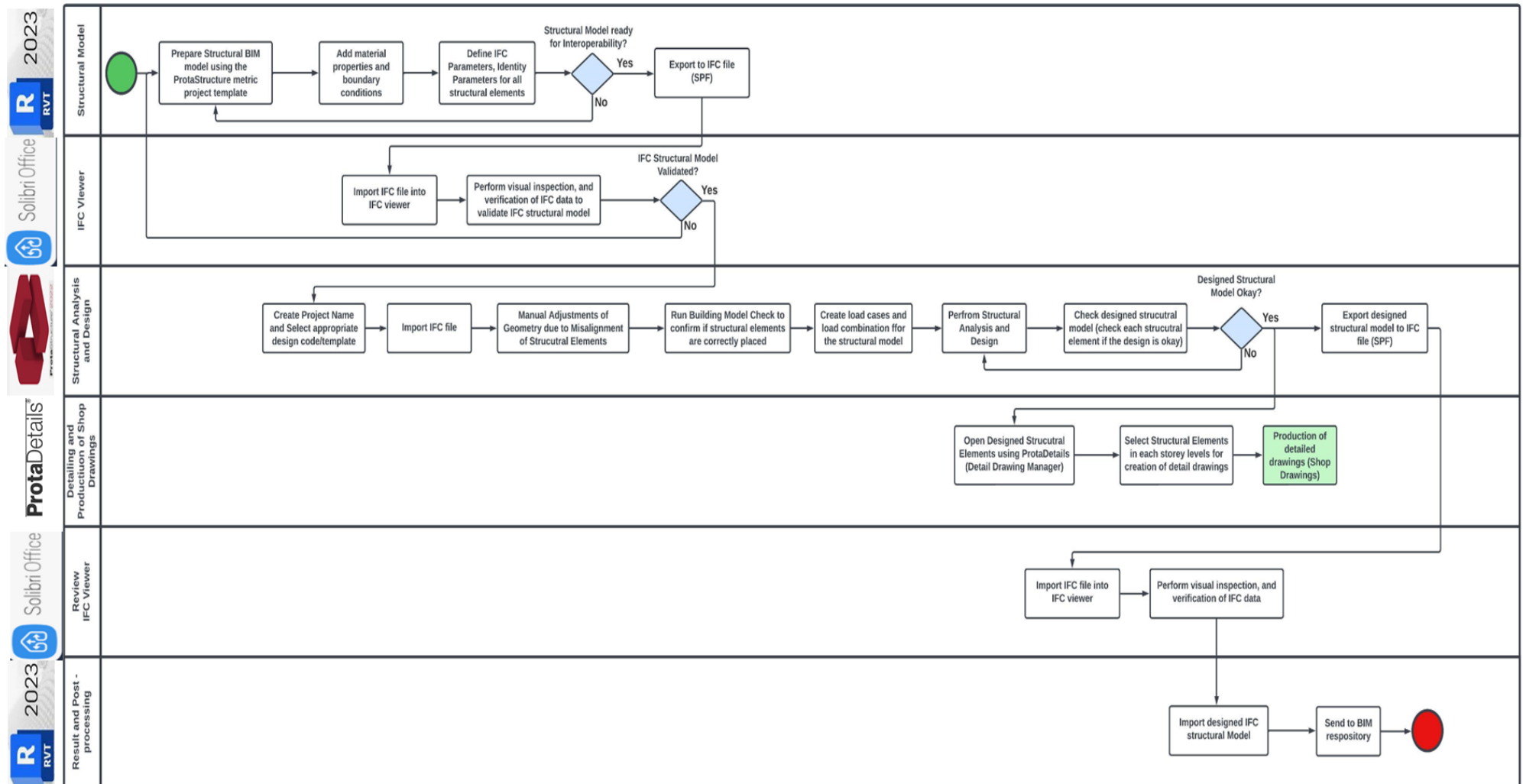**Figure 37**: *BIM Interoperability Workflow between Autodesk Revit and ProtaStructure Using IFC*

4   CASE STUDIES

4.1   Introduction

In this chapter, two case studies are introduced, which played a vital role in shaping the conclusions of this thesis. The first case study examines interoperability between CAD and FEM through a bi-directional link, specifically involving data exchange scenarios between Revit and Protastructure. The focus lies on evaluating the seamless transfer of data between these two platforms. The second case study, on the other hand, explores interoperability between Revit and Protastructure, employing the IFC format for data exchange scenarios between the two platforms.

4.1.1   Overview of Case Study Model

The case study model chosen for this thesis focuses on a mixed-use development (commercial building). This building typology combines various functions, integrating commercial spaces such as retail stores, offices, restaurants, and other services within a single structure.

The structural model acquired presents a comprehensive and detailed depiction of the building's design and analysis. It was achieved through a seamless exchange of structural information between Computer-Aided Design (CAD) and Finite Element Modelling (FEM) platforms, playing a crucial role in streamlining the design and analysis process. The initial phase involved creating a meticulous CAD model that encompassed all architectural elements, geometries, and material properties. This CAD model served as the foundation for the subsequent structural analysis, ensuring precise representation of the building's various components.

4.1.2   Case Study Description and Parameters

Geometry

The structural model represents a three-story reinforced concrete frame building. It spans **68.7 m** in the longitudinal direction and **16.2 m** in the transverse direction, with a total building height of **14.4 m**. The cross-sectional dimensions of the structural members are as follows: on the first, second, and third floors, the beams have a cross-section of **230×600 mm**, while the columns have a mix of cross-sections, including **230x230 mm**, **300x230 mm**, **300x300 mm**, **450x300 mm**, **500x300 mm**, and **500×500 mm**. In the roof floor, the predominant cross-section for beams is **230×450 mm**.

Figures 41 to 46 show the architectural representation of the building, the structural model developed for the thesis case studies, the plan view (first and third floors), elevation views, respectively.

Figure 38: *Architectural representation of the project utilized in the case studies*
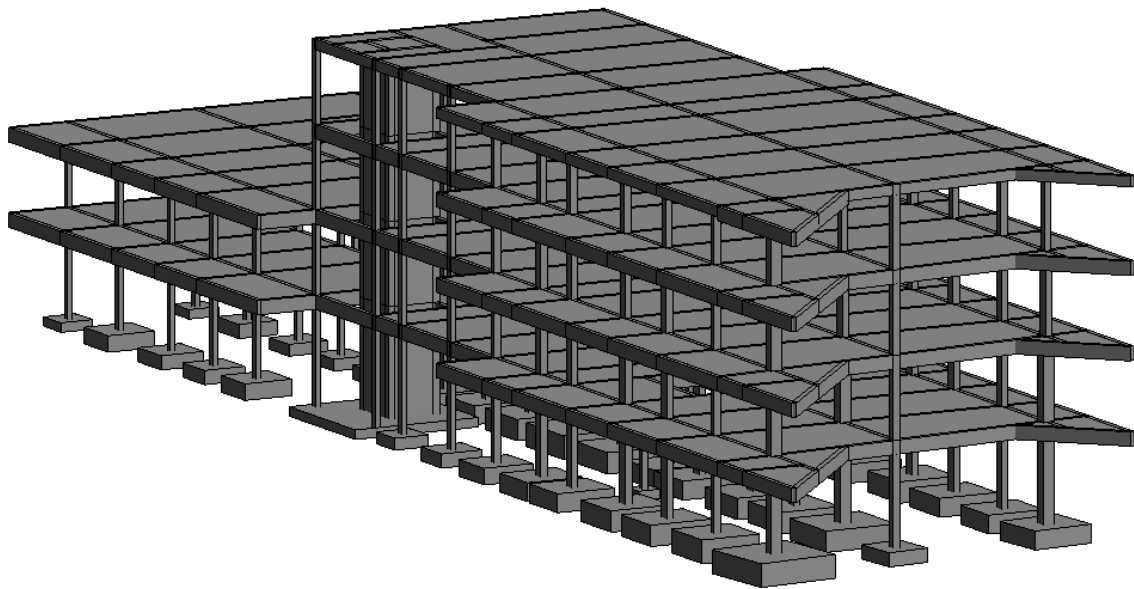
Figure 39: *Structural Model as designed in this thesis.*
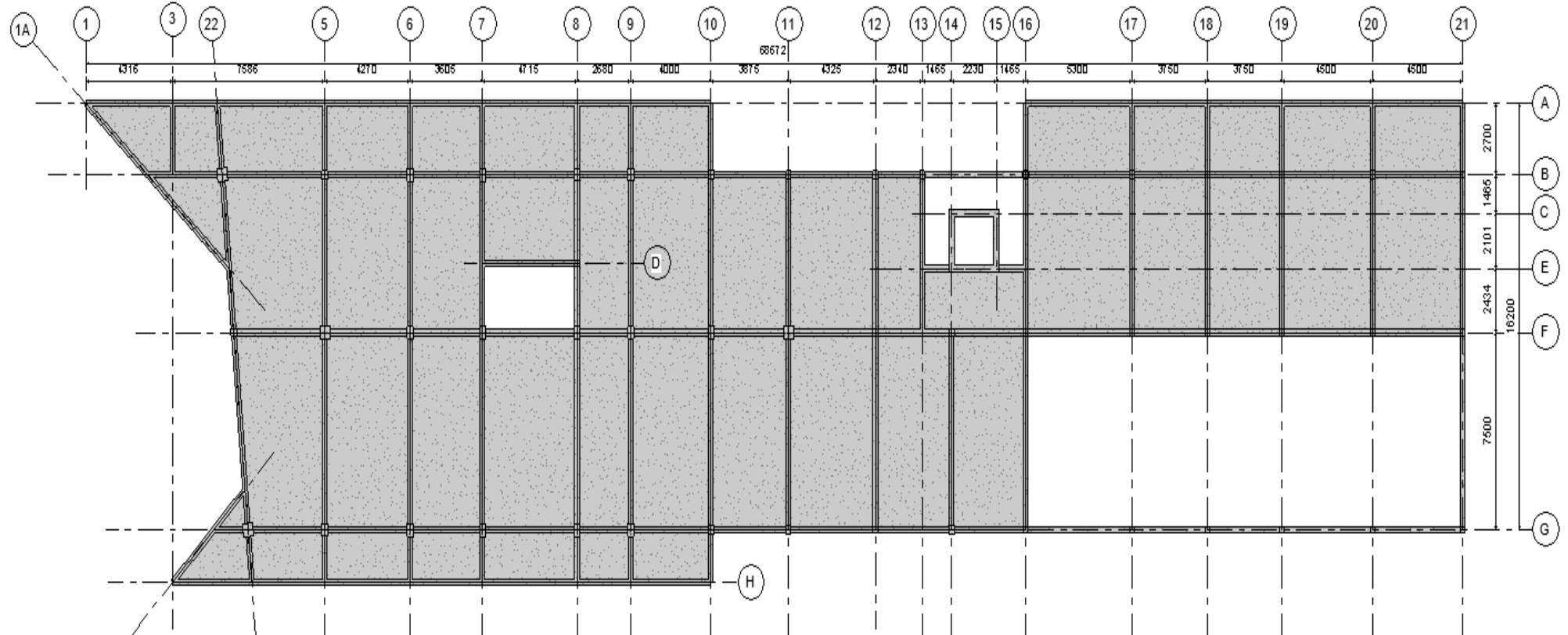
Figure 40: *First-floor plan view of the model*
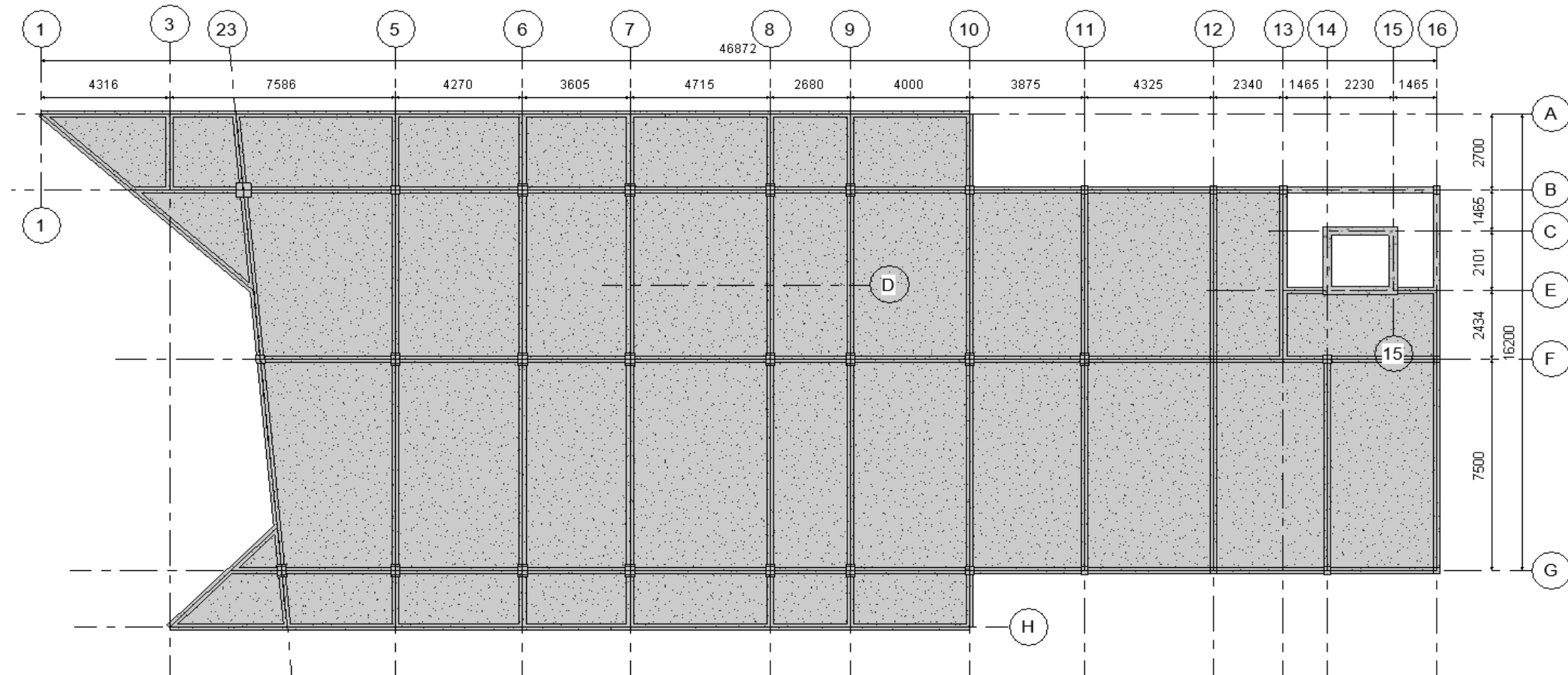
Figure 41: *Third-floor plan view of the mode*

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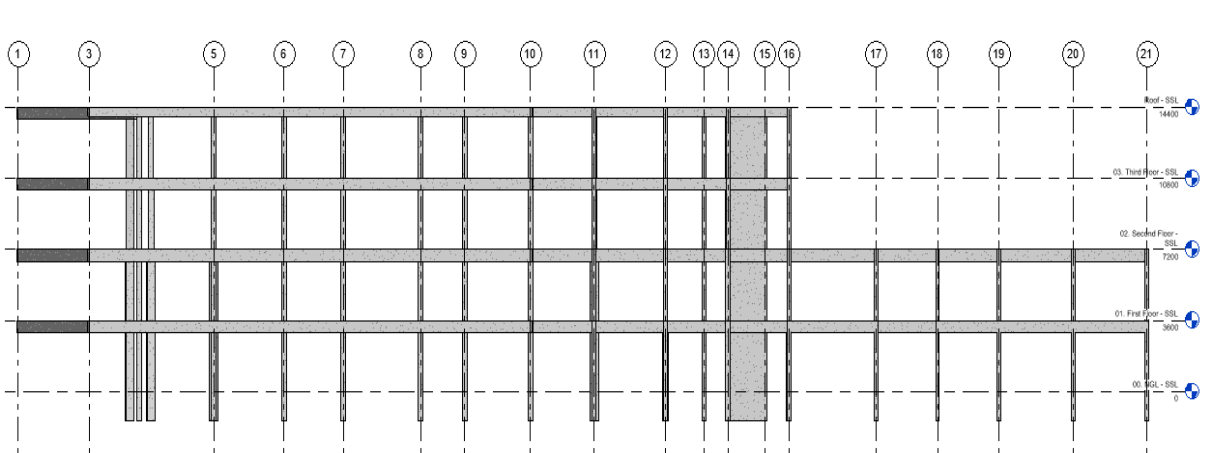
Figure 42: *Side Elevation of the model*
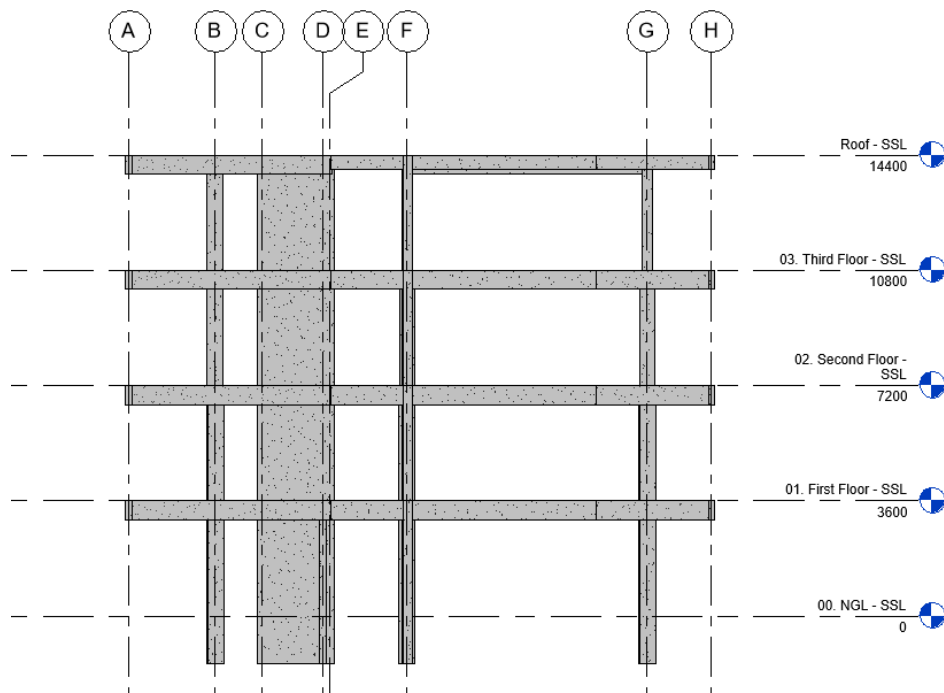
Figure 43: *Front Elevation of the model*

Material Properties

Concrete C25/30

According to EC2, the following material parameters are considered:

- Compressive strength f_{ck} = 25 MPa

- Tensile strength f_{ctm} = 2.5 MPa

- Modulus of Elasticity E_{c0m} = 31 GPa

- Unit Weight (reinforced concrete)   = 24 kN/m³

- Partial safety factor γ_c = 1.50

- Poisson's ratio ν = 0.20

- Design strength f_{cd} = 16.67 MPa = 1.67 kN/cm²

Reinforcing steel

Steel grade S 410 in accordance with EC3 is chosen for all reinforcing steel.

- Yield strength f_{yk} = 410 MPa

- Partial safety factor γ_c = 1.15

- Modulus of elasticity E   =210 GPa

Load Cases

Load cases considered in the study are summarized in Table 3.

Floor	Dead Load (kN/m²)		Live Loads (kN/m²)	Wind load (windward) (kN/m²)
	Self. wt.	Perm. load		
First Floor	4.2	3	3	0.75
Second Floor	4.2	3	3	0.75
Third floor	4.2	3	3	0.75
Roof floor	3.6	2	1	0.75

Table 3: *Summarized Load cases considered in the case study*

Dead load represents the self-weight of the structure and permanent elements like walls, columns, and floors. In Eurocode, dead load is considered as a uniformly distributed load on the structure's elements.

Live load includes transient and movable loads such as occupants, furniture, and equipment. The magnitude of live load can vary based on the intended use and occupancy of the structure.

Wind load represents the lateral force exerted by wind on the structure. The value of wind load depends on factors like the building's height, shape, exposure, and local wind speed.

Loads Combinations

According to EN 1990 (2002), load cases are combined to analyze and design structures effectively. Common load combinations include:

- DL + LL: Considering dead load and live load together for maximum impact.
- DL + WL: Accounting for the combined effect of dead load and wind load.

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- DL + LL + WL: Including dead load, live load, and wind load simultaneously to simulate real-world conditions.

The design combination and partial safety factors were all considered based on equation 6.10 as highlighted in the figure below

Figure 44: *Design values of actions in Table A1.2(B)* (EN 1990, 2002)

Figure 45: *Combination of actions equations in Figure 47*

Load combinations in structural engineering involve considering different scenarios of applied loads to ensure that the structure can safely withstand a wide range of conditions. Eurocode provides guidelines for load combinations to design structures effectively.

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Load Combination Editor

P-Delta Analysis

☐ Apply P-Delta Analysis

Approximate slenderness checks using moment magnification method will not be applied when P-Delta analysis is performed.

Totals

Number of Vertical Load Cases =	4
Number of Lateral Load Cases =	6
Number of Thermal Loading Cases =	0
Number of Stage Construction Load =	0

No	Combination	LL Red	R/C	Steel	G	Q	Qp1	Qp2	NGx	NQx	NGy	NQy	Wx	Wy
1	G+Q	✓	✓	✓	1.35	1.50	0	0	0	0	0	0	0	0
2	G+Qp1	✓	✓	✓	1.35	0	1.50	0	0	0	0	0	0	0
3	G+Qp2	✓	✓	✓	1.35	0	0	1.50	0	0	0	0	0	0
4	G+Q+Wx+Nx	✓	✓	✓	1.35	1.50	0	0	1.00	1.00	0	0	1.125	0
5	G+Wx+Nx+Q	✓	✓	✓	1.35	1.05	0	0	1.00	1.00	0	0	1.50	0
6	G+Wx+Nx	✓	✓	✓	1.10	0	0	0	1.00	0	0	0	1.50	0
7	G+Q-Wx-Nx	✓	✓	✓	1.35	1.50	0	0	-1.00	-1.00	0	0	-1.125	0
8	G-Wx-Nx+Q	✓	✓	✓	1.35	1.05	0	0	-1.00	-1.00	0	0	-1.50	0
9	G-Wx-Nx	✓	✓	✓	1.10	0	0	0	-1.00	0	0	0	-1.50	0
10	G+Q+Wy+Ny	✓	✓	✓	1.35	1.50	0	0	0	0	1.00	1.00	0	1.125
11	G+Wy+Ny+Q	✓	✓	✓	1.35	1.05	0	0	0	0	1.00	1.00	0	1.50
12	G+Wy+Ny	✓	✓	✓	1.10	0	0	0	0	0	1.00	0	0	1.50
13	G+Q-Wy-Ny	✓	✓	✓	1.35	1.50	0	0	0	0	-1.00	-1.00	0	-1.125
14	G-Wy-Ny+Q	✓	✓	✓	1.35	1.05	0	0	0	0	-1.00	-1.00	0	-1.50
15	G-Wy-Ny	✓	✓	✓	1.10	0	0	0	0	0	-1.00	0	0	-1.50

Figure 46: *Load combination of dead, live, and wind loads as defined in Protastructure*

4.2   Case Study 1 – S-BIM Model Transfer Between Revit and ProtaStructure via ProtaBIM

Case study 1 focus on the model and data interoperability using bi-directional link. Autodesk Revit represent BIM authoring software used for S-BIM modelling. The interconnected finite element method (FEM) software - ProtaStructure collaborate in conjunction to conduct independent structural analysis and design on the S-BIM model, facilitated by a bi-directional communication link – ProtaBIM, which acts as the conduit for seamless S-BIM model exchange. However, when using the ProtaStructure software, ProtaDetails is primarily employed by structural engineers to generate detailed plans and shop drawings subsequent to the completion of, structural analysis, and design phases. Figure 39 provides a detailed workflow for this exchange scenerio.
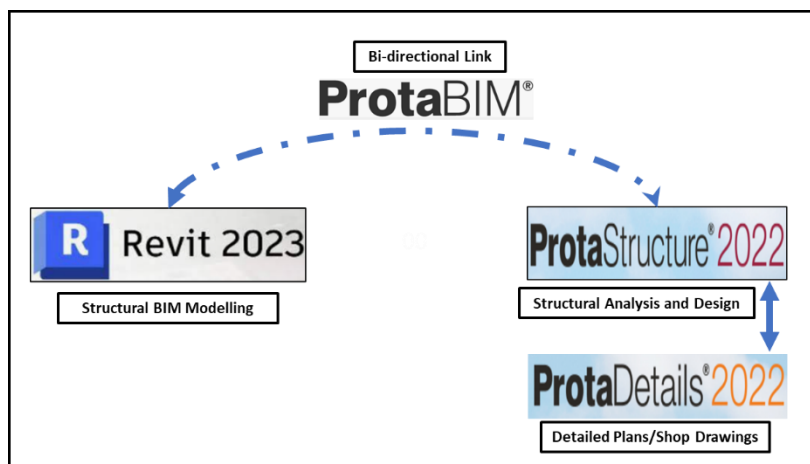
Figure 47: *Exchnage Scenerio Between Revit and ProtaStructure using ProtaBIM*

The fundamental stages of combining models in the context of Revit and ProtaStructure encompass Model Generation, Model Transmission, and Model Integration. This comprehensive sequence of

actions is referred to as round-trip interoperability. The Structural BIM model is originated in Revit. Subsequently, the model is transfered to the alternate software as needed.
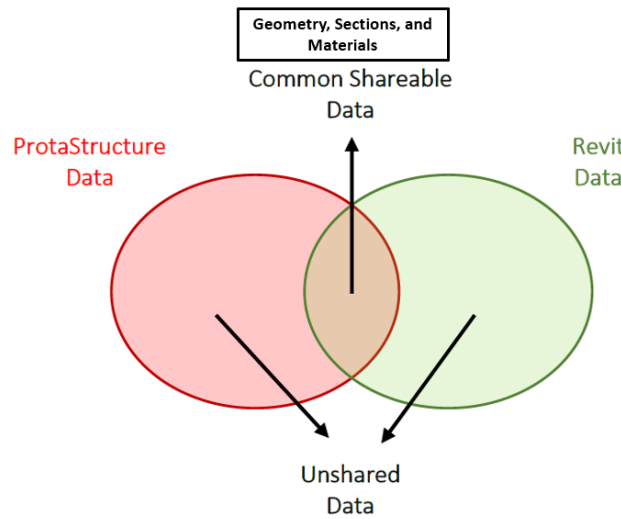
Figure 48: *Common Data Shared Between Revit and ProtaStructure during Exchange*

When analyzing the two softwares, it becomes evident that they operate using distinct data and data structures. Nevertheless, there exist certain data points that are mutually compatible and can be exchanged between these applications. The transmitted model encompasses this shared data seen in Figure 51. The process of transferring data between ProtaStructure and Revit exclusively involves tangible information which involves characteristics like shape, cross-sections, and materials.

It is important to emphasize that while working with Revit, the recommended approach is to start a fresh project using one of the available template files, such as "**ProtaStructure_Metric_2023.rte**" as seen in Figure 52.
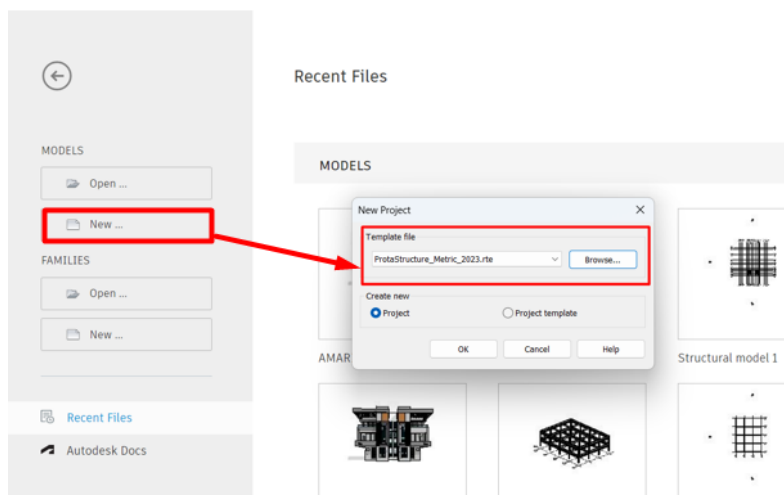
Figure 49: *Creating a new project using the ProtaStructure template*

Starting with the recommended template, ProtaStructure sections will be automatically associated with the established families within the Revit project. Conversely, without this approach, ProtaBIM might encounter challenges when aligning ProtaStructure sections with Revit families. However, ProtaBIM

offers a "Family Mapping" feature that enables you to manually establish the correspondence between ProtaStructure sections and Revit families, allowing you to leverage your pre-existing family files (Prota, 2023).

4.2.1 Trip 1 – Export Structural Model from Revit to ProtaStructure

It is important to note that the export of curved members, walls, slabs, footings, as well as load cases and load combinations, is not applicable in the current version of ProtaBIM. Also, suitable mapping between Boundary Conditions in Revit and Supports in ProtaStructure is not present. As a result, supports are autogenerated at the base of each individual column. All designated beams and columns from the Revit platform are imported, on the condition that they adhere to the geometric limitations prescribed by ProtaStructure (namely, vertical columns and walls exclusively, and horizontal beams solely). There inherent orientation, cross-sectional dimensions, and member release attributes will be upheld in the process.
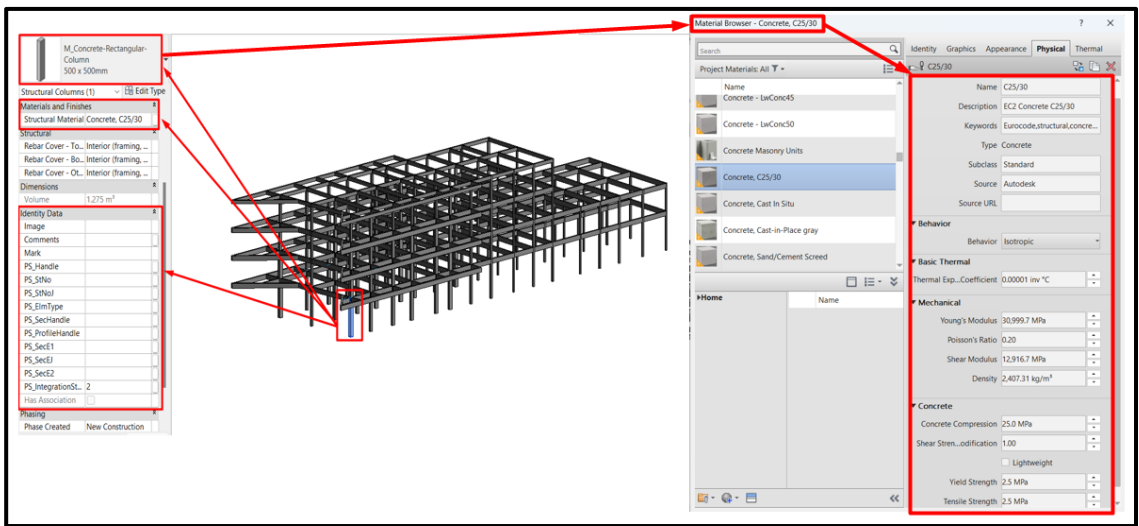
Figure 50: *Structural Model showing Material Properties and Identity Data of a Column before Export*

However, once the structural model is completed in Revit – including the creation of structural beams and columns – the following steps should be taken to ensure a successful export of the model from Revit to ProtaStructure as shown in Figure 39 (BIM Interoperability Workflow between Autodesk Revit and ProtaStructure Using ProtaBIM).

1. **Initiate Export to ProtaStructure**

Access the ProtaBIM ribbon tab, then opt for the Export to ProtaStructure function.

2. **Project Identification**

Create project name and select appropriate design code

3. Mapping Sections

Upon opening the "Map Sections" dialog, Revit Families (displayed in the left pane) are automatically associated with corresponding ProtaStructure Sections (shown in the middle pane) and presented in the Mapping List (visible in the right pane).

Items in green: Present and successfully mapped.

If the listed sections not be present, the option to generate new ProtaStructure sections is available..

4. Opening ProtaStructure Model

Within the "Open Project" window, select the "Data Folder," and subsequently, opt for the identical project name that was established earlier. Afterward, click the OK button. In this interface, the concrete grade and the number of stories will become visible.
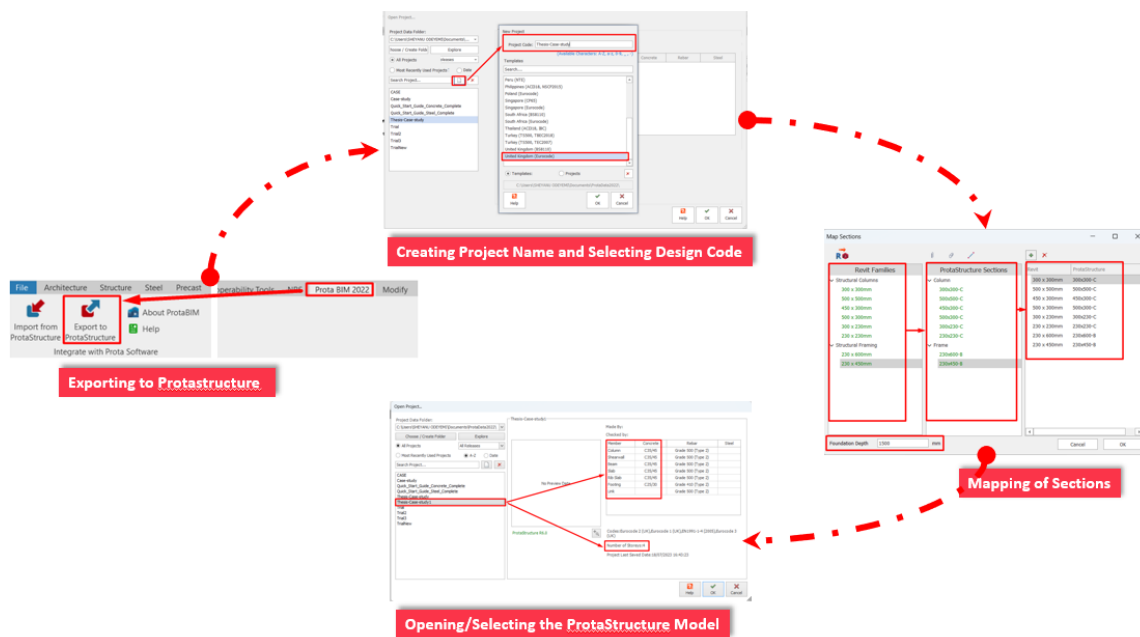
Figure 51: *ProtaBIM Process for Export of Structural Model from Revit to ProtaStructure*

5. Importing of Revit Model

Access the BIM ribbon and opt for the "Revit Import" command. Within the Import menu, specify the structural elements you intend to import, then proceed by clicking the "Import" button. Following a successful import, two subsequent windows will sequentially emerge: the "Move Member to Axis" window, followed by the "Building Model Check" window. Commence the process by selecting the "Start" button, and if preferred, you may subsequently close the window.

"The primary objective of the Building Model Check is to validate the precise alignment of all elements in accordance with their respective axes, and to verify the orthogonal alignment of grid and axis lines."

6. BIM Integration Status

Upon the successful import of the Revit model, the perspective will automatically transition to a 3D view. During this phase, the BIM Integration Status color-coded system will be engaged, distinctly illustrating the classification of members into categories such as new, updated, deleted, or unchanged.
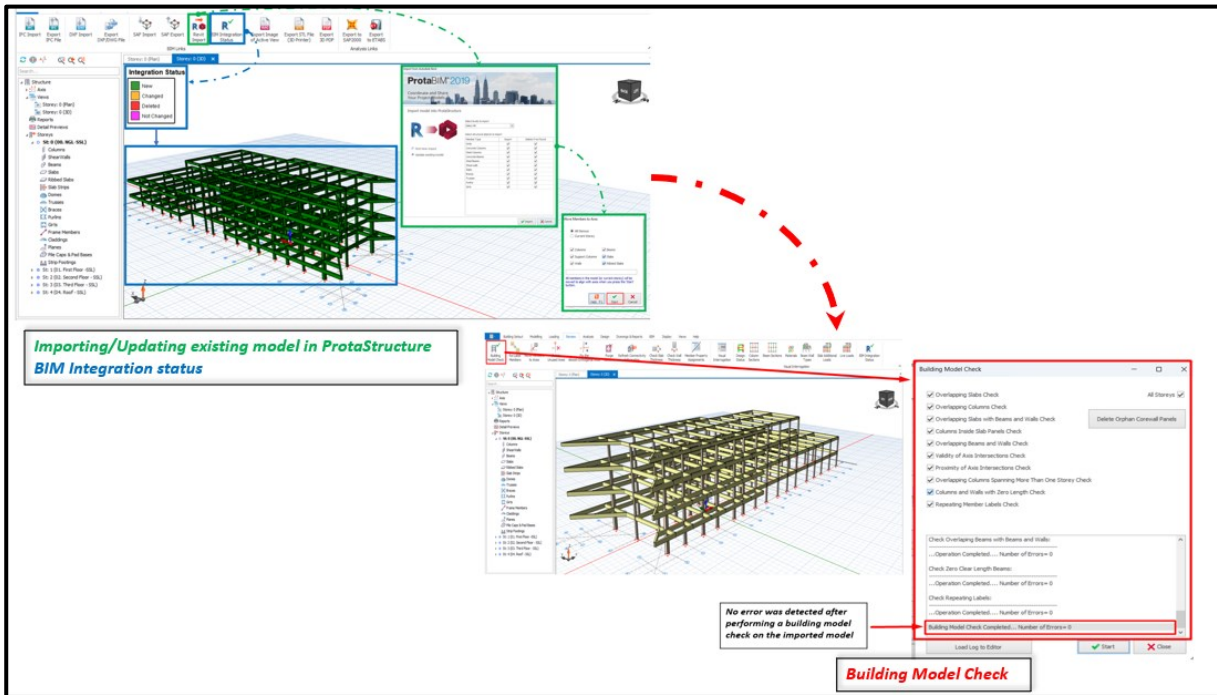
Figure 52: *Structural Model Import, BIM Integration Status and Building Model Check in ProtaStructure*

Define Load Cases and Load Combinations

Prior to initiating the creation of slabs, it is required to define load cases and combinations. Based on the load cases and load combinations outlined in Table 3, and exemplified in Figures 47 and 48, the process involved the manual inclusion of load cases and the careful selection of load combinations. Nevertheless, it is noteworthy that the Loading Generator functionality is also available, offering the option to automate the setup of both load cases and combinations.
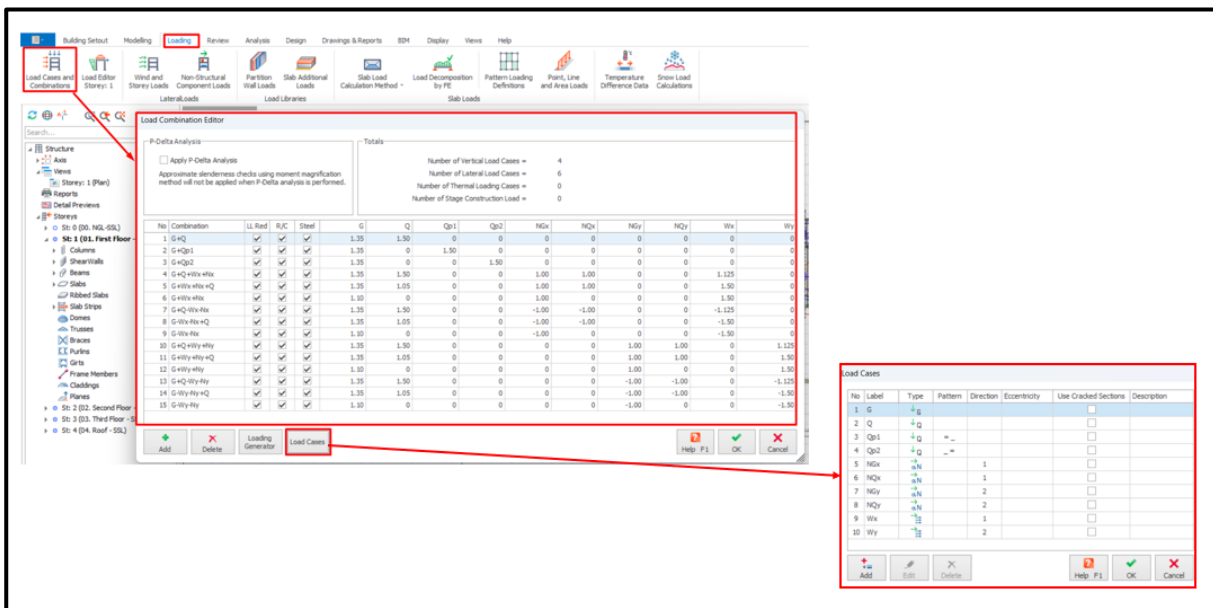
Figure 53: *Load Cases andd Load Combinations in ProtaStructure*

Placement of Structural Elements – Slabs and Walls

Given the inherent limitations surrounding the seamless transfer of slab and wall elements during the interoperability transition from Revit to ProtaStructure, the essential task of creating these structural

components, including slabs and walls, was undertaken within the operational framework of the ProtaStructure platform

Perform Structural Analysis and Design

Prior to initiating the analysis, it is strongly recommended to conduct a thorough assessment of the model's integrity. The building model check is designed to identify overt modelling errors, with any warnings or errors offering clear indications of the specific affected members.

Careful review and correction of any warnings or errors are essential prerequisites before progressing with the analysis. Once the absence of errors is ascertained, the analysis can be initiated. Subsequent to triggering this process, the Batch Design Options dialog will be presented, facilitating an automated design procedure for columns, walls, and beams post-analysis.
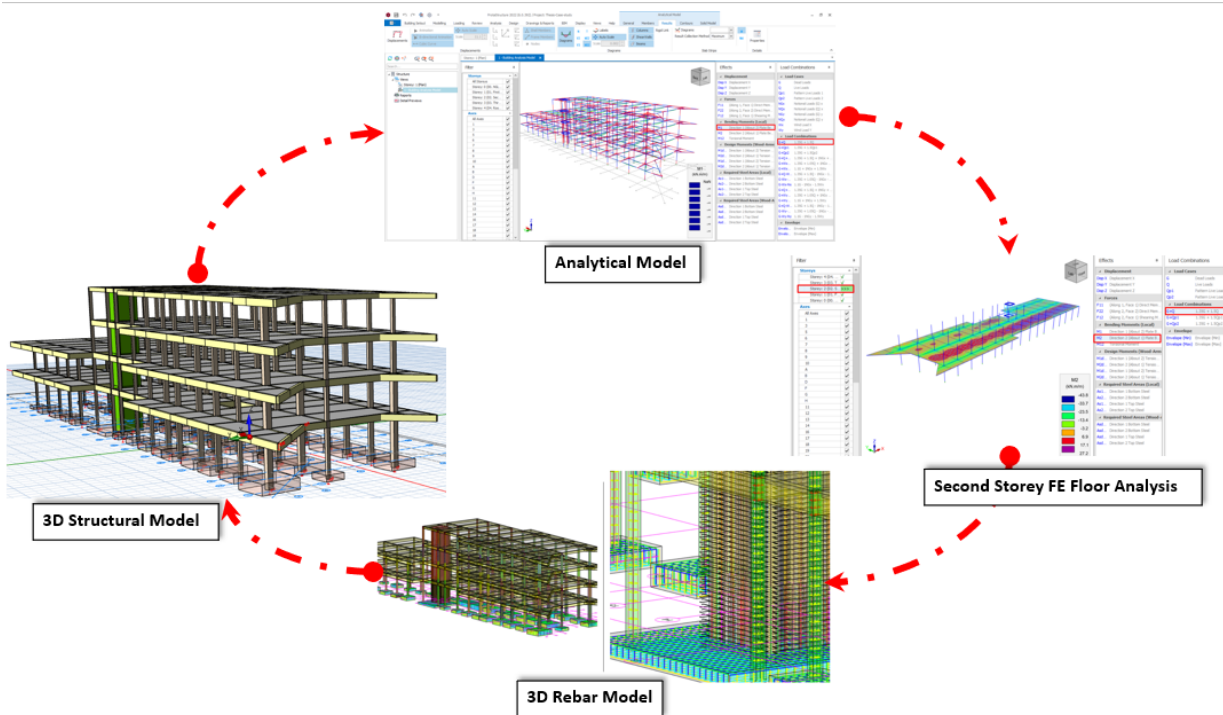
Figure 54: *Structural Analysis and Design Process in ProtaStructure*

4.2.2   Trip 2 – Import Structural Model from ProtaStructure to Revit

After the structural model is designed in Protastructure, the following steps should be taken to ensure a successful export of the model from ProtaStructure to Revit:

1. **Initiating Import Process in Revit**

Access the ProtaBIM ribbon tab located on the Revit toolbar.

Click on the "Import from ProtaStructure" command within the ProtaBIM tab.

2. **Selecting the Protastructure Model**

Click on the "..." button to choose the desired Project Folder from your system. Navigate to the Project Folder and select the ".prota" file associated with the project. Click "Open" to proceed.

3. **Import Options**

To update the structural model in Revit, the "Update existing model" option is automatically chosen. Define the structural elements to import into Revit by specifying the object types in the provided table. To start the import process, set up the structural object types and click "Start."

"Consider enabling the "Import slabs by interior points" option if you encounter issues like slab overlap with beams and columns. Only enable this option if needed for the initial import."

4. Mapping ProtaStructure Sections with Revit Families

ProtaStructure objects will be converted to Revit objects, requiring the mapping of ProtaStructure sections (columns, beams, frames) to "Loadable Revit Families." The mapping dialog will show ProtaStructure Sections displayed in the left pane, available Revit Family Instances shown in the middle pane, and the Mapping List visible in the right pane. Sections will be automatically mapped to suitable Revit Family Instances.

"You can modify the mapping using your preferred loadable families and address any unmapped sections by selecting a section, choosing a family instance, and clicking the "+" symbol to add it to the Mapping List."
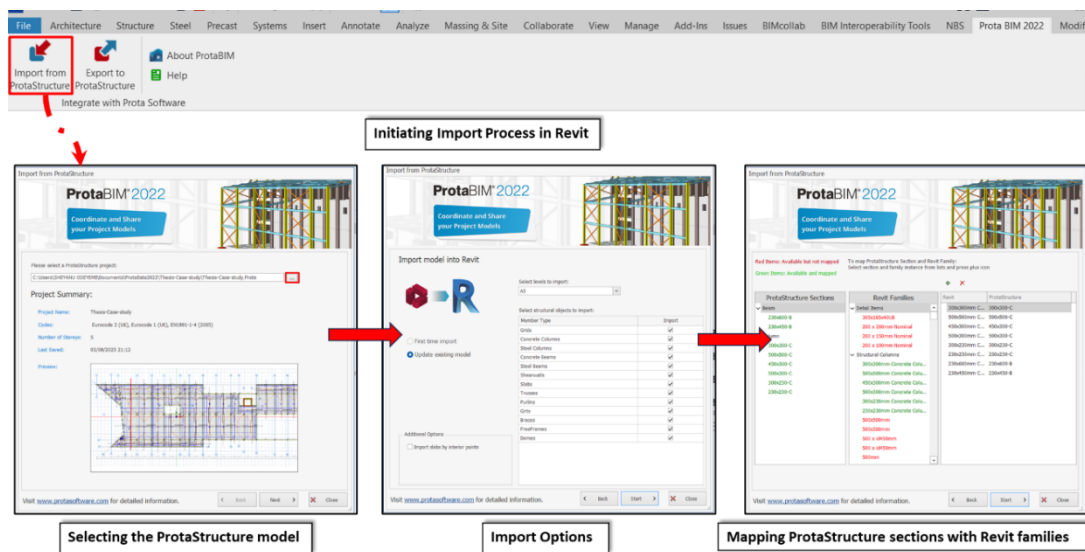
Figure 55: *ProtaBIM Process for Import of Structural Model from ProtaStructure to Revit*

5. Start Import and Generate Members

After mapping, click the "Start" button to initiate the import process. A Model Import Summary will be presented upon completion, listing the successfully imported elements. Once the dialog is closed, Revit will continue generating members based on the imported data. Depending on the model's size, this step might take some time.

Note: *Slabs and shearwalls are "System Families" in Revit. Ensure that the required slab and wall system families exist in your Revit project, as they are essential for proper import. Each slab and wall system family must include at least one "Structural Layer" associated with a "Structural Material."*

Figure 56: *Designed Structural Model Imported in Revit Showing Material Properties and Identity Data*

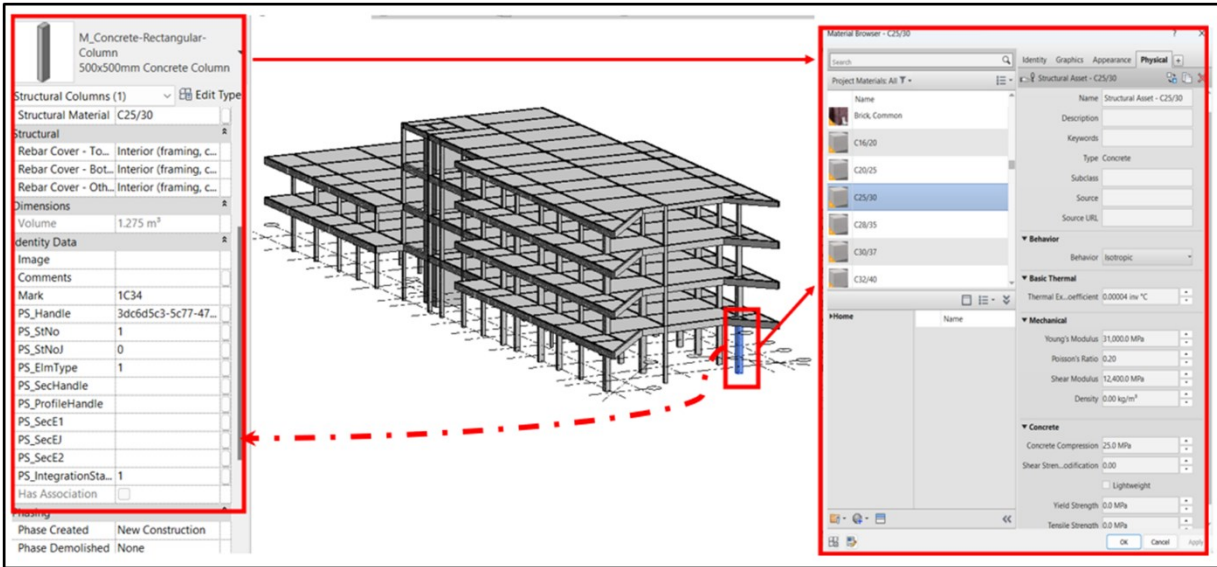| Description	EVALUATION OF INTEROPERABILITY REQUIREMENTS					Export and Import
	Export Structural Model from Revit to ProtaStructure Using ProtaBIM			Import Structural Model from ProtaStructure to Revit Using ProtaBIM		
	TRIP 1 - Autodesk Revit to ProtaStructure	Comment		TRIP 2 - ProtaStructure to Autodesk Revit	Comment	Round Trip - (Trip 1 and Trip 2)
Geometry						
Overall Model	✔	Geometry of the overall model is correct but ProtaBIM (bi-directional does not support transfer of slabs, walls and footings into ProtaStructure		✔	Geometry of the overall model is correct but ProtaBIM (bi-directional does not support import of footings into Revit	✔
Grids	✔	All grid/axis lines in Revit are exported correctly		✔	All grid/axis lines in ProtaStructure are exported correctly	✔
Storey Details (Height/Level)	✔	Information is exported correctly. level in Revit where data exists is imported as a storey.		✔	Information is imported correctly. Storey in ProtaStructure where data exists is imported as level in Revit	✔
Score (%)	100%			100%		100%
Geometry - Structural Elements (Framing, Column, Slab, Footing)						
Beam (Length)	✔	Beam Length is exported correctly		✔	Beam Length is imported correctly	✔
Beam (Cross section)	✔	Beam Cross-section is exported correctly		✔	Beam Cross-section is imported correctly	✔
Column (Length)	✔	Column Length is exported correctly		✔	Column Length is imported correctly	✔
Column (Cross section)	✔	Column Cross-section is exported correctly		✔	Column Cross-section is imported correctly	✔
Slab Thickness	✖	Link does not support the export of Slab		✔	Slab Thickness is imported correctly	◪✔
Slab (Cross section)	✖	Link does not support the export of Slab		✔	Slab Cross-Section is imported correctly	◪✔
Footing (Depth)	⊖	This is not applicable because footing depth and cross sections are determined after structural analysis and design in ProtaStructure		✖	Link does not support the import of Footing	✖
Footing (Cross section)	⊖	This is not applicable because footing depth and cross sections are determined after structural analysis and design in ProtaStructure		✖	Link does not support the import of Footing	✖
Score (%)	67%			75%		70%
Material Properties						
Material Type (Concrete)	✔	Material Type was exported correctly		✔	Material Type was imported correctly	✔
Material Grade	◪✔	Modification is required in ProtaStructure. The exported concrete grade is C25/30 from Revit but Protastrucutre used a default concrete material grade of C35/45		✔	Material Grade was imported correctly	◪✔
Yield stress (fy)	✖	Yield Stress was not exported		✖	Yield Stress was not imported	✖
Modulus of elasticity €	◪✔	Modification is required in ProtaStructure due to change in the concrete grade		✔	Modulus of Elasticity was imported correctly	◪✔
Shear modulus (G)	◪✔	Modification is required in ProtaStructure		✔	Shear Modulus was imported correctly	◪✔
Density, ρ	✔	Density was exported correctly		✔	Density was imported correctly	✔
Poisson's ratio	✔	Poisson's ratio was exported correctly		✔	Poisson's ratio was imported correctly	✔
Score (%)	65%			86%		76%
Load Cases and Combination						
Dead Load	✖	Link does not support the export of load cases		✖	Link does not support the export of load cases	✖
Live Load	✖	Link does not support the export of load cases		✖	Link does not support the export of load cases	✖
Wind Load	✖	Link does not support the export of load cases		✖	Link does not support the export of load cases	✖
Load Combination	✖	Link does not support the export of Load Combination		✖	Link does not support the export of Load Combination	✖
Score (%)	0%			0%		0%
Boundary Conditions						
Fixed	◪✔	There is no suitable mapping between Boundary Conditions in Revit and Supports in ProtaStructure, so by default, supports are created at the bottom of every column		✖	There is no suitable mapping for Boundary Conditions between both softwares. The exported boundary conditions were not imported	◪✔
Score (%)	50%			0%		25%
Overall Score (%)	56%			52%		54%

✔	The exchange of information/elements is correct
✖	The exchange of information/element is not possible
◪✔	The exchange of information/element is partially successful / Modification is required in the recipient software
⊖	Not Applicable

Table 4: *Evaluation Criteria with Corresponding Result for Bi-directional Ineroperability Between Revit and ProtaStructure Using ProtaBIM as Exchange Scenerio*

4.3   Case Study 2 – S-BIM Model Transfer Between Revit and ProtaStructure via IFC

Case study 2 shows the utilization of Industry Foundation Classes (IFC) as an intermediary (Indirect Link) which   plays a pivotal role in facilitating the seamless exchange of structural building information models (S-BIM) between Autodesk Revit, a BIM authoring software, and ProtaStructure, an interconnected finite element method (FEM) software used for structural analysis and design.

IFC serves as the indirect link for model and data interoperability. It acts as the bridge that enables the transition of the S-BIM model from Revit to ProtaStructure, where it undergoes detail structural analysis and design processes. The information contained within the IFC file retains its integrity during the transfer, ensuring that essential properties, geometry, and relationships are transfered.
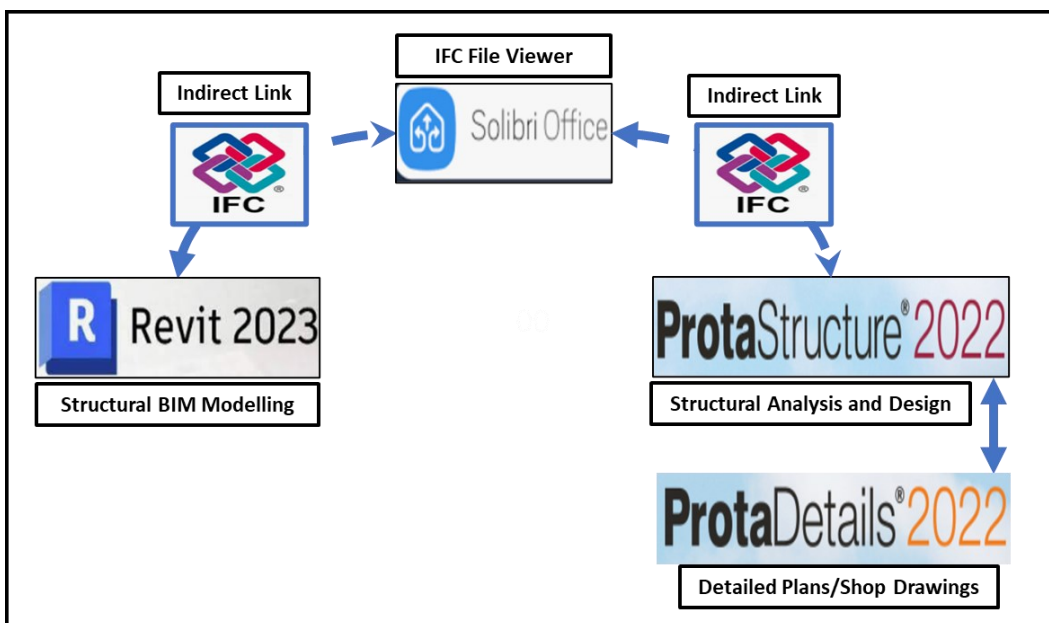
Figure 57: *Exchnage Scenerio Between Revit and ProtaStructure using IFC*

In adherence to a comprehensive approach to quality assurance, the IFC file extracted from Revit is subjected to an additional tier of meticulous scrutiny through the utilization of Solibri Model Checker. This procedural step is designed to ascertain the seamless alignment of the IFC file with the envisaged design specifications and industry standards. With utmost precision, Solibri Model Checker assesses various aspects within the IFC file, encompassing attributes such as geometric attributes, elemental properties, and relational interconnections. This process culminates in the provision of a comprehensive overview that underscores the extent to which the IFC file harmonizes with the defined project prerequisites.

4.3.1   Trip 1 – Export Structural Model from Revit to ProtaStructure via IFC

While preparing the structural model for export to IFC, detail attention to metadata becomes paramount. This process gains significance due to the IFC format's role as a medium for seamless data exchange between BIM authoring software, such as Revit, and analysis platforms such as

ProtaStructure. Beyond its function as a bearer of geometric data, the IFC format holds the capacity to incorporate vital contextual information. Therefore, prior to exporting the structural model from Revit to IFC format, a focus on inputting comprehensive metadata is essential.

This metadata encompasses a range of critical details: keynotes for annotating specific notes, model manufacturer information to ensure accurate component sourcing, detailed descriptions clarifying element attributes, assembly codes for effective tracking, type marks for distinct categorization, and the inclusion of Omniclass Numbers and Titles for precise classification, coupled with the IFC parameters.
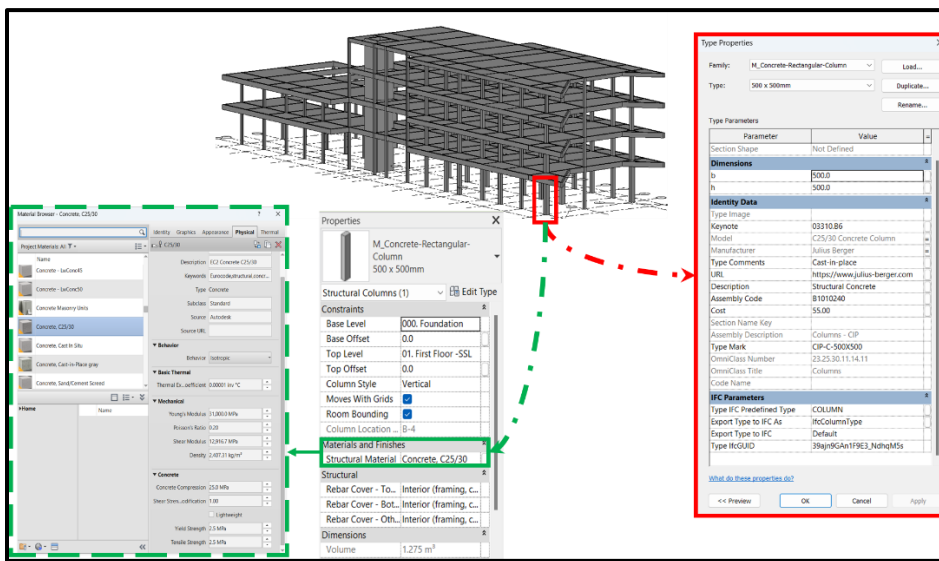
Figure 58: *Structural Model showing the Metadata and Material Properties of the Selected Element*

The integration of these metadata elements within the IFC file transforms it into more than a mere geometric representation. Instead, it evolves into a repository of information that bolsters the depth and precision of the BIM model. This heightened information density, in turn, facilitates collaboration, analysis, and project management throughout the entire project lifecycle. By embedding detailed metadata during the IFC export process, the resultant IFC file emerges as a comprehensive asset, reinforcing efficient collaboration, enabling accurate analysis, and advancing the attainment of project objectives with utmost efficacy.

After completing the structural model in Revit, the subsequent steps were followed to successfully export it to the IFC format and import into ProtaStructure, as depicted in Figure 61.

1. Access Export Options

On the Revit ribbon, navigate to the "File" tab.

2. Select IFC Export:

Click on "Export," and from list, choose "IFC."

3. Define Export Location:

In the "Export IFC" dialog box, under "File name," click "Browse" to specify the folder to save the IFC file.

4. Select an IFC Setup:

Under "Current selected setup," choose the appropriate IFC setup for your export. Then, click "Modify setup" to customize the configuration.

Within the "Modify Setup" dialog, there are several tabs to configure your IFC export:

General Tab

IFC version: Select the desired IFC version for the export. Typically, "IFC 2x3 Coordination View 2.0" is the default choice for structural models.

Exchange requirement: Specify the exchange requirement; in this case, it is "Structural reference exchange."

File Type: Ensure "IFC" is selected.

Phase to export: Choose the relevant phase of the document to export.

Additional Content Tab

Export 2D plan view elements: This include 2D elements like grids, notes, and filled regions if necessary.

Export only elements visible in view: This option is selected to export only the visible elements in the current view.

Property Sets Tab

Export IFC common property sets: This include common IFC property sets.

Advanced Tab

Use active view when creating geometry: This option uses the active view to generate exported geometry.

Include IFCSITE elevation in the site local placement origin: This box is checked to include the elevation from the Z offset of the IFCSITE local placement.

5. Confirm and Export

After configuring the setup to requirements, click "OK" to save settings.

6.   **Final Export**

Upon returning to the "Export IFC" dialog box, kindly initiate the export process by selecting the "Export" button.
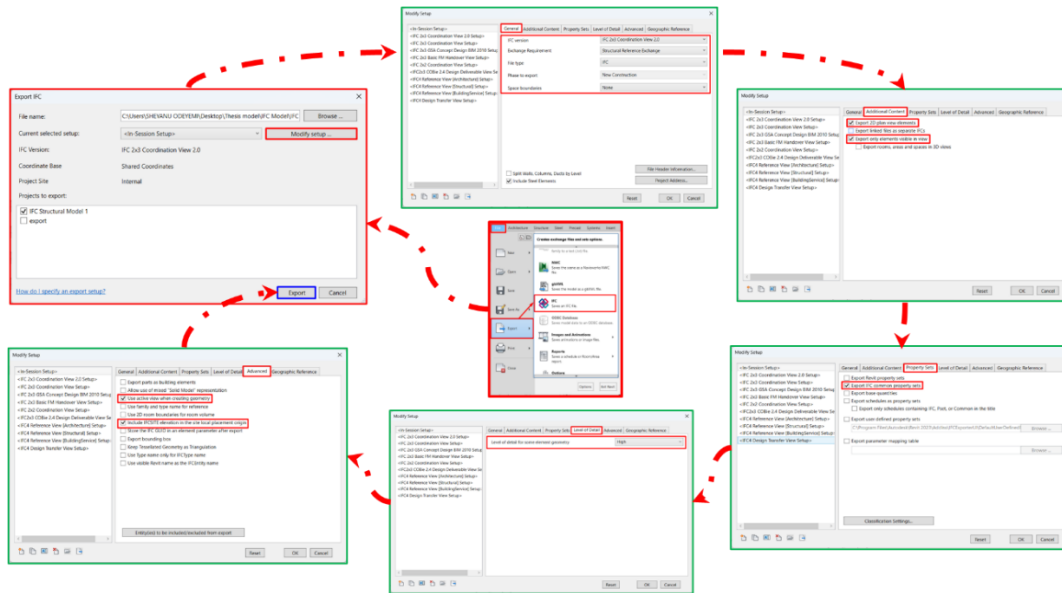
Figure 59: *Autodesk Revit to IFC Export Process/Cycle*

7.   **IFC Structural Model Validation in Solibri Model Checker**

Following the successful completion of the IFC export process from Revit, the resultant IFC file was then meticulously imported into Solibri Model Check, a highly regarded IFC model checker. This critical step was undertaken to facilitate a comprehensive visual inspection and thorough verification of the IFC data, thus ensuring the validation of the IFC Structural model's accuracy and integrity. This showed the exported IFC model is accurate and ready for import into ProtaStructure.
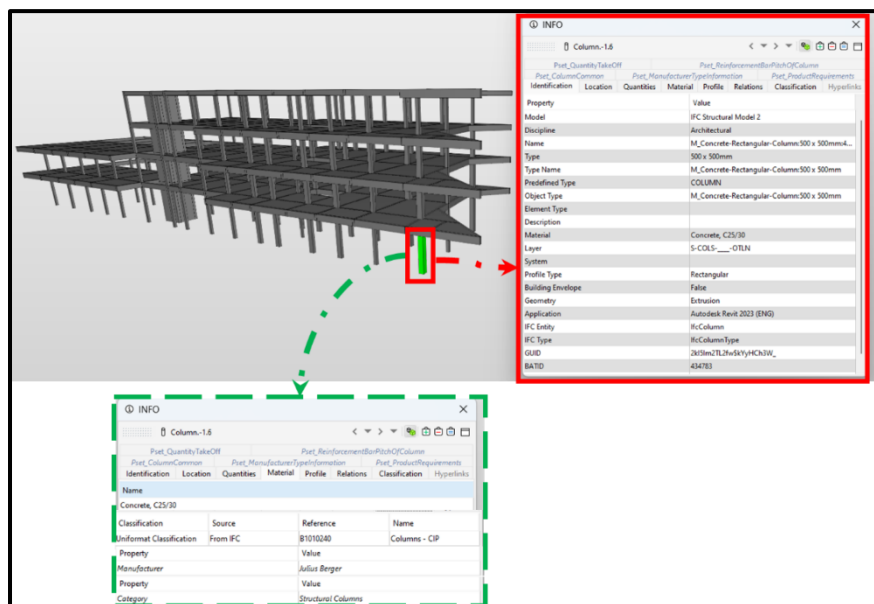
Figure 60: *IFC Structural Model Imported to Solibri Model Checker for Validation*

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8. Import IFC Structural Model into ProtaStructure

Prior to the importation process into ProtaStructure, it is crucial to acknowledge the procedures that have preceded this stage. Firstly, the structural model was carefully created in Revit, showcasing precision and attention to detail. Following this, the IFC file underwent a thorough validation process in Solibri Model Checker, ensuring the accuracy and reliability of the structural model's data. This comprehensive validation step not only serves to confirm the integrity of the structural model but also lays the foundation for a seamless transition into ProtaStructure, where further analysis and design endeavors will take place.

To import the IFC Structural model into ProtaStructure, the following steps were taken:

- **Project Selection**

The import process was initiated by setting up a new project designated for the IFC file. The choice between creating a new project or opening an existing one should always align with the specific project requirements at hand. The project name was inputted and the design code for the project (Eurocode) was also selected during this process.

- **Access the Import IFC Functionality**

Access the BIM ribbon and choose the "IFC Import" command. The "Import Model From IFC" windows will emerge, showing the "Browse" icon for navigating your computer and selecting the intended IFC file for import.

- **Specify Import Settings (if applicable):**

This include options for deleting existing model (if applicable) , coordinate systems, and other import parameters (foundation depth, and structural elements connectivity tolerance). Configure these settings as needed.

- **Initiate the Import**

After configuring any necessary settings, initiate the import process. This is typically done by clicking an "Import IFC" button.

- **Review and Confirm**

Once the import process is complete, review the imported IFC model within the ProtaStructure environment and run building model check to validate the precise alignment of all elements in accordance with their respective axes

A significant number of errors was noted after performing the building model check on the imported IFC structural model, majorly due to the mutiple grid lines and displacement of structural member (beams) in ProtaStructure.
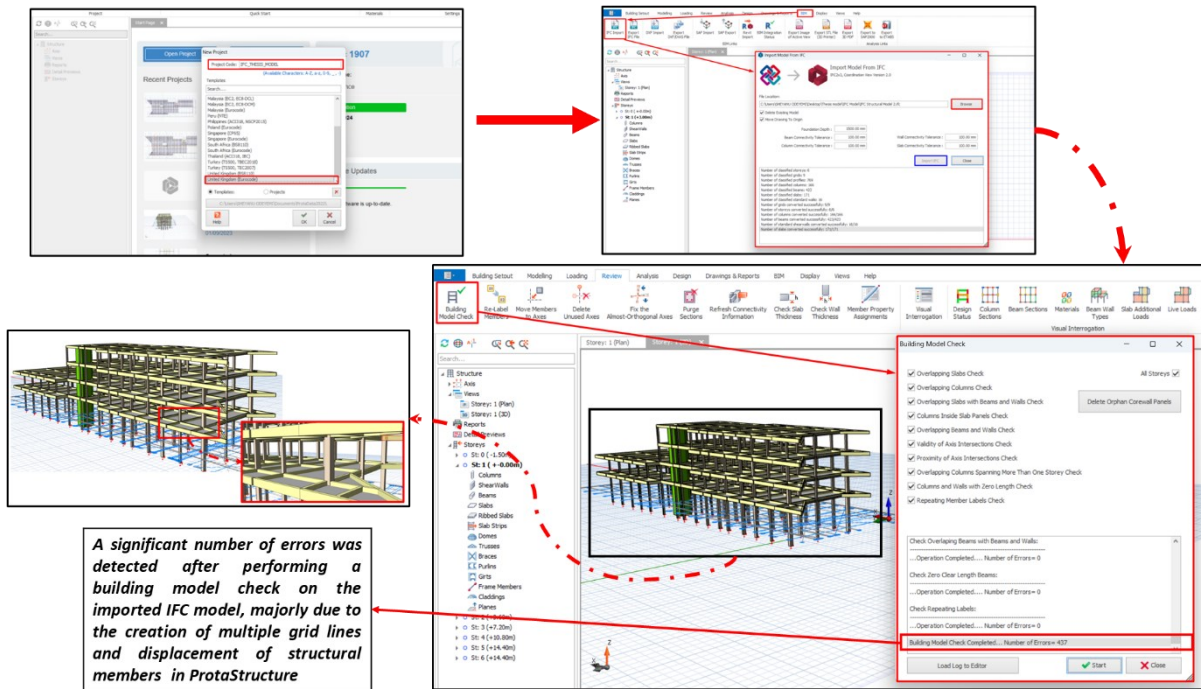
Figure 61: *IFC Structural Model Import Process Within ProtaStructure*

Manual Adjustment of Displaced Structural Member

After importing the IFC structural model into ProtaStructure, it was neccesary to perform manual adjustments on displaced structural members (beams). While the initial import process strives for accuracy, structural elements can occasionally require fine-tuning to align with specific project requirements. This manual adjustment phase involves precisely positioning and aligning these elements within the ProtaStructure environment to ensure structural integrity and adherence to design specifications. It is a crucial step in the workflow, allowing engineers and designers to optimize the model and further refine it for analysis and design tasks, ultimately contributing to the overall success of the structural project.
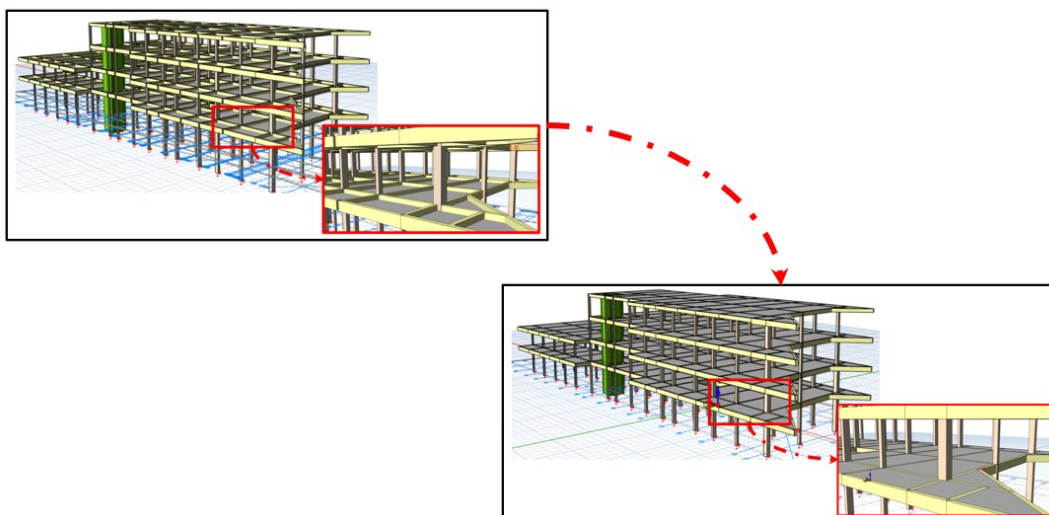
Figure 62: *Unadjusted and Manually Adjusted Structural Model in ProtaStructure*

Define Load Cases and Load Combinations

The limitation arises from the IFC structural model's inability to support the import of load cases and combinations directly into the structural analysis software. Load cases and combinations are fundamental components of structural engineering, representing various applied loads and their combinations that a structure may experience during its lifecycle. The absence of this capability necessitates an additional manual step in the structural modelling process, where engineers and designers must input load cases and combinations within the analysis software separately. While this introduces an extra layer of effort and potential for human error, it underscores the importance of attention to detail when translating a structural model from IFC format into the analysis environment.

Perform Structural Analysis and Design

Following the definition of load cases and load combinations, the structural analysis and design phase commences as a pivotal stage in the workflow. Load cases represent specific scenarios of applied forces and constraints on a structure, while load combinations account for various combinations of these cases, reflecting real-world conditions. With these critical elements in place, comprehensive analysis and design was carried out, evaluating its response to different load scenarios. This analysis provides essential insights into factors such as stress distribution, deformation, and safety margins, guiding the design process

4.3.2   Trip 2 – Import Structural Model from ProtaStructure to Revit via IFC

ProtaStructure, like many structural analysis and design software, offers the capability to export models in the IFC file format. This standardized format enjoys widespread compatibility with prominent BIM software applications, including the industry-standard platform, Revit. Nevertheless, ProtaStructure's distinctive feature lies in its seamless export proficiency, tailored to adhere to the IFC 2X3 Coordination View 2.0 specification. This specific alignment ensures an unparalleled degree of precision, surpassing mere compliance with industry standards. It guarantees the steadfast preservation of structural data/geometry consistency and accuracy upon integration into diverse BIM platforms, including but not limited to Revit.

The steps outlined below were executed to effectively validate and import the designed structural model created in ProtaStructure into Revit, utilizing the IFC file format:

1.   **Export the Structural Model as an IFC File**

To export the Structural model to an IFC file, access the BIM ribbon and choose the "Export IFC File" command as shown in figure 65. The "Export IFC" windows will emerge, showing the "Browse" icon for navigating and selecting the intended IFC file location. Afterwards, click on the "Export IFC" highlighted in blue.

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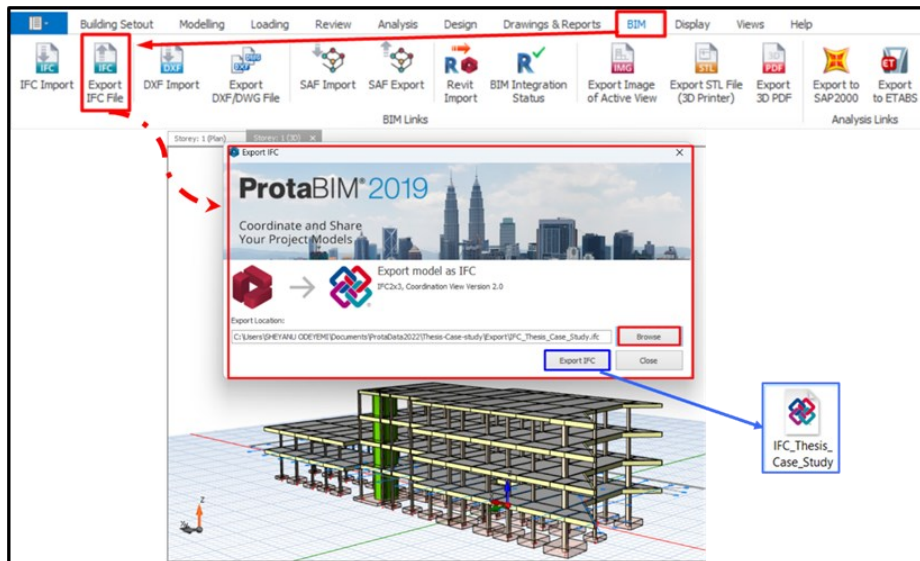
Figure 63: *Export Designed Structural Model to IFC Format*

2. Import the IFC File into Solibri Model Checker (IFC Model Checker) For Review

The significance of importing the IFC File (IFC Structural Model) into Solibri Model Checker for review assumes a vital role in the process by facilitating a visual inspection and validation of structural data and geometry before importing into Revit.. This iensures the precision, integrity of the model and also addresses a specific concern regarding metadata preservation.

In this instance, visual inspection revealed that the geometry (position of all strucutral element) is satisfactory while validation of the structural data showed there is loss of metadata, including vital identity data that had been carefully inputted before export to ProtaStructure. Solibri Model Checker becomes an essential tool in detecting such metadata losses as it undergoes the transition between ProtaStructure and Revit. This validation process guarantees that the structural model remains accurate geometrically and in compliance with the original design intent.
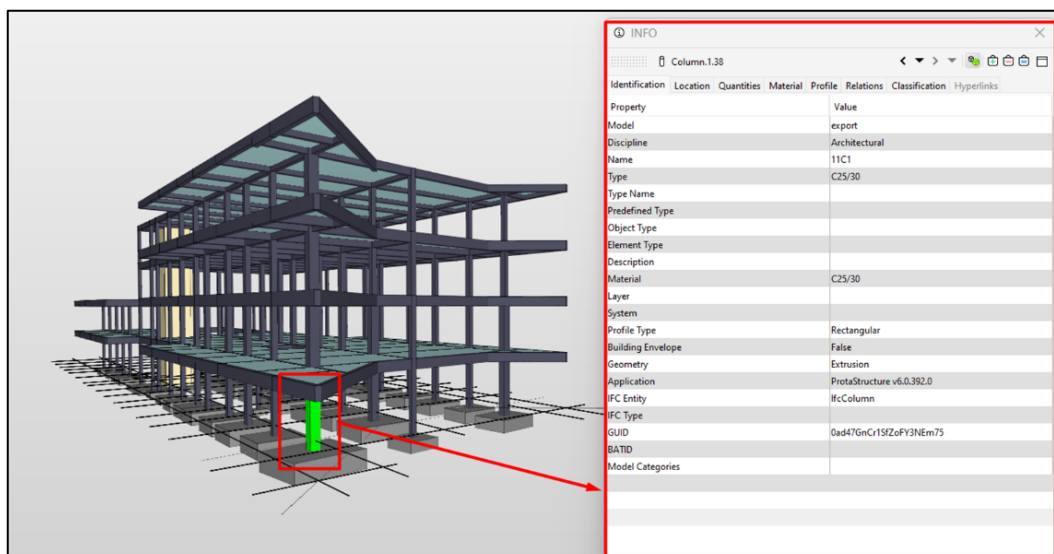
Figure 64: *IFC Structural Model in Solibri Model Checker*

3.   Import IFC Structural Model to Revit

Following review of the IFC Structural Model in Solibri Model Checker to ensure both precision and the preservation of essential metadata, the last stage of importing this validated model into Autodesk Revit represents a vital role in the BIM workflow. This process seamlessly integrates the structural model and data into the comprehensive BIM environment, for assessment of the model's accuracy in terms of connections, placements, and details. It is of paramount importance to evaluate these elements, as they directly influence the structural integrity and overall coordination with other building components within the Revit model. It is also key to note that adjustments of the structural model's geometry were not required to ensure seamless coordination with other building components. This comprehensive evaluation and potential model refinements within Revit is crucial in guaranteeing the structural model's seamless integration into the overall building design, ultimately contributing to an efficient and well-coordinated construction project.

Figure 65: *IFC Structural Model Imported in Revit showing missing IFC parameter*

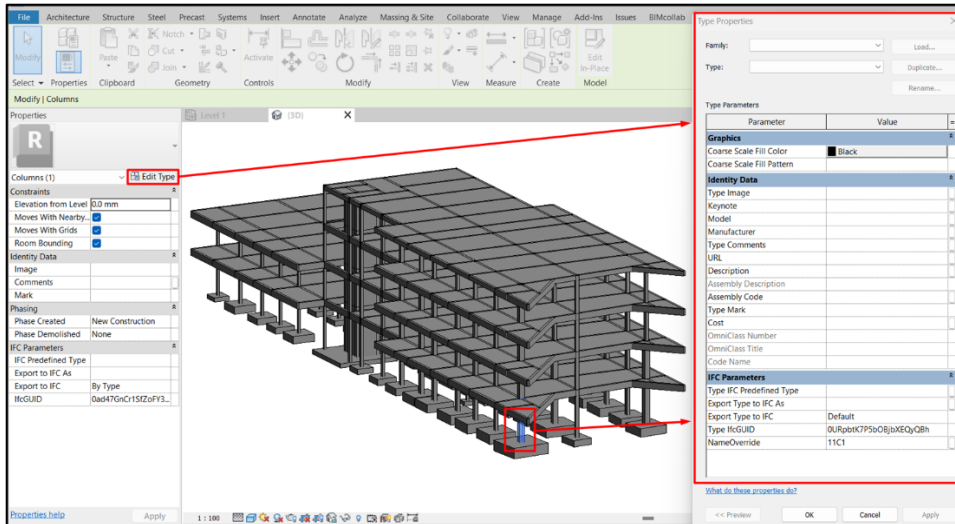| EVALUATION OF INTEROPERABILITY REQUIREMENTS					Export and Import
Description	Export Structural Model from Revit to ProtaStructure Using IFC		Import Structural Model from ProtaStructure to Revit Using IFC		Round Trip - (Trip 1 and Trip 2)
	TRIP 1 (IFC) - Autodesk Revit to ProtaStructure	Comment	TRIP 2 (IFC) - ProtaStructure to Autodesk Revit	Comment	
Geometry					
Overall Model	◪✔	Geometry of the overall model is not totally correct, it was necessary to perform manual adjustments on displaced structural members (beams)	✔	Geometry of the overall model is imported correctly	◪✔
Grids	◪✔	Multiple grid/axis lines were created in ProtaStructure. Adjustment was also necessary to fix this issue	✔	All grid/axis lines in ProtaStructure are exported correctly	◪✔
Storey Details (Height/Level)	✔	Information is exported correctly. level in Revit where data exists is imported as a storey.	✔	Information is imported correctly. Storey in ProtaStructure where data exists is imported as level in Revit	✔
Score (%)	75%		100%		85%
Geometry - Structural Elements (Framing, Column, Slab, Footing)					
Beam (Length)	◪✔	The geometry of all beams imported into ProtaStructure is poor. ProtaStructure used the beam's neutral axis (located at the centroid of the beam's cross-section) to connect with other structural elements which caused distortion of the geometry along the Z coordinate (delZ). Manual adjustment is required.	✔	Beam Length is imported correctly	◪✔
Beam (Cross section)	◪✔	The geometry of all beams imported into ProtaStructure is poor. ProtaStructure used the beam's neutral axis (located at the centroid of the beam's cross-section) to connect with other structural elements which caused distortion of the geometry along the Z coordinate (delZ). Manual adjustment is required.	✔	Beam Cross-section is imported correctly	◪✔
Column (Length)	✔	Column Length is exported correctly	✔	Column Length is imported correctly	✔
Column (Cross section)	✔	Column Cross-section is exported correctly	✔	Column Cross-section is imported correctly	✔
Slab Thickness	✔	Slab Thickness is exported correctly	✔	Slab Thickness is imported correctly	✔
Slab (Cross section)	✔	Slab Cross-section is exported correctly	✔	Slab Cross-Section is imported correctly	✔
Footing (Depth)	⊖	This is not applicable because footing depth and cross sections are determined after structural analysis and design in ProtaStructure	✔	Footing Depth is imported correctly	✔
Footing (Cross section)	⊖	This is not applicable because footing depth and cross sections are determined after structural analysis and design in ProtaStructure	✔	Footing Cross-Section is imported correctly	✔
Score (%)	75%		100%		88%
Material Properties					
Material Type (Concrete	✔	Material Type was exported correctly	✔	Material Type was imported correctly	✔
Material Grade	◪✔	Modification is required in ProtaStructure. The exported concrete grade is C25/30 from Revit but Protastrucutre used a default concrete material grade of C35/45	✔	Material grade of C25/30 was imported correctly	◪✔
Yield stress (fy)	✗	Yield Stress was not exported	✗	Yield Stress was not imported	✗
Modulus of elasticity €	◪✔	Modification is required in ProtaStructure due to change in the concrete grade	✗	Modulus of Elasticity was not imported	◪✔
Shear modulus (G)	◪✔	Modification is required in ProtaStructure due to change in the concrete grade	✗	Shear Modulus was not imported	◪✔
Density, ρ	✔	Density was exported correctly	✗	Density was not imported	◪✔
Poisson's ratio	◪✔	Modification is required in ProtaStructure due to change in the concrete grade	✗	Poisson's Ratio was not imported	◪✔
Score (%)	55%		30%		43%
Load Cases and Combination					
Dead Load	✗	Link does not support the export of load cases	✗	Link does not support the export of load cases	✗
Live Load	✗	Link does not support the export of load cases	✗	Link does not support the export of load cases	✗
Wind Load	✗	Link does not support the export of load cases	✗	Link does not support the export of load cases	✗
Load Combination	✗	Link does not support the export of Load Combination	✗	Link does not support the export of Load Combination	✗
Score (%)	0%		0%		0%
Boundary Conditions					
Fixed	✗	Export was not successful due to limitations in the IFC format	✗	inport was not successful due to limitations in the IFC format	✗
Score (%)	0%		0%		0%
Overall Score (%)	41%		46%		43%

✔	The exchange of information/elements is correct
✗	The exchange of information/element is not possible
◪✔	The exchange of information/element is partially successful / Modification is required in the recipient software
⊖	Not Applicable

Table 5: *Evaluation Criteria with Corresponding Result for Bi-directional Ineroperability Between Revit and ProtaStructure Using IFC as Exchange Scenerio*

5   RESULTS AND DISCUSSION

This Chapter presents the results obtained from the case studies and provides a comprehensive discussion of these results. It evaluates the effectiveness of the implemented interoperability methods, both through the bi-directional link - ProtaBIM and IFC format.

5.1   Case Study 1: Revit to ProtaStructure Using ProtaBIM as Bi-directional Link

As previously mentioned, Case study 1 focus on the model and data interoperability using ProtaBIM. Autodesk Revit represent BIM authoring software used for S-BIM modelling and ProtaStructure (FEM software) is used to conduct independent structural analysis and design on the S-BIM model.

The case study evaluates the effectiveness and seamlessness of data exchange between Revit and ProtaStructure via Bi-directional link (ProtaBIM). Furthermore, the study underscore significant discoveries and insights derived from this process. The results obtained from the exchange scenarios, encompassing both Case Study 1 and Case Study 2 are compared and presented in Table 6.
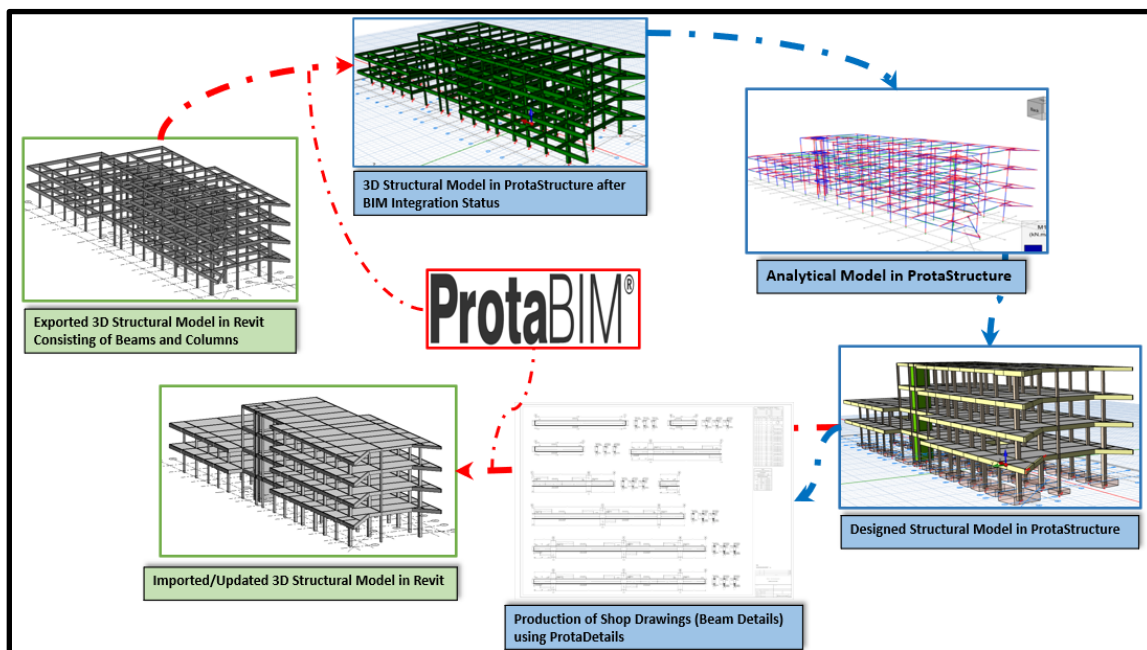
Figure 66: *Bi-directional Interoperability Between Revit and ProtaStructure using ProtaBIM as Exchange Scenerio and ProtaDetails for Shop Drawings*

Geometry

The model geometry, consisting columns and beams, was originally created within Autodesk Revit. while the structural elements - slabs and walls were developed in ProtaStructure because the present version of ProtaBIM does not offer support for the export of walls and slabs. However, despite this limitation, the transfer of geometry, consisting of columns and beams, from Revit to ProtaStructure were seamlessly transfer without any significant issues. Similarly, the model geometry, including columns, beams, walls, and slabs, that was developed within ProtaStructure, was also efficiently

exported to Autodesk Revit. All grid lines were successfully exchanged between both software and verse versa. Storey details/informations were exported correctly between both softwares. Levels in Revit where data exists are imported as a storey.

During the testing phase, the study unveiled difficulties when attempting to export slabs and walls from Autodesk Revit to ProtaStructure, as well as to transfering footings geometry from ProtaStructure to Autodesk Revit.

Material Properties

Material properties play a pivotal role in structural design and analysis, serving as fundamental components without which conducting such analysis would be impossible. In this context, Material Type (Concrete) was exported successfully between both softwares and vice versa. Modification was required in ProtaStructure due to a discrepancy in the concrete grade. In the export from Revit, the concrete grade assigned was C25/30. However, ProtaStructure automatically used a default concrete material grade of C35/45. This alteration in the concrete grade during the export process also had an impact on the mechanical properties and design parameters, which were automatically adjusted in response to the concrete grade change within ProtaStructure. The density and Poisson's ratio of the material were constant throughout the exchange scenerios. It is noted that the yield stress was not exchanged during the integration process, this is as a result of ProtaStructure not embedding the yield stress paramteter in the material properties of the software. Furthermore, the exchange of material grade and the corresponding mechanical properties from ProtaStructure to Revit were successful. The exchange of material properties can be seen on figures 53 and 59, where the material properties of column was shown before export from Revit and after import into Revit

The figure below also shows the material type, grade and other mechanical properties in ProtaStructure as imported from Revit
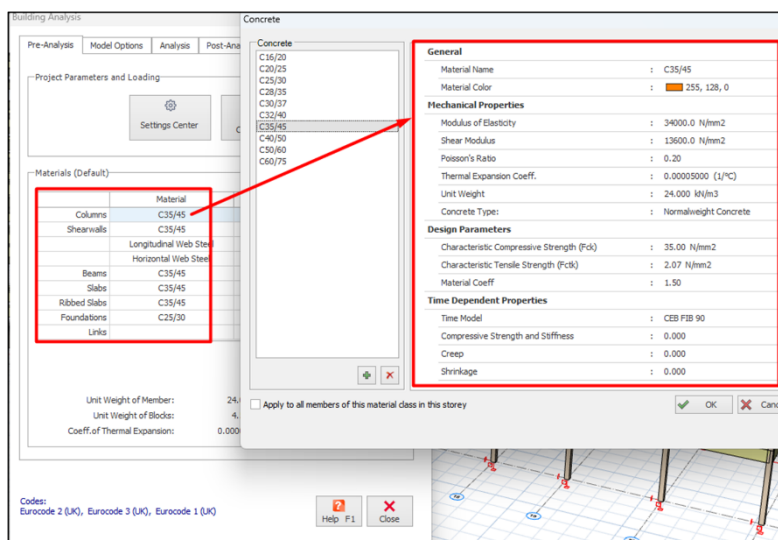

Figure 67: *Material Properties Table in ProtaStructure after export from Revit*

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It can be seen in figure 70 that protastructure used the default material grade of C35/45 for the exported structural elements.

Load Cases and Load Combinations

During the testing phase, the study revealed challenges in the seamless transfer of load cases and combinations between Revit and ProtaStructure. This difficulty arose because the current version of ProtaBIM lacks support for load cases and combinations. However, it is important to note that this case study specifically considers three distinct load cases: dead loads, live loads, and wind loads.

In structural analysis, the combination of dead and live loads is essential to estimate the most critical effects of actions on the structure, leading to the determination of maximum internal forces. To accommodate various design scenarios, this study adopts a total of 15 load combinations, accounting for both favorable and unfavorable conditions, as depicted in Figure 49. For the sake of simplification within this case study, our focus is solely on the ultimate limit state. The design combinations and partial safety factors are chosen in accordance with the stipulations outlined in Eurocode 2, as shown in Figures 47 and 48. It is also important to clarify that these load cases and combinations have been inputted into ProtaStructure exclusively for the purposes of structural analysis and design.

Boundary Conditions

Boundary conditions serve as crucial information for communicating support conditions (such as fixed, pinned, roller, etc.) to Finite Element analysis software. However, during the data exchange process, it became apparent that there is no direct mapping available between the boundary conditions in Revit and the supports in ProtaStructure. As a result, supports are automatically generated at the base of each column in ProtaStructure by default. It is important to note that in Revit, whether they are point, line, or area conditions are applied only on the analytical model.

5.2   Case Study 2: Revit to ProtaStructure Using IFC Format

Case study 2 evaluates the effectiveness and seamlessness of model and data exchange between Revit and ProtaStructure via IFC.
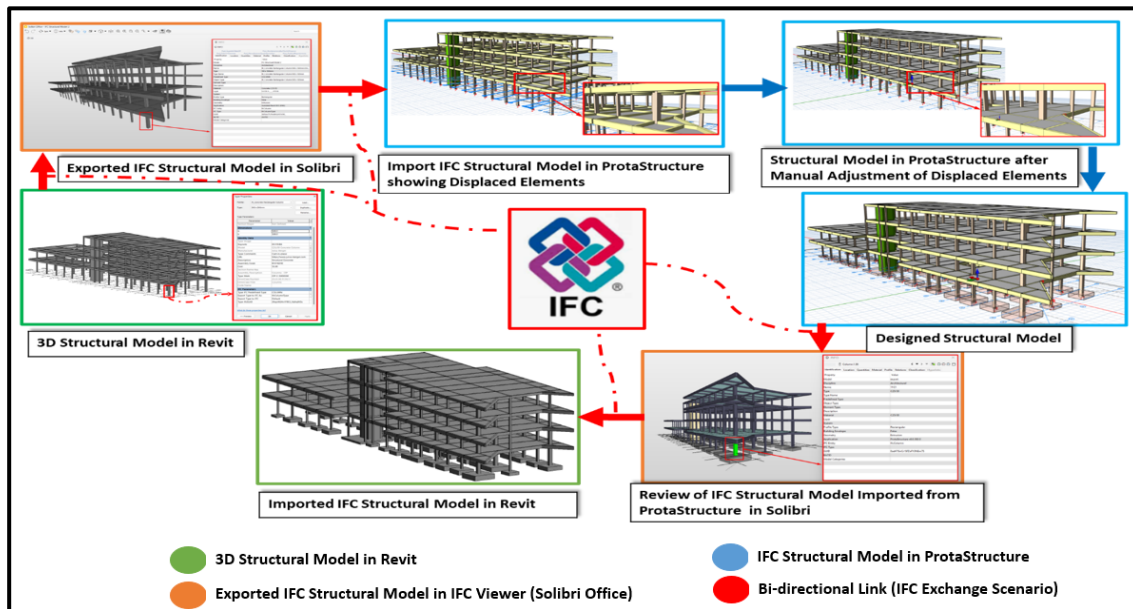

Figure 68: *Bi-directional Interoperability Between Revit and ProtaStructure using IFC as Exchange Scenerio*

Geometry

The model geometry, consisting columns, beams, walls, and slabs, was created in Autodesk Revit and subsequently exported using the IFC 2X3 Coordination 2.0 format. Prior to importing this IFC Structural Model into ProtaStructure, a validation step was conducted using the Solibri Model Checker. This validation aimed to verify the accuracy of the geometry and other metadata inputs. Upon importing the IFC Structural Model into ProtaStructure, it was observed that the geometry of columns, slabs, and walls had been successfully imported and appropriately positioned. However, manual adjustments were required for all beams. This was necessitated by the poor quality of the beam geometry imported into ProtaStructure, as shown in Figure 65. In ProtaStructure, the software utilized the neutral axis of the beams (located at the centroid of the beam's cross-section) for connections with other structural elements. Unfortunately, this approach resulted in distortion of the geometry along the Z-coordinate (delZ). Furthermore, it is noteworthy that the export of the designed geometries, including columns, beams, slabs, walls, and footings, via IFC from ProtaStructure and their subsequent import into Revit, was executed seamlessly and resulted in their proper placement within the model.

During testing, it was observed that certain grid lines imported into ProtaStructure via IFC required modifications due to multiple duplications that occurred after the import process. However, it is essential to note that the export of the grid lines from ProtaStructure and their subsequent import into

Revit were completed successfully and accurately exchanged between both software applications. Furthermore, storey details and information were exported correctly and seamlessly transferred between both software platforms.

Material Properties

Material Type (Concrete) was exported successfully between both softwares and vice versa. Modification was required in ProtaStructure due to a discrepancy in the concrete grade. In the export from Revit, the concrete grade assigned was C25/30. However, ProtaStructure automatically used a default concrete material grade of C35/45. This alteration in the concrete grade during the export process also had an impact on the mechanical properties and design parameters, which were automatically adjusted in response to the concrete grade change within ProtaStructure. The density of material was constant throughout the exchange scenerios. It is noted that the yield stress was not exchanged during the integration process, this is as a result of ProtaStructure not embedding the yield stress parameter in the material properties of the software. However, upon validation of the exported designed structural model via IFC from ProtaStructure in Solibri Model Checker as seen in Figures 67 and 68 , the material type and grade were only exchanged.

Load Cases and Load Combinations

The study revealed challenges in the seamless transfer of load cases and combinations between Revit and ProtaStructure via IFC as the exchange format does not support the transfer of these informations. Consequently, load cases and combinations had to be manually inputted into ProtaStructure exclusively for the purpose of conducting structural analysis and design.

Boundary Conditions

During the data exchange process, the study showed that boundary conditions for the strucural elements cannot be exchange due to limitations in the IFC format. This limitation not only presents a significant obstacle but also emphasizes the imperative of addressing deficiencies in the data exchange procedure between Revit and ProtaStructure via IFC format. It is also important to note supports are automatically generated at the base of each column in ProtaStructure by default for strucutral analysis and design purpose.

5.3   Case Study 1 and 2: Comparison of Results

Table 6 presents a comparison of the outcomes derived from two distinct exchange scenarios in case studies 1 and 2, alongside their respective evaluations. These evaluations are determined using a percentage-based grading system, wherein the grade is calculated by dividing the number of correctly transferred structural elements/properties by the total number of elements in each category and then multiplying the result by one hundred percent.

Description	EVALUATION OF INTEROPERABILITY REQUIREMENTS					
	Export Structural Model from Revit to ProtaStructure		Import Structural Model from ProtaStructure to Revit		Export and Import	
	TRIP 1 (ProtaBIM) - Autodesk Revit to ProtaStructure	TRIP 1 (IFC) - Autodesk Revit to ProtaStructure	TRIP 2 (ProtaBIM) - ProtaStructure to Autodesk Revit	TRIP 2 (IFC) - ProtaStructure to Autodesk Revit	Round Trip - (Trip 1 and Trip 2)	Round Trip - (Trip 1 and Trip 2)
Geometry						
Overall Model	✔	◐✔	✔	✔	✔	◐✔
Grids	✔	◐✔	✔	✔	✔	◐✔
Storey Details (Height/Level)	✔	✔	✔	✔	✔	✔
Score (%)	100%	75%	100%	100%	100%	85%
Geometry - Structural Elements (Framing, Column, Slab, Footing)						
Beam (Length)	✔	◐✔	✔	✔	✔	◐✔
Beam (Cross section)	✔	◐✔	✔	✔	✔	◐✔
Column (Length)	✔	✔	✔	✔	✔	✔
Column (Cross section)	✔	✔	✔	✔	✔	✔
Slab Thickness	✗	✔	✔	✔	◐✔	✔
Slab (Cross section)	✗	✔	✔	✔	◐✔	✔
Footing (Depth)	⊖	⊖	✗	✔	✗	✔
Footing (Cross section)	⊖	⊖	✗	✔	✗	✔
Score (%)	67%	75%	75%	100%	70%	88%
Material Properties						
Material Type (Concrete)	✔	✔	✔	✔	✔	✔
Material Grade	◐✔	◐✔	✔	✔	◐✔	◐✔
Yield stress (fy)	✗	✗	✗	✗	✗	✗
Modulus of elasticity E	◐✔	◐✔	✔	✗	◐✔	◐✔
Shear modulus (G)	◐✔	◐✔	✔	✗	◐✔	◐✔
Density, ρ	✔	✔	✔	✗	✔	◐✔
Poisson's ratio	✔	◐✔	✔	✗	✔	◐✔
Score (%)	65%	55%	86%	30%	76%	43%
Load Cases and Combination						
Dead Load	✗	✗	✗	✗	✗	✗
Live Load	✗	✗	✗	✗	✗	✗
Wind Load	✗	✗	✗	✗	✗	✗
Load Combination	✗	✗	✗	✗	✗	✗
Score (%)	0%	0%	0%	0%	0%	0%
Boundary Conditions						
Fixed	◐✔	✗	✗	✗	◐✔	✗
Score (%)	50%	0%	0%	0%	25%	0%
Overall Score (%)	56%	41%	52%	46%	54%	43%

✔	The exchange of information/elements is correct
✗	The exchange of information/element is not possible
◐✔	The exchange of information/element is partially successful / Modification is required in the recipient software
⊖	Not Applicable

Table 6: *Comparison of Results for Case Studies 1 and 2*

For material properites and boundary conditions with comment marked as partially succesful, a grade of 50% was allocated. For beams and grids where all elements were exchanged but modification was needed in the recipient software, a grade of 50% was allocated. For elements/properties marked as (Transfer of element/information is correct) a grade of 100% is allocated.

6   CONCLUSION AND RECOMMENDATION

6.1   Conclusion

In this research, the evaluation of bi-directional interoperability between Autodesk Revit and ProtaStructure, employing both ProtaBIM and IFC methods, revealed significant insights into the strengths, and weaknesses of each approach.

Two case studies (cases studies 1 and 2) are evaluated to understand interoperability challenges. Case study 1 and 2 reports on the Bi-directional link exchange (ProtaBIM) and IFC capabilities between Revit (BIM platform) and ProtaStructure (FEM software. The process consists of two milestones which are: Trip 1 and 2, exporting structural model from Autodesk Revit to ProtaStructure using both Bi-directional Link (ProtaBIM) and IFC 2X3 and importing structural model from ProtaStructure to Autodesk Revit using both Bi-directional Link (ProtaBIM) and IFC 2X3 respectively.

Comprehensively, the study shows that case study 1 (Revit to ProtaStructure using the ProtaBIM) achieved the best result in terms of bi-directional interoperability. ProtaBIM excels in exporting and importing overall model geometry, achieving 100% success rate. However, it faces challenges when transferring slabs, walls, and footings into ProtaStructure due to a lack of support for these elements. Grids and storey details are accurately exchanged, achieving a 100% success rate. Comparing to IFC-based interoperability, geometry presents a mixed picture. While it imports correctly into Revit with a 100% success rate, manual adjustments are required to address structural member displacement (75% success) when importing into ProtaStructure. Grids also pose challenges, resulting in multiple lines in ProtaStructure.

In the interoperability of structural elements, ProtaBIM exhibits a tale of two successes. Beams, columns, and their cross-sections experience smooth exchange with a 100% success rate. However, slabs and walls encounter limitations as ProtaBIM lacks support for their export (0% success), though importing them into Revit is successful. Material properties, especially concrete grades, demand attention. ProtaBIM handles material type and density well, but concrete grade and related parameters require adjustment in ProtaStructure. Key mechanical properties like yield stress, modulus of elasticity, shear modulus, and Poisson's ratio also do not successfully transfer. Load cases, load combinations, and boundary conditions, critical for structural analysis and design, face challenges in ProtaBIM, achieving a 0% success rate. On the other hand, IFC-based interoperability exchange structural elements relatively well. Columns, slabs, and their cross-sections successfully traverse the platforms with a 100% success rate. However, beams encounter hurdles during export from Revit, distorting in ProtaStructure due to the use of the neutral axis, requiring manual adjustment. Material properties, including material type and density, transition seamlessly, but concrete grades and the corresponding mechanical properties requires adjustments in ProtaStructure. Notably, these properties

do not successfully transfer from Revit. Finally, load cases, load combinations, and boundary conditions also face obstacles in the IFC-based interoperability, achieving a 0% success rate.

Based on the findings, it is evident that the most advantageous approach for achieving bi-directional interoperability between Autodesk Revit and ProtaStructure lies in the export of structural models from Revit to ProtaStructure using ProtaBIM, paired with the import of models from ProtaStructure to Revit via the IFC format. This judicious combination of methods harnesses their respective strengths, resulting in an elevated overall success rate of interoperability—56% for export and 46% for import. Furthermore, it effectively addresses the inherent limitations associated with each method when employed in isolation.

6.2   Recommendation

Drawing from the research results, the following are recommended:

1. **Further investigation into ProtaBIM for export:** Given its higher success rate for exporting from Revit to ProtaStructure (56%), exploring and enhancing ProtaBIM's capabilities to support the export of additional structural elements like walls and slabs is recommended. This will contribute to a more comprehensive and seamless exchange process.

2. **Enhancing IFC compatibility:** Efforts should be made to improve IFC support in both Revit and ProtaStructure, particularly in terms of transferring load cases, load combinations, and boundary conditions. The development of standardized mapping and conversion rules for these elements could significantly improve interoperability.

 3. **Industry standards:** Collaboration within the AEC industry to establish and promote industry-wide standards for BIM interoperability is crucial. This will ensure consistency and compatibility between different software platforms, ultimately benefiting all stakeholders in the construction process.

The pursuit of seamless bi-directional interoperability between architectural and structural BIM platforms is essential for optimizing workflows, reducing errors, and enhancing collaboration in the AEC industry. This research has provided valuable insights into the challenges and potential solutions for achieving this goal. By implementing the recommendations outlined here and building on the strengths of ProtaBIM and the IFC format, we can work towards a more interconnected and efficient future for structural design and analysis within the domain of BIM.

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APPENDIX