TAMPERE UNIVERSITY OF APPLIED SCIENCES

Analysis of the interoperability from BIM to FEM

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ABSTRACT

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The aim of this study is to investigate the efficiency of a conversion from BIM-software to FEM-software. With this information, the engineer can save time, because he or she knows which conversions can be properly executed and which data losses will occur during each conversion when a BIM-model is being transferred.

In the first part of the thesis, the different possibilities to exchange the models between BIM-software and FEM-software are theoretically investigated and explained. Next, a simple model was created to examine the conversion practically. We did this by modelling a simple steel and concrete beam where, if possible in the BIM-software, boundary conditions were assigned to the nodes, loads were applied and for the concrete beam, reinforcement was designed. The possible conversions were reviewed and the properties of the sections, materials, geometry, boundary conditions and loads were compared. To investigate the conversion of node connections, their positions and the transfer of the slabs, an advanced model was designed and transferred for links where good results were obtained in the simple model. The conversions are performed using an IFC data format, a direct link or another intermediate file. Due to the IFC data format being promoted as an exchange format that is sufficient for a lot of software, it will be the focus of the authors to examine these conversions.

The results did not support the expectations that using an IFC file format is the ideal manner to exchange information between BIM-software and FEM-software. If a direct link is available between two programs, this is still recommended. Even an intermediate file, developed to be used between two specific programs, had better results for most of the conversions than using an IFC file format. However, IFC is a file format that can be used as long as the engineer knows which data is imported correctly from the BIM-model.

Foreword

After several years of study to obtain a master's degree in construction engineering, we, students at KU Leuven, have finally built up a solid understanding of the mathematical and constructional basics which enable us to do what we love the most: creating things. Some will let constructions come to life behind their desk by performing calculations, while others will see them grow every day on the site. We were able to explore both options thanks to an internship and two site surveys.

In our field, the learning process never stops, however our time as students is coming to an end. It is important that in the future we are able to search and process information and develop this ability to its maximum. All our acquired knowledge and skills will be combined in one final project, our master's thesis.

In the second semester of our master, we had the opportunity to study at Tampere University of Applied Sciences in Finland thanks to the Erasmus+ programme. These last few months were a journey; apart from writing our thesis with trial and error, we were submerged in many international cultures, which made our stay in Finland even more interesting. We would like to show our appreciation and gratitude for the involvement in our thesis to the people who helped us along the way.

A special acknowledgement goes to our supervisors Jaakko Aumala and Tytti Kaitala, who helped us through every step of the process. They introduced us to the Finnish education system, helped us to find an interesting subject and were the first persons we could go to when we had questions.

Writing our thesis abroad would not have been possible without Guido Kips, Hilde Lauwereys and Ilse Roelandt. They provided us with the necessary information about studying at a foreign university and helped us with all the administration for the exchange programme.

Last but certainly not least, we would like to thank our family and friends for their endless support and motivation.

Beirnaert Febe and Alice Lippens

May, 2018

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ABBREVIATIONS AND TERMS

AEC	Architecture, Engineering and Construction
AECO	Architecture, Engineering, Construction and Operations
AIA	American Institute of Architects
BCF	BIM Collaboration Format
BIM	Building Information Modelling
	Building Information Model
	Building Information Management
BS	British Standards
bsDD	BuildingSMART Data Dictionary
BSI	British Standards Institution
CAD	Computer Aided Design
CSI	Computer & Structures Inc.
DAM	Direct Analysis Method
DOF	Degrees of freedom
FEA	Finite Element Analysis
FEM	Finite Element Method
FM	Facility Management
HVAC	Heating, ventilation, air conditioning and cooling
IAI	International Alliance for Interoperability
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
IFD	International Framework for Dictionaries
ISM	Integrated Structural Modelling
ISO	International Organization for Standardization
LOD	Level Of Detail/ Level Of Development
MEP	Mechanical, electrical and plumbing
MVD	Model View Definitions
NBN	Normalisation Belge/Belgische Normalisatie
O&M	Operations & Maintenance
PAS	Publicly Available Specifications
RSA	Robot Structural Analysis
SMC	Solibri Model Checker

SLS	Serviceability Limit State
SMV	Solibri Model Viewer
ULS	Ultimate Limit State
XML	Extensible Markup Language

1 INTRODUCTION

1.1. CAD

Since the beginning of mankind, people are looking for a roof over their head. First living in cages, later on starting to make their own buildings. From little houses to pyramids and cathedrals, people have always been fascinated by architectural design. Nowadays, structures have become too complex and too time consuming to draw by hand. Only people with the correct qualifications, like architects or civil engineers, are allowed to lead the design process.

Every construction is built from a combination of different plans (architectural, plumbing, electrical, etc.) designed by different people (architect and engineers). During the design process and even the construction process, the plans may change due to collisions (for example a ventilation duct and a beam cannot intersect), cost, client requirement, and so on. Until the mid-20th century, the AEC design process was based on paper-based modes of communication, which often led to mistakes on the construction site and consequently to delays.

Due to the digital revolution, there is the possibility to use CAD (Computer Aided Design). This technology for design and technical documentation is widely used in the AEC-industry (architects, engineers and construction) [1].

When CAD software was introduced to the public in the 80's, it was only possible to draw in 2D. Over the next few years, the technology evolved and drawing in 3D was born. CAD software in 2D and 3D makes use of the same basic technology. Vectors are drawn in a 2D or 3D space, according to the program. The vectors can contain extra information, such as the layer they are part of, a specific line type. The previous is necessary to make the model structured.

An efficient building design process is the result of a good collaboration between the different participants, which can only be achieved if the plans that are made by the architect and engineers are unambiguously. Every change must be shared with the other members of the design team, which requires good communication.

Software companies offer solutions such as real-time technology (web tools) to make the design process as efficient as possible.

Currently, CAD software is not the only software used by the world's leading architecture, engineering and construction firms because since 2002 there is something better on the market: Building Information Modelling or BIM [2].

1.2. BIM

Many efforts have been made in order to share the different CAD-plans as efficient as possible. However, the workflow is still not ideal, especially when a combination of paper plans and digital plans is used. Overlaps can be overlooked during the design process and can cause problems on the construction site.

The possible problems with overlaps can be prevented when all the plans are combined in one model. The vectors used in CAD plans are banned and instead parametric objects are used. Every sector can use the model as a reference to base their own plans and calculations on. When adjustments have to be made, only one model has to be updated rather than each participants model individually. Eventually, there will be less interaction required between the members of the design team due to everybody having the same model at his disposal (figure 1). The traditional workflow is chaotic, while the new workflow is time-saving and reduces the chance of making mistakes. This improved workflow is better known as BIM [2].

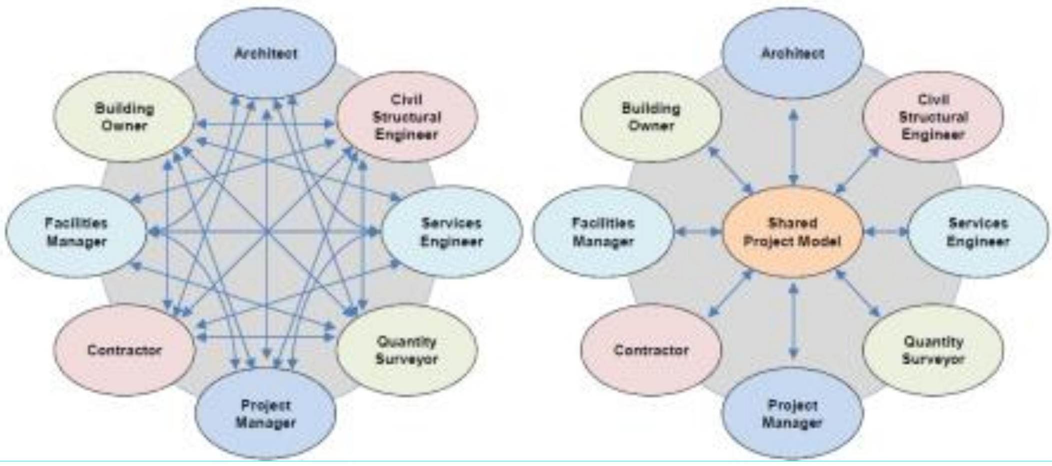


Figure 1: Traditional interaction model vs. BIM [3]

According to the National Institute of Building Sciences USA, BIM can be defined as:

> Building Information Modeling is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition [4].

Depending on the perspective, BIM has three different definitions.
First, BIM can stand for Building Information Modelling and represents the process of creating and managing the 3D model with the corresponding information about the structure during its life-cycle.
As a result of this process, the projects participants will be able to use the produced model as source for the overview of all the teams. In this digital model, information about the phases of the building process can be found. During the construction period, the model is updated several times until the construction is completed. Due to all the updates of the model, the model will be transformed into an as-built model.
The actual model gives BIM its second definition: Building Information Model.
Recently, a third meaning of the word BIM has been introduced: Building Information Management. In projects of every size, the different stakeholders have to create, manage and (re)use their digital information during the life-cycle of the construction. BIM is not just a 3D representation of the building, it can also contain additional information about the planning (4D), the costs (5D) and the management of the construction (6D). The focus of BIM in the third meaning has moved from the modelling process to the information itself [4].

1.3. FEM

In the design process, the architect is responsible for designing the construction together with the project team. One of the members of this team is the structural engineer, his job is to make sure that the construction will not collapse when a certain load is applied. For example, the strength and the fire resistance of every building element can be calculated by using the methods described in the Eurocodes. They must be applied to every structure in Europe, which will implement a uniform level of safety for all the constructions in Europe. Currently, there are 10 standards (reference design codes) in use:

EN1990	Eurocode: Basis of structural design
EN1991	Eurocode 1: Actions on structures
EN1992	Eurocode 2: Design of concrete structures
EN1993	Eurocode 3: Design of steel structures
EN1994	Eurocode 4: Design of composite steel and concrete structures
EN1995	Eurocode 5: Design of timber structures
EN1996	Eurocode 6: Design of masonry structures
EN1997	Eurocode 7: Geotechnical design
EN1998	Eurocode 8: Design of structures for earthquake resistance
EN1999	Eurocode 9: Design of aluminium structures

In addition to these ten standards, every country has the possibility to publish a national annex. The methods and values given in the national annexes overrule the ones in the reference design codes [5].

The calculations can be done by hand; however, this process would be too time-consuming, so computers are taking over most of the work, they are efficient and fast. Nevertheless, an engineer should not follow the results of the software blindly. By making some manual checks, serious mistakes can be avoided and more trust in the software will be gained.

The goal of the software is to solve numerically physical equations, which is also called ‘finite element analysis’ (FEA) and can be achieved by using the finite element method (FEM). FEM exists since the introduction of the computer in the late 50’s. Back in those days, the direct stiffness method was generalized and improved by M. Jonathan (Jon) Turner. He worked for Boeing, which means that the roots of FEM can be found in the aerospace industry. Nowadays, several industries make use of FEM, such as the mechanical and AEC industry [6].

Thanks to FEM, a whole range of problems can be solved by using Ordinary Differential Equations (ODE) and Partial Differential Equation (PDE) in combination with the boundary conditions. The method splits a geometrical model with boundary condition into finite elements, in other words: a mesh is created, and performs a simulation on the model. Thanks to this simulation, the engineer can see where the weak/ critical points in the design are located and if adjustments should be made. It is possible to make simulations of stress, strain, heat transfer, etc. [7]. More information about FEM can be found in chapter 3: FEM.

1.4. Problem definition

The transition from CAD to BIM is still ongoing, however, the advantages to use BIM are clear and BIM will continue to develop in the future. Eventually it is a timesaving technique that will become the standard in the AEC industry. The structural engineer will use FEM-software to make the calculations for the building which can be linked to the BIM-model. His job consists of two majors parts: modelling the construction and analysing the results. The structural model often had to be made from scratch, but if importing the geometrical model and data from the BIM-model into the FEM-software would be possible, more time could be spent on the analysis of the results.

Most of the FEM-software provide a way to import data from a BIM-model, which means that the analyses of the construction can be made quickly and relatively easy. The engineer would almost become unnecessary. However, this is not the case, especially when a BIM-model is used as the foundation for the structural model.

Everybody can push a button to make an analysis in the design process, but few can understand the calculations and check the accuracy.

Major errors can occur, some even undetectable, especially for those who are not aware of the thinking process behind the calculations.

FEA can solve almost every problem concerning for example stress and strain. You can say that FEM-software is a powerful tool for engineers as long as you keep in mind that the right questions have to be asked. This can be illustrated with a simple example.

When software is programmed to say ‘yes’ or ‘no’ and you ask which colour your sweater is, the program will still provide you an answer. This answer could be an error, which is good because the user of the software will notice that the question asked is not suitable for this program. The program could also provide the answer ‘yes’, which is even worse. If the user does not have the proper background to do these kind of analyses, he will be satisfied because he has an answer to the question, however he does not notice that the answer is nonsense.

Just because it is possible to import the foundation from a BIM-model, the geometry, boundaries, and so on are not necessarily correct. Some information may be incomplete or was never implemented (a fire safety engineer must supply some extra data for his analysis). Data can also be lost during the transition, or the values of certain properties can change (mostly to the default value).

It is even possible that the transition from BIM-software A to FEM-software B went perfect, but the transition from BIM-software A to FEM-software C will cause problems [7].

The scope of this master's thesis is to investigate which BIM-software is compatible with certain FEM-software, resulting that the structural engineer does not have to make a model from scratch.

In the next two chapters, chapter two and chapter three, more information will be provided about the concepts BIM and FEM. Different possibilities to link these types of programs are available, which are described in chapter four. In this chapter, the implementation problems that can occur are also explained.

Different kind of links between a wide range of software programs will be investigated in this thesis. The basic information of the used software programs can be found back in chapter five. After this, in the sixth chapter, the data formats that make the link possible will be explained followed by the description of the used method. The investigation of the case will be elaborated in the eighth chapter and we will end by giving the conclusion in the ninth and final chapter.

2 BIM

2.1. Building process

Traditionally, the building process is seen as a linear process that starts with the design of the building and ends with the architect handing over the keys to the client. The time needed for the design and the actual construction of the building are considered, however, the use of the building, renovation and demolition are not a part of this process although the building process does not stop here for the client. Even after the completion of the building, he still expects support when certain problems occur or when he decides to renovate the building and the plans must be changed. Nowadays, the building process is seen as a circular process in which every phase has an influence on the next [8].

Every member of the design team will produce information at some point. When everybody is providing information based on their standard, it will be hard for the other participants to efficiently find the necessary information. Gaps in the data are harder to detect and the information can change of interpretation. With a standardized process, agreed standards and methods during the design process, these problems will not appear. The PAS (Publicly Available Specifications) 1192 guidelines are used on an international level and are reviewed every two years. If the standard becomes outdated, it will be withdrawn, or changes will be made. It is also possible that the standard still applies, in that case the PAS document will become a formal British Standard BS [9], [10].

According to ‘RIBA Plan of Work 2013’ provided by the Royal Institute of British Architects, there are eight project stages defined that are used as a standard in the United Kingdom and are the guideline for the British PAS 1192. The infrastructure to support BIM is provided in the model, which promotes the use of BIM. The process is thoroughly developed and each stage consist of the following phases:

0. Strategic Definition

The vision of the company and the strategy of the client are defined.

1. Preparation and Brief

In this phase, the goals of the project are determined. The quality, ambition, durability and budget are agreed upon and a feasibility study of the wishes and the site are carried out. All of this will be included in the Initial Project Brief.

2. Concept Design

The first design is proposed, the preliminary cost estimation and the chosen and to be followed strategies are analysed. This phase is also included in a Final Project Brief.

3. Developed Design

In this phase the design is fully developed, including the suggestions for the coordination of the construction phase. The cost estimation and strategies are possibly revised and changed.

4. Technical Design

The technical design for the architectural, structural and services information is drawn to ensure an easy execution.

5. Construction

This phase should follow the Technical Design as close as possible. During the construction, problems can arise, these have to be solved in coordination with the according team.

6. Handover and Close Out

The construction is finished, the Building Contract is closed and the keys are handed over to the client.

7. In use

The use and maintenance of the building are in accordance to the predetermined service schedule.

The design process can be split up in different phases which all take up a certain amount of time: pre-design (PD), schematic design (SD), design development (DD), construction documentation (CD), procurement (PR), construction administration (CA) and last but not least operation (OP). OP covers the use of the building, renovations and demolition. Every adjustment to the design takes a certain amount of effort which depends on the phase the building is in (figure 2).

Line number 1 shows the possibility to have an impact on the cost and functionalities of the construction. In the design phase it is relatively easy to make adjustments while it is much harder during the construction phase. The second line represents the impact on the costs when the design changes. Figure 2 shows that during the CD-phase, adjustments to the design are more expensive than during the PD. The third line shows how the effort during a traditional building process is divided. It clearly shows that the design phase goes relatively fast and most of the time and effort is focused on the construction documentation. This is the other way around when the building is designed in BIM, as is shown by line 4, more time is spent on the design and optimization of the building. Line 4 matches relatively well with line 1, which means that most of the time and effort is spent during the phases where the decisions can be made relatively easy and the costs to make these are low. With this knowledge considered, it can be decided that the design process where BIM is used, is preferred over the traditional design process [2].

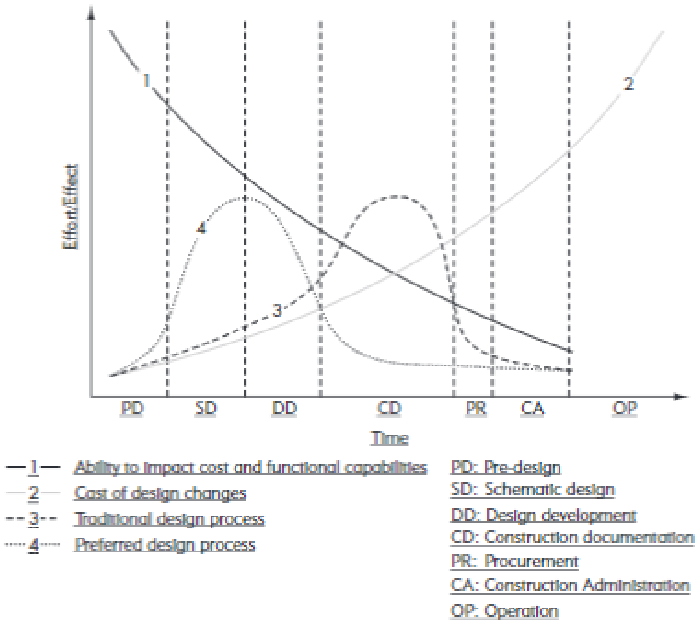


Figure 2: Effort/ Effect in function of the design phase [2]

2.2. Level of maturity

Not every design company has already made the transition from CAD to BIM and if they did, the capability of the BIM-model may vary between the companies. In order to have a clear view about the capabilities of the models, maturity levels were defined.
In 2008, Mark Bew and Mervyn Richards developed the UK maturity model. This is the BIM framework, it categorizes the BIM-technology used in a model in four different maturity levels by combining standards, guidance notes and their relationship to each other. These are displayed in a maturity model which has a recognizable wedge shape as be shown in figure 3 [11].

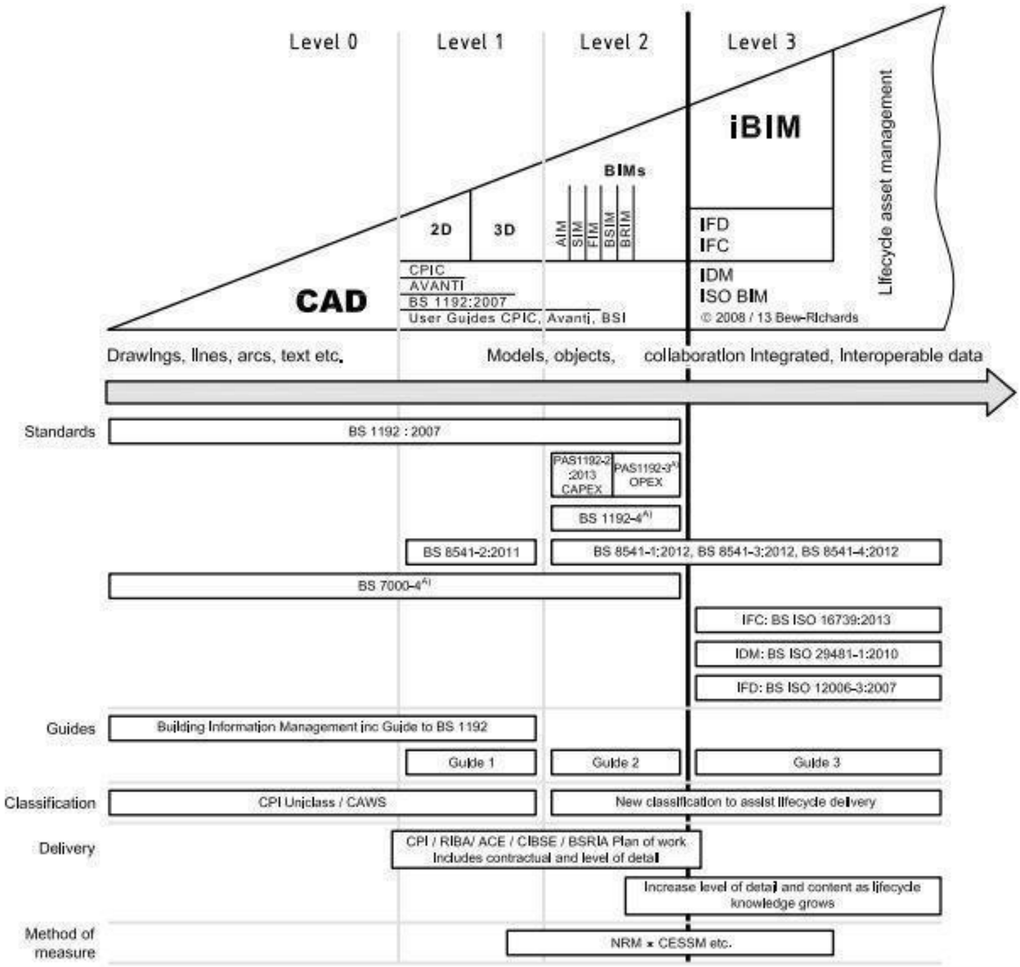


Figure 3: Maturity model UK [11]

According to the British Standards Institution (BSI) B/555 committee (construction design, modelling and data exchange), the maturity levels have the following characteristics:

- Level 0 cannot be seen as BIM-material, the model consists of unmanaged CAD, probably in 2D, and the drawings consists of vectors and are possibly provided with text. The medium that is used the most to exchange data of maturity level 0 is paper (or electronic paper like PDF).
- Most of the AEC industry has achieved level 1 which is described by the standard BS 1192:2007. Level 1 is managed CAD in 2D or 3D and may include some extra information. However, it still does not get the title 'BIM' because it is only possible to share standard data sets if there is a collaboration tool available providing a common data environment, like Google Drive. For example, it is not possible to integrate models from level 1 in standalone cost management software.
- There can be spoken about BIM when minimum level 2 is reached. The most crucial part of level 2 is the collaborative working between the project team members. The data exchange is enabled by a common file format (for example IFC) in the managed 3D environment. The participants can work with separate discipline BIM software as long as the information is exchangeable, which means it is not necessary to work in the same shared model. Extra dimensions can be implemented in the model like 4D (time-management) and 5D (cost calculations). Currently, the transition process from level 1 to 2 is ongoing in the AEC industry.
- A single, online, collaborative model is necessary to achieve level 3. The sixth dimension (life-cycle information) is also integrated in the project. When the requirements of ISO BIM are satisfied, a new name is used, iBIM (integrated BIM) [10]

As mentioned before, in order to be able to speak of a BIM-model a minimum of maturity level 2 is required. Guidelines are needed to distinguish the level 2 BIM-models from lower level BIM-models. The guidelines BS 1192 published in 2007 by the BSI are internationally accepted [10].

2.3. Parametric design

BIM-software has made it possible to use parametric design, which replaces vectors, used in CAD-software to represent building elements, by parametric objects. These objects are created in a model family and contain different parameters (such as distances, angles) which can be manipulated by a set of relations (parallel to, attached to, etc.) and rules. For example, when a window is created, the position of the top border must be higher than the windowsill. The defined rules also enable the possibility to automatically modify associated geometry, in other words: a roof must be supported by walls and a door must fit in a wall. When using parametric design, it is not possible to make changes to the properties if the rules are conflicting. This is possible in vector drawings which can cause problems due to the lack of any control protocol. It takes a lot of time to create model families in parametric design, however, changes can be made quickly later on in the design process. The properties implemented in the models will be used afterwards to exchange data to other disciplines (e.g. energy analyses). Eventually, vector design will be less precise and more time-consuming than parametric design [2].

2.4. Dimensions

As previously mentioned a level 2 (or higher) BIM-model is built with parametric objects, it consists of geometrical data and additional information such as materials, lambda values, which are properties from the third dimension. However, a BIM-model is much more powerful and can contain a fourth, fifth and even sixth dimension, if this option is permitted by the maturity level (see paragraph 2.2 ‘Level of maturity’).

2D is not used in this BIM-model, the geometry is created completely in the third dimension, however, it is possible to derive 2D plans (sheets) from the model, which will be used on the construction site. The clash detection tools are implemented in this dimension as well as the basics for visualisation.

The different disciplines (such as structure, energy) can use their own model or a shared model due to the possibility to exchange data with IFC. Although, this can give problems for the ICT-infrastructure considering the size of the files will be much larger and the ICT-software will be more complex.

Clash detection is always possible, even if a federated model is used because there are specialized tools on the market, for example Solibri Model Viewer [10].

The construction process is not finished in one day and even when the building is completed, there is always a possibility that a renovation will be executed. To introduce the concept of ‘time’, a fourth dimension is added. This dimension is extremely powerful in a world where ‘time is money’ and it is essential for the planning process. Animations can be made to visualize the construction sequence and site logistics. Nevertheless, one of the most important factors is the ability to communicate with planning platforms, these are a helpful tool when generating the planning sequence and can be updated on site using Field BIM tool to keep track of the progress [10].

Traditionally, cost estimations were made at the final stage of the design process. With BIM, a fifth dimension ‘costs’ can be implemented in the design process. The model contains information about the quantities of the building materials and components. The only obstacle is to import this information efficiently in cost planning software. When a library with project-based data is linked to the cost planning software, cost estimations can be made quickly. If the cost estimations are made during the design process, adjustments can immediately be made when exceeding the maximum budget

When the construction is finished, the BIM-model is updated until the as-built model is obtained. This model can still be useful for different purposes such as facility management and sustainability, which is a post-construction phase also known as the Operations & Maintenance phase. Some refer to the O&M phase in the sixth dimension, others in the seventh. In the last case, the sixth dimension will stand for sustainability and provide information for energy analyses. The purpose of 6D is to improve the facility management practices, which means that both definitions are correct because the domain of O&M overlaps with the sustainability of the construction [12].

2.5. Level of detail

Every construction process requires plans which hold some essential information about the structure. According to the phase of the design process, the model gets a level of detail (LOD), also known as level of development and gives the user a proper image of the level of completeness of the model.

The American Institute of Architects (AIA) defined 5 levels of detail in the document E202- 2008, which range from the lowest level LOD 100 to highest level LOD 500 as illustrated in figure 4. Each level contains all the characteristics of the previous levels.

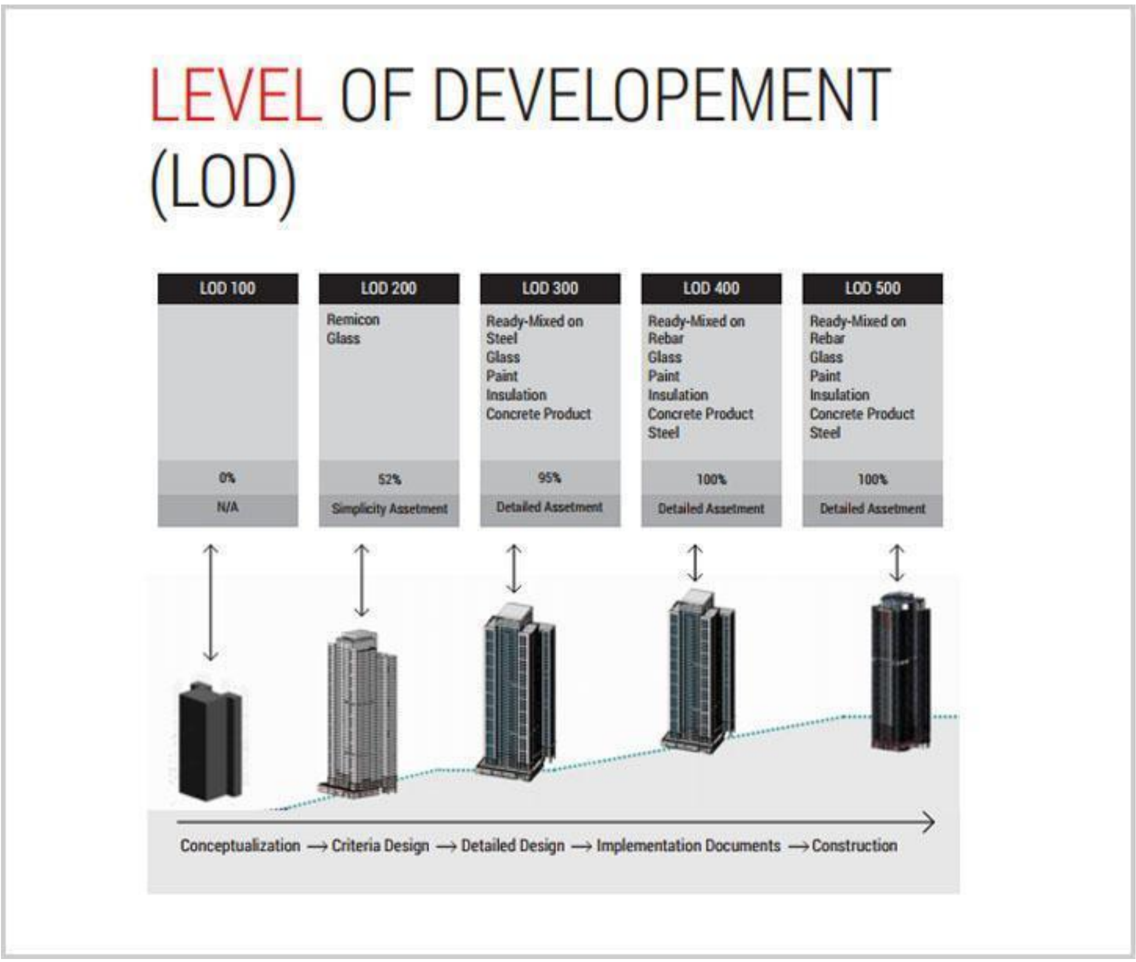


Figure 4: Level of development [13]

LOD 100 can be used in the beginning of the design process when there is not much detail required. A model with LOD 100 contains the overall building characteristics like area, height, volume, location and orientation. The geometrical shape and masses are represented in this model, which are necessary for project phasing, feasibility studies and basic cost estimations.

In the next level, LOD 200, the general shape of the building is further elaborated. The model elements are modelled as generalized systems or assemblies with approximate characteristics. The overall shape of the building can be refined by adding walls, floors and ceilings, some non-geometric information can be added however this is not a requirement. This means that the specific materials or components of the elements do not have to be known at this stage. The main goal of LOD 200 is to get a more detailed view over the project, the details of the individual elements will be determined in a higher level. Cost estimating in LOD 200 is based on conceptual estimating techniques which make use of the provided data (volume, quantities, etc.).

LOD 300 is reached when the building elements are specific assemblies, which means there are accurate terms available of the quantity, size, shape, location and orientation. In LOD 200 it was not necessary to define the windows, doors and skylights, these elements could be represented by an opening. In LOD 300 however, it should be possible to develop construction documents with the given information. This means that the dimensions of the building elements are known, together with specific performance information (lambda value, thickness of the components, etc.).
LOD 300 is a sufficient start point to develop a BIM-model. There are enough details for the construction documents and cost calculations and the time needed for the design process is acceptable. Clash detection, model checks and 4D-planning are possible for LOD 300 and higher.

When information about the complete fabrication, assembly and detailing is added to LOD 300, a new level of detail is reached, LOD 400. The elements contain enough details to be suitable for construction and conceptual cost estimating techniques are no longer necessary, because the actual cost of the specific elements when purchased is available.

The final level is LOD 500, here the elements of the model are updated so the sizes, orientations, locations, shapes and quantities are accurate. The elements in the model also contain some non-geometric data. These updates lead to the as-built model. This model can later be used to add, maintain or alter data of the project if the necessary license is provided. [14]

2.6. OpenBIM

As said in paragraph 2.2 ‘Level of maturity’, members of the project team have the option to work with discipline models or with a shared model. Discipline models have the advantage that they are easier to handle because of their size. Every participant can use their own model in specific software and later on, all the models will be combined and can be reviewed for clash detection. Every software has its own approach to handle data, which means that problems can arise when someone opens a model made in software A, with software B. These problems are for example information losses, information changes (to a default value) or gaps in the data. The shortcomings can be solved by providing a standard that can support different software packages.
This standard is called openBIM and provided by buildingSMART in collaboration with other software companies. BuildingSMART is an international organization without profit objective and provides the open standards and workflows that make sure a universal approach to the collaborative design, realisation and exploitation of building is possible.

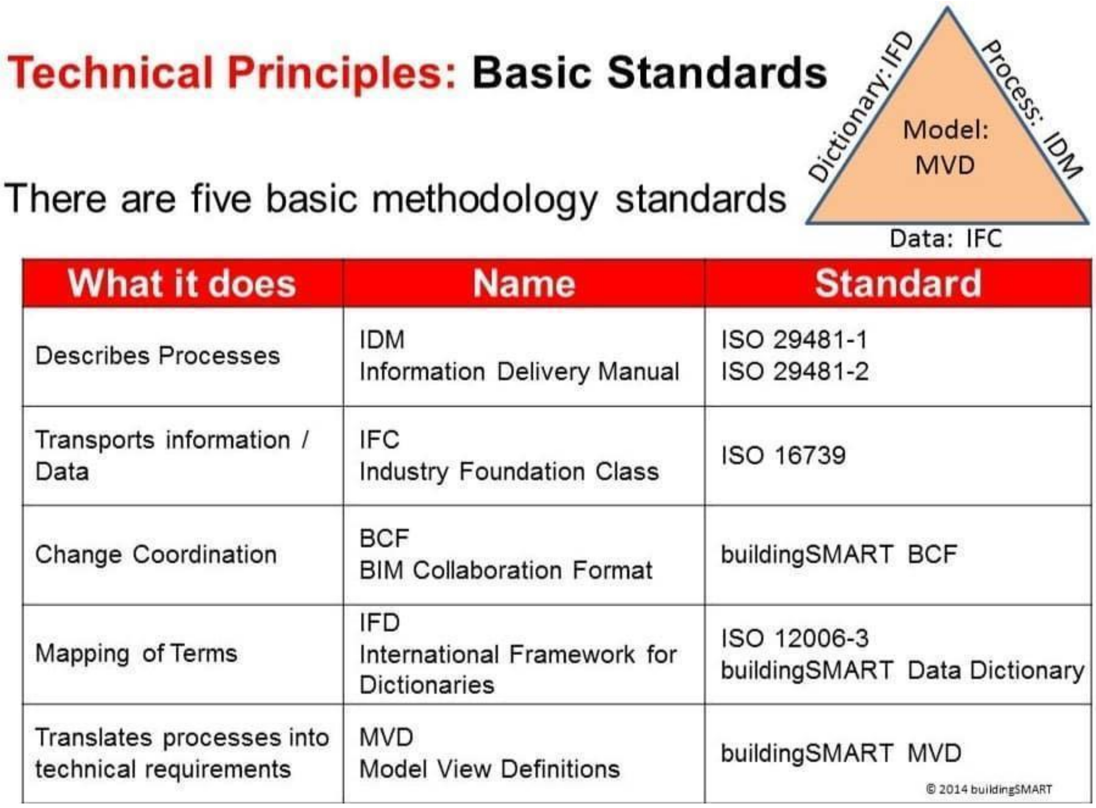
To achieve openBIM, BuildingSMART provides the following:

- a neutral Data Model to exchange information between different programs
- the BuildSMART Data Dictionary to standardize terms. Thanks to this dictionary an object (for example a window) will be interpreted the same in China as in Finland because the same data language is used.
- the ability to transform process requirements into technical requirements by providing the necessary methodology and technology [15].

The goal of openBIM is to exchange information between different partners efficiently and unambiguously. This is made possible by following 5 basic standards: IDM, IFC, BCF, IFD and MVD [16]. In this thesis, the following definition of a standard is used:

> “A standard is an approved specification of a limited set of solutions to actual or potential matching problems, prepared for the benefits of the party or parties involved, balancing their needs, and intended and expected to be used repeatedly or continuously, during a certain period, by a substantial number of the parties for whom they are meant.” [17]

Figure 5 gives an overview of the methodologies with the corresponding standards.



What it does	Name	Standard
Describes Processes	IDM Information Delivery Manual	ISO 29481-1 ISO 29481-2
Transports information / Data	IFC Industry Foundation Class	ISO 16739
Change Coordination	BCF BIM Collaboration Format	buildingSMART BCF
Mapping of Terms	IFD International Framework for Dictionaries	ISO 12006-3 buildingSMART Data Dictionary
Translates processes into technical requirements	MVD Model View Definitions	buildingSMART MVD

Figure 5:Technical Principles: Basic Standards [16]

IDM

IDM stands for ‘Information Delivery Manual’ and is the process standard. IDMs are crucial to provide information about the role of every project member, they describe the information processes during the life-cycle of the construction, or in other words, which information is required at what time and which member should provide it. As shown in figure 5, there are 2 standards for IDMs: ISO 29481-1 and ISO 29481-2.

ISO 29481-1 describes the methodology and format of IDMs, which should make the interoperability between software applications easier while the guidelines for the interaction framework are provided by ISO 29481-2. It focuses on how the coordination between project team members should be during the life-cycle [16], [18]

IFC

IFC is the abbreviation for 'Industry Foundation Classes', which is a neutral data format to describe, share and exchange information between different software packages in the AEC industry. ISO 16739 is the standard that must be followed. In paragraph 6.10 'Standardized solution: IFC', more information will be provided about this data format [16].

BCF

During the design process, there is a need to exchange information multiple times between the members of the design team. In the traditional design process, every time there was a question, problem or proposal, the issue had to be described, send to the other party and be encoded, which was a time-consuming process. The alternative was to implement the information in the IFC and the whole BIM-model had to be send back and forth. Data losses could occur every time the model was imported or exported.

The solution was an open file format based on XML (Extensible Markup Language) that made it possible to add comments to an IFC-model. In 2010, 'bcfXML v1' was released by Tekla Corporation and Solibri Inc, which is replaced by 'bcfXML v2.2' since March 2017.

Every project team member uses the necessary software, which is not always compatible. As long as an export to an IFC-model was possible, no problems occurred. The IFC-file could be opened by others in a viewer, like Solibri Model Checker or Tekla BIMsight and comments could be added in bcfXML-files. These files were send back and could be opened with a plug-in for BCF (BIM Collaboration Format). Due to the bcfXML-file which specifies to which part the comment was related, making adjustments to the model goes relatively quickly [16], [19].

IFD

The International Framework for Dictionaries (IFD) is a standard that was used to create the BuildingSMART Data Dictionary (bsDD). This library contains and explains terms of the AEC industry from all over the world to make sure the terms are unambiguous. It means that a 'door' in English, 'deur' in Dutch and 'ovi' in Finnish will refer to the same object and the properties will be interpreted the same. For example, dimensions can be provided in different units (metric or SI). IFD requires an object to be described with its corresponding definition, properties and relations to other objects. If everybody uses the same library, there will be little room for error [2], [16].

MVD

When working in a discipline model, most of the time it is unnecessary to show the data of the whole model or, the other way, the data should be more detailed. For example, a fire safety engineer must know detailed information about the fire behaviour of the building elements, as this is unnecessary information for energy analysis. There is the possibility to use a subset of IFC data for a specific model. All the necessary IFC concepts (classes, attributes, relationships, etc.) for a subset are described by the Model View Definitions (MVD). It can be seen as a constraint or expansion, depending on the needs of the user, or of the IFC guidelines [2], [16], [20]. Extra information about MVD can be found in paragraph 6.10.5 'MVD'.

3 FEM

3.1. Analyses

The structural analysis of a construction is the responsibility of the structural engineer. First, the engineer must ensure that a construction will not collapse under a certain load in the worst-case scenario. However, there are also other requirements that have to be taken into account, for example, the horizontal and vertical deflections cannot be unreasonable big, even if the beam is capable of carrying the weight of the roof. The restrictions for the deflections are given in NBN EN 1990. Depending on the project, there will be made a static, stability or vibration analysis. Some projects require different kinds of analyses. For example, in an earthquake-prone area, a vibration analysis will be necessary, while in other areas only a static analysis is required.

Loads can be moved and have fixed values. If they are only considered without the dynamical effects, the performed analysis is static.
The static linear analysis can be used for most of the problems if the following conditions are met:

- Hook's law should be applicable on the materials: $\sigma = E \times \varepsilon$
- The deformations of the structure must be small
- All constraints work in two directions, if the displacements are prevented in one direction, they are also prevented in the opposite direction.
- The loading does not change the parameters of the structure.

If one of these conditions is not satisfied, there is still the option to perform a non-linear analysis.

When the critical load for buckling has to be calculated, a stability analysis will be used. This is the second group of analyses and will be used when time-independent loads are important. It can also be used to check if a second order calculation is necessary.

The dynamic analysis is the most complex group of analyses. Time-dependent loads are taken into consideration, these are shock, seismic and moving loads with their dynamical effects. Dynamic analyses are mostly used in areas with a high chance of earthquakes or for the analysis of an pedestrian bridge [21].
All these kinds of analyses are based on methods which are described in the Eurocodes. When done manually, they would take too much time, nowadays software is available that can solve the necessary differential equations. However, it can come in handy to control certain elements of the construction manually.
FEM-software provides the engineer to determine the most critical points of the structure. The construction will be safe if these points meet the requirements of the Eurocodes.

3.2. Basic principles

The finite element method can be used for mechanical or civil engineering problems. At the start of an analyses and during this process executed by an engineer, some assumptions have to be made to simplify the problem. There can be spoken about an elastic analysis when the following assumptions are met:

The material of the structure must be elastic, which means that

- The materials are following Hook's law, therefore the relationship between stress and strain is linear.
- The applied loads only cause small deformations. If the dislocations are too significant and change the original design diagram, it is not possible to perform an elastic analysis.
- The principles of superposition can be used. This is a method that is used when multiple loads that are acting simultaneously are taken into consideration. A factor (reactions, stress, strain, etc.) will be determined for each load separately and afterwards the algebraic sum will be made, which gives the same result as when the problem would not be subdivided in smaller parts [21].

An observant reader will notice that a few conditions are identical for the static linear analysis, this is logical because the static linear analysis is an elastic analysis.

All of the previously mentioned assumptions can be made for most of the structural analyses, which means that an elastic analysis can be performed. However, for some complex structures, these simplifications are changing the model too much and they have to be reviewed. With the assumptions kept in mind, the procedure can start. According to Prasad Konda and Tarannum SA. this always consists of the same basic steps [22]:

1. **Pre-processing**

   This phase consists of several steps that should not be rushed.

   First, a model will be made representing the geometry of the structure. It is a simplification of the reality and consists of points, lines, areas and volumes. Depending on the software, the model can be made in 2D or 3D. In this geometrical phase, the materials and boundary conditions are also implemented. Then, the engineer determines the value and placement of the loads that should be applied such as the self-weight of the elements, imposed loads or wind loads. The final step of the pre-processing phase is to subdivide the model into finite elements.

   The elements are form-retraining and are connected to each other by nodes. The best example of form-retraining elements are triangles. Apart from a geometrical shape, the elements also contain a limited number of degrees of freedom (DOF), these are the parameters in the equations that can vary independently from each other.

   The combination of the geometrical shape and the DOF enables the engineer or software to describe the behaviour of the elements, all these elements together are called a mesh. It is important to check if the mesh does not contain any irregularities, as these can cause strange results in the post-processing phase. The size of each element in the mesh is also important. Too coarse elements may lead to an inadequate resolution of the parametric distribution. On the other hand, too fine elements would ask a lot of computing time without significantly improving the results. Even more, it is not even possible to get the exact results due to the assumptions that were made earlier. To get a reasonably approach of the reality, some experience is required [23]. But if an appropriate mesh is chosen, the obtained results will enable the engineer to choose elements for the structure that are capable to handle the applied loads.

2. Processing

In the processing phase, a system of linear algebraic equations will be solved. As a result, a certain factor (reactions, stress, etc.) of every node will be known. Due to the fact that form-retraining figures are used, it is possible to interpolate within an element. As a result, the factor for every point within the element will be known.

For the most common problems, structural engineers are mainly interested in the stresses and strains of a construction. The assumptions that were made earlier, ensure that the stresses can be calculated with Hook's law. The function of the displacements within the element, in combination with Hook's law, is used to determine the strains, these are necessary to calculate the deformations.

3. Post-processing

This phase visualises the numerical output of the processing phase to make it easier for the engineer to interpret the results. It is more time-consuming to interpret the numerical outputs than the graphic outputs and displays. Critical points can quickly be found when colour-coded maps are made. Most of the time the colour red will indicate the weak points of the structure. If these points do not meet the requirements of the NBN EN 1990, some adjustments must be made to the model.

Time can be saved in the pre-processing phase by importing data from a BIM-model. However, a good collaboration between the architect and engineer is necessary because otherwise a lot of time will be lost with figuring out the assumptions made by the architect. If there is a good communication between the different parties, mistakes are less likely to happen.

4 Interoperability

4.1. Definition

When a structural analysis is performed with FEM-software, some basic steps should be followed. The procedure containing these steps is explained in chapter 3: FEM and exists of a pre-processing, processing and post-processing phase.

The pre-processing phase exists of modelling the geometry of the construction from scratch and making some important assumptions. The modelling is a time-consuming process that can be optimized thanks to the technology available today.

If a solid connection can be realised between the BIM- and FEM-model, the BIM-model can provide the geometrical structure and additional data (for example boundary conditions) for the FEM-model. This would save time during the pre-processing phase. In order to achieve this connection, interoperability is inevitable which means that program B should be able to handle the information provided by program A, even if the interface and the programming language are different [24].

This can be done by translating the model into a file format, readable by the other software-packages. However, retaining information from the original file is quite a challenge due to the available software-packages handling information in a different way.

A large number of software companies provide BIM- and FEM-software. Their software packages come with modelling and construction-related software tools to make sure their programs are compatible. Most of the time, the link between the programs is satisfactory. Issues arise when a connection between the software from two different vendors has to be made [25]. There was a need to create standards to ensure the interoperability, especially when 3D-parametric objects are downloaded from the internet or e-platforms are used [25]. These standards were provided by the International Alliance of Interoperability, better known as BuildingSMART.

Figure 6: Logo BuildingSmart [9]

The IFC standards are their biggest accomplishment, they are also published by the International Organization for Standardization and ought to be followed by the entire AEC industry (figure 6) [9].

As said before, the greatest benefit of interoperability is that it speeds up the design process because information from one model can be reused. Another advantage of the interoperability between programs is that it improves the quality by:

- Automating the tasks, like the conversion of the model or the addition of new information so human mistakes are less likely to happen.
- Implementing the model correctly, the geometry is completely the same and mistakes due to different dimensions are avoided.
- Providing tools in the software such as partial models and special filters. These make it easier to navigate in the model and find certain information. [26]

4.2. Connections

There are different approaches to establish the connection between the BIM- and FEM-software. They can be categorized by the routing mechanisms of information, or by the exchange format of information. When the connections are characterised by the routing mechanisms of information, the following approaches are possible (figure 7) [26]:

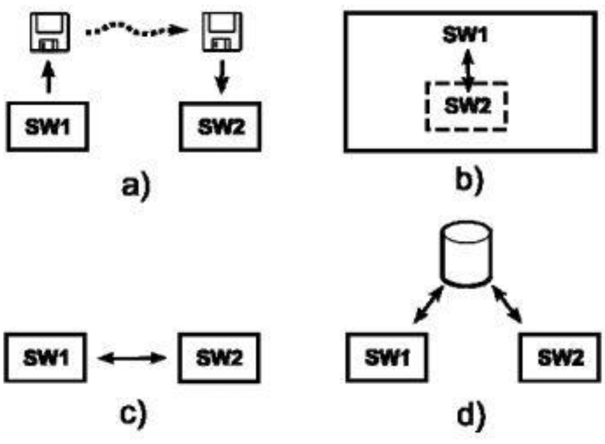


Figure 7: Routing scenarios: a) File-based b) add-on c) direct link d) database connection [26]

- **File-based**

  The most common way to exchange information is by using a file-based operation. The information is extracted from the model into a file in a selected format. This file format can either be one of the communicating systems or an intermediate format.

  An example of a communicating system is ISM, which can be used to establish the link between AECOsim Building Designer and STAAD.Pro, both from Bentley, see paragraph 6.4 'Integrated Structural Modelling'. For the intermediate format, IFC is an example, more information can be found in paragraph 6.6 'Standardized solution: IFC'.

  The advantage of using an intermediate format is that exchanging information between software from different vendors is possible and applications become more independent from each other. However, there is also a disadvantage. Two conversions must take place to exchange the information. The first one from the source format to the intermediate format and the second one from the intermediate format to the destination format. Due to the conversions being the weakest points of the process and two conversions have to take place, data loss is more likely to happen.

  The other option is using native files to exchange information. Here there is only one conversion necessary so the risk of data loss decreases. However, more software maintenance is necessary especially when the conversion process or a program is updated because both programs must be able to handle the information in the same way.

- **Add-on**

  The extension of software features added to an existing program is called an add-on, even if there are no visible signs of the interoperability. One example of an add-on is the connection between ArchiCAD architectural design software and the VIP-Energy's analysis engine. It is not possible to make use of all the functionalities of VIP-Energy package in ArchiCAD, but the add-on provides a subset of functionalities, which will make the information transition easier. The subset makes it possible for the architect to make a quick estimation of the energy performance in the architect domain and presents the results in a host-system.

It is a handy tool for the architect who does not fully understand all the aspects of the energy analysis. However, this tool cannot replace the full equipped program the energy engineer uses.

When the calculations need to be more precise and reliable, the file-based operation is used by the add-on. This means exporting the full input data from the architectural software to the main VIP program to perform an extended analysis.

- **Direct link**

  If the possibility to use a direct link is available, two standalone programs will be able to exchange information in real time. Unlike a file-based solution, the user cannot see the data transfer. One example of a direct link is the connection between Revit and Robot Structural Analysis (see paragraph 6.1 'Direct link between Revit and Robot Structural Analysis').

  The source system provides the information for the operation, but calculations will be performed in the destination system. When a direct link is used, data can be exchanged much faster compared to the file-based solution. However, it also implicates the next requirement. Both tools must be available at the same time, although this does not necessarily mean that both software programs must be installed on the same computer.

  If the software programs are installed on the same computer, a greater knowledge from the users is demanded, because they must be able to work with both tools.

  This demand of the user is not required when the link is established between software of different users. However, it is necessary that both users can work simultaneously on the task, this exchange process takes a lot of effort to organize.

- **Database connection**

  This method does not exchange information but shares it. A model is stored in a local or remote database, then, the relevant information can be extracted for a different software using a specialized tool.

  The database connection has the same advantages as an add-on and a direct link. Even more so, it is not necessary that both programs are available at the same time, which simplifies the organization of the exchange process unlike direct links [26].

The connections can also be divided based on the exchange formats of information. There are proprietary formats and open standard formats. The used format will have repercussions on the interoperability of the programs.

- **Proprietary format**
  When two different programs from the same vendor are used, the availability of a proprietary format is highly possible. The program accepts or outputs the data in a specific way and will enable a smooth transition between the different programs. If the two software programs are not from the same vendor, the use of a proprietary format will not be possible, therefore other solutions are available [27], [28].
- **Open standard format**
  It is a safe choice to use universal or open formats when it is unknown which software will be used in the next phase. By standardizing these formats, information can be exchanged between different software applications. In the AEC industry, IFC is the best-known example of an open standard format. It is developed and maintained by BuildingSMART and published by ISO, which means that it is an international norm. More information about IFC can be found in paragraph 6.6 'Standardized solution: IFC' [16].

4.3. Conversions

The conversion from one program to another can be made manually, automatically or semi-automatically [26]:

Manual conversions

When a manual conversion is performed, the information will be imported in the destination tool without alterations. The functionality for storage and presentation of the two systems must match, otherwise the file cannot be imported. After the destination program has imported the data, an interpretation of the data can be performed by the user. One example of a manual conversion is a DWG based exchange. Programs as FEM-design are able to import the CAD information, later the user has to interpret the information and make BIM-objects with the provided tools in the program.

Automatic conversions

To speed up the conversion process, an automatic conversion can be used. The incoming data will be converted automatically by following predefined rules. However, automatic conversions should be handled with great care due to the process having its limitations, which can cause incomplete conversions. For example, the geometrical model made in an architectural program can be imported in FEM-software. If the model exists of relatively easy shapes, problems are not expected or easily detected. However, when the user is unaware of the limits of the conversion and complex shapes are imported, most of the time the conversion will create an incorrect model.

Semi-automatic conversions

When using a semi-automatic conversion, the model is not completely converted. The user can manually choose on which part of the model the operation should be executed using the predefined algorithms and rules.

4.4. Implementation problems

As said before, conversions can be executed manually, automatically or semi-automatically and improve the design process. However, every conversion has its limitations to be considered, otherwise, the conversion will produce incorrect models. To fully understand the conversion process, some of the most important difficulties will be explained in the following paragraphs.

4.4.1 Different views

The design process exists of different aspects. The architectural design on one side and the structural and energy analysis on the other, are all important parts of the process. The same model will be used for every operation, but the perspective will be different because some tools require a different form of geometry, a different level of detail or will handle concepts in a different way.

Ideally, the information from the architectural model is reused in the other applications, which means that the data for the destination tools does not have to be redefined but will be generated based on the data of the source tool. The conversion comes with some difficulties, which can be illustrated with the conversion from the physical to the analytical model. The conversion will depend on the model used in the source tool. Models made in the conceptual design phase will be simplified and converted in a different way compared to models made in the design phase due to having a different level of detail.

The correct approach for the conversion must be selected based on the incoming model's nature, which is a functionality of some 'intelligent' computer systems. However, the limits of this function are often overlooked due to the software vendors extolling the effectiveness of the interoperability of their programs while the limitations are not emphasized enough. Even when customization parameters are used, it remains a challenge to design and implement a fully automatic solution suitable for every situation [26].

4.4.2 Conversion of geometry

The goal of FEM-software is to make a structural analysis based on an analysis model. The geometrical model of this analysis is different from the model in the design tools, especially from the architectural tools where the main goal is to create a physical model.

The physical model exists of 3D parametric objects and cannot contain any clashes. As said before, BIM-programs are made to avoid clashes in the model, they detect and provide the location of the clashes quickly and make it easy to eliminate them. All the 3D objects together will create a representation model that provides a visualisation of the project and is used to create drawings in a later stage of the design process.

The analysis software does not need 3D objects but needs a continuous analytical model which is created by representations of the parametric objects in 1D and 2D. The software can visualize the model in 3D by generating a 3D extent of the representations, for example a beam will be represented by a single line. This will cause clashes in the representation model, for example the cross-sections may clash, but these are irrelevant for the analysis.

Before the conversion of the models between different tools was possible, the structural engineer translated the physical model into an analysis model and built the analysis model from scratch. Sometimes it was possible to speed up this process by importing a DWG-file, which is a manual conversion. To make a correct analysis model, the structural engineer has some specific knowledge at his disposal which is difficult to put into algorithms for the software.

For example, only the structural parts of the architectural model are necessary for the analysis model. This means that the boundaries of the elements in the different models will not match and will cause apparent incompatibility (figure 8). When guidelines for the modelling activity are provided, it is possible to make an automatic conversion in some cases.

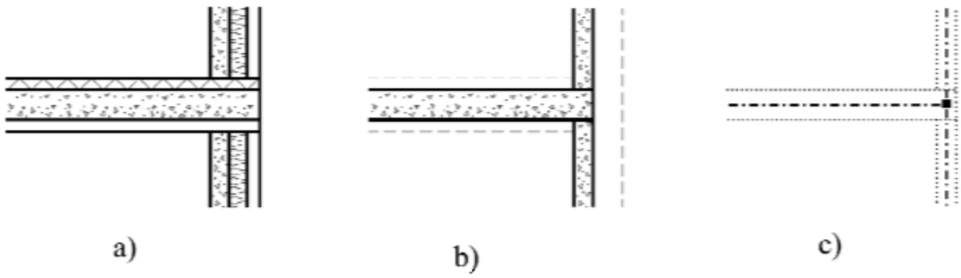


Figure 8:a) architectural model, b) structural model c) analytical model [26]

Ideally, there would exist a general method to convert every occurring 3D architectural situation into an analytical model. A general method is still not achieved, but some steps in the right direction are already made. For instance, to keep the conversion process simple, the modelling tools have limitations but by providing some special purpose connections, the most common situations can be handled. However, not every situation can be managed with this approach because it is too difficult and expensive to implement this while the wished results are not achieved [26].

Some programs contain a structural and an analytical model, for example Revit, which makes it easier to export information to FEM-software. The exchange will happen based on the analytical model. However, the main goal of the modelling software is to create a visual appealing model, which will be used for further purposes. Even an excellent architectural model does not ensure a good underlying analytical model.
As shown in figure 9, the representation model gives the impression that the columns and beam are connected. However, this is not the case for the analytical model. The analytical model should be checked before the exchange, or tools to fix these issues should be provided by the software vendor [29], [30].

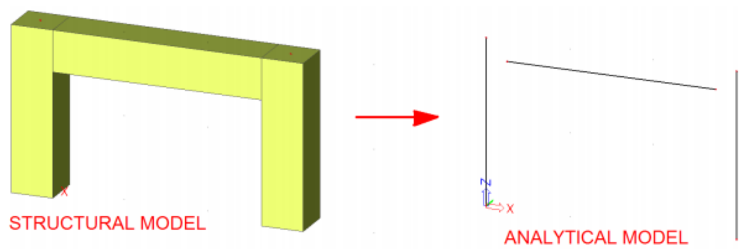


Figure 9: Conversion from a structural to an analytical model [30]

4.4.3 Translation of compatible information

A BIM-model is a model that exists of 3D parametric objects which means that the objects contain extra information apart from the geometric information. Information from the architectural model will be reused in the other disciplines, which is an advantage at first sight. However, it can cause complications when concepts are handled differently, which is often the case when it comes to using associated material attributes.

This problem can be illustrated by looking at the properties of ‘concrete’, a material that can be found in an architectural and structural model. The first problem arises when the identification of the material in both models should take place. There is a big chance that the properties of ‘concrete’ in both problems are a little bit different. Some will not be used in the architectural application while they are essential for the structural application and the other way around. It is also possible that both applications generate information with the same parameters, but a different approach is used.

All the parameters should be generated based on the Eurocodes, but there is still the choice between only defining the main parameters and calculate the dependent values by the provided formulas or defining all parameters with the help of the tables with standard material parameters. Both approaches should have the same outcome, but this is not always the case.

The following characteristics for concrete C25/30 can be found when the values are derived from table 3.1 of the EN 1992-1-1:2005: f_{cm}= 33 N/mm² and f_{ctm}= 2,6 N/mm². When the formula given in the same table for f_{ctm} is used, another value is generated: $f_{ctm} = 0{,}3 \times f_{ck}^{2/3} = 0{,}3 \times 25^{2/3} = 2{,}56496$.

The difference between these 2 values is small, however when two programs use another approach and therefore generate the parameters differently, it becomes difficult to make use of parameter-based pairing.

In many design tools, it is even possible to define custom materials, which will make the conversion even more complex and will make a generic conversion impossible. Some software vendors, like Strusoft (the provider of FEM-design), provide a conversion table that makes the explicitly pairing of the materials between both programs possible. Thanks to this table the user has more control over the parameters, which shifts the responsibility to obtain a correct conversion form the software provider to the user [26].

4.4.4 Recurring exchange

Designing a building is a circular process due to the ongoing reconsideration of the design, adjustments are made constantly. Most of the time, the adjustments have an influence on the other discipline models, which means that recurring exchanges between the interconnected software tools must be made. Instead of transferring the complete model from one application to another, another protocol will be followed; information about the changes will be transferred between the tools. By identifying these changes, it will be possible to invalidate the information that has been changed compared to the previous model. The parts that are not related to the changes and therefore are unaffected, must be kept intact in the destination system. During this process, some problems will arise.

The first challenge appears in the identification of the changes. It is preferred that the information about the state of the previous model is stored in the source tool, but it is also possible to store this information in the destination tool. The information exists of the data that is added, changed or deleted in comparison with the previous model. There is taken notice of these changes in the design history of the model in the source tool. Eventually, the changes will be exported to the destination tool with the help of a sending system. To get a proper exchange, the change management of the source system should be able to identify the changes on the required level of detail, which is often not the case. The functionality can be absent and even when it is provided, there is a big chance that it is not detailed enough to achieve a reliable exchange of information.
Here is an example to explain this subject; a change to an object can be identified, but the type of change is unknown. In this case the destination system must identify the change. If the re-exported model does not have changes which are relevant to the structural analyses, it is not necessary to update the related analysis model. In the situation where the change management is not detailed enough, and the source system only provides change notifications on object level, the destination system must identify the type of change by comparing the object attribute level. Following the recognition of the changes, the necessary updates of the model should be executed on the receiving side in two steps. First the changed incoming model information format must be repeatedly translated and converted to the format of the corresponding destination model.

It is possible that previously identified conditions for automatic conversion could fail which leads to the requirement of manual control. Due to this, the workflow of the interoperability may also change.

Secondly, changes must be made to the additional elements of the model in the receiving software. An example of this situation is when the geometry of a slab is changed and the loads that are relevant to this slab are not changed with the geometry, or loads that are not relevant to this slab are now active on the new geometry of the slab. In case that the analytical tool is not designed for a handling related to the change management, the changes can only be corrected manually. The operations of the change management are very complex and therefore it is required to intervene manually or, for the general cases, at least perform a manual review. For software developers, the lack of aligned procedures of change management between different construction design tools makes it even harder to supply an effective automated aid for recurring exchange. The Strusoft tools require due to these shortcomings a significant number of manual handlings to follow up the changes made in the interconnected design tools. These include the manual comparison of incoming details and manual modifications to the existing destination model [26].

4.4.5 Procedural uncertainties

One construction will be represented by multiple models: an architectural, structural, analytical, etc. These models will not look exactly the same because of their nature, which is already mentioned in paragraph 4.4.2 'Conversion of geometry'. Often the same concepts return in various models and it is possible to define them in each of the used software. Because of this possibility, the question raises in which system (sending of receiving) the information should be created.

Nowadays, the structural information is defined in structural modelling systems like Tekla Structures. These systems can achieve a high level of detail even for connections between different building elements. The actual analysis must be done in another program which requires an information transfer. Adjustments in the analysis model have as an implication that the structural model must also be changed. This workflow will demand more work and a better developed data exchange operation. Another option is to avoid the information transfer by using an add-on to perform the analysis. However, even with these add-on's structural modelling tools cannot reach the required level for structural analyses [26].

4.4.6 Different level of features

Every software application provides some features that cannot be found in other programs. For example, some modelling programs are perfectly capable of creating curved surface objects (like walls). It can take a little longer for the software developers to implement calculations for these curved objects in the structural analysis tools. This can lead to a situation in which the feature is available in the modelling software, but a conversion is impossible because the same feature is not supported in the analysis software. Curved objects are a very specific example, but the same issues arise when a different information level about the materials is used.

Different methods can be used to deal with the difference in features.

- The easiest method is to drop the unsupported concepts, which means that the feature and the corresponding data will be lost. When the destination program does not support a curved wall, the user will notice it immediately.

The real problem arises when it is not easy to spot the difference in features, for example when the information level about the used materials is different. Ideally, the software should inform the user about the loss of information, but it is quite difficult to discuss a non-existing concept.

- The feature can also be substituted, which will still lead to a data loss, but it will be less problematic compared to dropping the unsupported concepts. The goal is to mimic the desired solution, which is a challenge for the developers.
  For the example with the curved wall, this would mean that the curved wall can be replaced by one or several straight walls. When you keep in mind that the data loss should be as little as possible, it becomes clear that when several walls are used, the original model will be better approached. There should be used as many walls until the error margin in acceptable. This solution still is not ideal, even if a reliable analysis can be executed. Due to executing a substitution, several variations of the same model will circulate around. When in a later phase all the information is brought together in one coordination model, errors in consolidating information will occur.
- The last solution is the most difficult one. The level of features of both programs will be synchronized. Normally, a synchronization happens in both ways, but this would lead to a degradation in one program and an elevation of features in the other. A degradation is undesirable because it results in a loss of functionality. Ideally, the synchronization happens in a way that only an elevation of the feature level takes place, or in other words: only the missing features are implemented in the program. The idea of this conversion is simple, but the implementation in the software is a bit harder [26]**.**

5 Software

The scope of this thesis is to analyse the interoperability of a variety of programs. The choice of software is based on the popularity and usability of the programs in Finland and Belgium. To obtain the required software, a student license was used in most cases. After some research, there was decided that the following software programs will be used for the analyses (table 1):

Table 1: Overview software

BIM-software	**FEM-software**	**Viewer/ clash detection**
ArchiCAD 20 INT	Autodesk Robot Structural Analysis Professional 2018 (RSA)	Solibri
Bentley AECOsim	Bentley Staad.Pro	Autodesk Model Checker for Revit
Revit 2017	ETABS 2016	BIM Expert
Tekla Structures	FEM Design	
Vectorworks 2018	RFEM	
	SCIA Engineer 17.1	

5.1. BIM-software

ArchiCAD 20 INT

Figure 10: Logo ArchiCAD [64]

ArchiCAD is an architectural software program provided by GRAPHISOFT which falls under the Nemetschek group and is a pioneer when it comes to the concept of openBIM (figure 10). It was developed in 1984 and was the first BIM-program for architects. The program is mainly used to design BIM-models, which can be used in other programs by using exchange formats. The exchange with FEM-software is made possible by using the IFC-format [31].

Bentley AECOsim Building Designer

Figure 11: Logo AECOsim [32]

Bentley AECOsim Building Designer CONNECT Edition is the design program of Bentley. AECO stands for Architecture, Engineering, Construction and Operations (figure 11). Apart from the design tools, the program has also some built-in tools for other disciplines, like mechanical, electrical, plumbing (MEP), structural and HVAC. These tools make sure that the exchange of information between AECOsim Building Designer and other programs is easy, fast and reliable, which enables an efficient workflow. For example, AECOsim Energy Simulator is one of the programs that have been developed specific for AECOsim Building Designer. To make the workflow even better, there is also a clash detection implemented in the software.

Every model made in a Bentley program can be exchanged with ISM (Integrated Structural Modelling) to other Bentley programs. However, there is also the possibility to exchange data with software from other vendors, for example, every conversion to FEM-software can be done with IFC [32].

Revit 2017

Revit is a powerful BIM-software from Autodesk, it is used to plan and design a project, to keep up with the changes during the construction and in a later phase to store information about the maintenance of the construction (figure 12). The software is not just designed for architects, due to some special features, engineers can use the same software for their models. Thanks to this possibility, the chance of overlap will be reduced.

Figure 12: Revit [32]

The architectural model made in Revit can be converted into different file-formats which makes it possible to import the model in FEM-software. The conversion from Revit to Robot Structural Analysis Professional should be smooth because both programs are from Autodesk, which means that the conversion process is handled with great care.

The conversion between Revit and Bentley STAAD.Pro is made possible with a direct link thanks to the ISM-plug in. CSiXRevit is another type of direct link that enables the conversion to ETABS. StruXML makes it possible to import architectural models in FEM-Design. Other FEM-software can make use of IFC to exchange the BIM-models [33], [34].

Tekla Structures

Next in the list of BIM-software is Tekla Structures, software designed by Tekla, part of Trimble (figure 13). Tekla Structures is a powerful program that enables the user to model even the most complex structures. Thanks to openBIM and IFC, it is possible for AEC and MEP to exchange their plans and improve the efficiency of the design process. Tekla is a pioneer when it comes to IFC, so when choosing a software to convert a BIM-model to FEM-software, Tekla Structures is an optimum choice. For some programs, there is also the option to use a proprietary format instead of IFC. This is the case for Bentley STAAD.Pro and FEM-Design, they are respectively using ISM and StruXML [35].

Figure 13: Logo Tekla Structures [35]

Vectorworks Architect 2018

Vectorworks Architect is a program from Vectorworks which is a part of the Nemetschek group, the same company group that provides ArchiCAD (figure 14). While ArchiCAD is suitable for architects and engineers, Vectorworks is focused on architects. The file-based exchange with IFC to other discipline models is provided, which means that the conversion to a structural model will happen through IFC [36].

Figure 14: Vectorworks Architect [36]

5.2. FEM-software

Autodesk Robot Structural Analysis Professional 2018 (RSA)

RSA is advanced structural analysis software developed by Autodesk (figure 15). The calculations of building elements and structures are happening with the national and international design codes that are implemented in the software [37]. It is possible to analyse concrete, steel, aluminium (Al) and wooden structures, these can be imported from BIM-software. The user has the choice between performing a linear or non-linear analysis. A Direct Analysis Method (DAM) is also an option, but this changes the original design in three different ways: loads are added to the combinations, the stiffness of every cross-section is reduced and a P-DELTA analysis is performed [38].

Figure 15: Logo RSA [38]

Bentley STAAD.Pro V8i SS6

STAAD.Pro is the software for 3D structural design and analyses from Bentley (figure 16). They have three programs for structural design and analysis, STAAD.Pro is the most simple and straightforward program to perform calculations. The program is able to implement static and dynamic loads, wind loads, earthquakes and moving loads, which are necessary according to the building codes. Apart from the European building codes (Eurocodes), the building codes from the U.S., the Nordic, Indian and Asian codes are also available for concrete, steel, aluminium and wood [38].

Figure 16: STAAD.Pro [38]

ETABS 2016

ETABS is FEM-software from CSI (Computer & Structures.Inc) to analyse concrete and steel structures (figure 17). The program is equipped with some tools which make it easier to design structures is the program. However, just like in the other FEM-software, it is possible to import a 3D model from other software. Beams, columns, connections and plates can be generated in concrete and steel. For walls there is the option between concrete and masonry. Calculations based on the building codes from all over the world are possible, these include linear and non-linear analyses for shrink, creep, flexural buckling and P-delta [34].

Figure 17: Logo ETABS [34]

FEM-Design

FEM-Design is developed by StruSoft, a Swedish software company (figure 18). It is possible to design concrete, steel and wooden structures and perform FE-analyses on the models. Again, there is the choice to make the structural model from scratch or import it from BIM-software. When calculations or controls are made, the Eurocodes with the national annexes are taken into account. To perform a linear, non-linear or dynamic analysis, a mesh is necessary, FEM-Design generates the mesh automatically, but this can also be done manually [39]

Figure 18: Logo FEM-Design [39]

RFEM 5.14

Dlubal is German company that provides the FEM-software called RFEM (figure 19). It can execute analyses based on the international building codes. Depending on the add-on module that is implemented, it can be used to define elements in concrete, steel, aluminium or wood. There is always the choice to perform a linear or non-linear analysis and with the correct add-on, even a dynamic analysis becomes possible [40].

Figure 19: Logo RFEM [40]

SCIA Engineer 17.1

Last in the row is SCIA Engineer by the Belgian company SCIA, also a part of the Nemetschek group (figure 20).

Figure 20: Logo SCIA Engineer [41]

It is possible to make calculations for concrete, steel, aluminium and wooden structures based on the national and international building codes. The mesh for the FE-analysis is automatically generated. The mesh will be fine at the nodes and coarse for the big surfaces, which means that the user does not have to think about the ideal size of the mesh. This program is able to perform linear, non-linear and dynamic analyses. Also deflections can be calculated with or without imperfections [41].

5.3. Overview

An overview of all the different FEM-software is given in table 2. In this table, the materials that are supported in the FEM-software are given. The different analyses that can be performed with the software are indicated. Only the two most common building materials, steel and concrete, will be investigated in this research.

Table 2: Overview FEM-software

Name	Company	Materials				Analyses		
		Steel	Concrete	Wood	Al	Linear	Non-linear	Dynamic
RSA	Autodesk	X	X	X	X	X	X	
STAAD.Pro	Bentley	X	X	X	X	X	X	X
ETABS 2016	CSI	X	X			X	X	
FEM-Design	StruSoft	X	X	X		X	X	X
RFEM	Dlubal	X	X	X	X	X	X	with add-on
SCIA Engineer 17.1	SCIA	X	X	X	X	X	X	X

6 Data formats

6.1. Direct link between Revit and Robot Structural Analysis

To exchange information between Revit and Robot Structural Analysis, which are both from the software vendor Autodesk, a direct link can be used. It is a bidirectional link, which means that analysis-related information can be added to the Revit model and in a later phase the Revit model can be updated based on the analysis results. Apart from the physical model, also the associated analytical model is created in Revit. Boundary conditions and load definitions that are necessary for the analysis are included in the analytical model. The structural engineer can link these models to RSA, which will save time. After the calculations, adjustments can be made to the physical model by transferring the information back to Revit, which is an important feature. The iterative process will continue until a satisfactory solution is found.

By installing the plug-in, an extra menu will appear in the Analyze tab in Revit as shown in figure 21. Both programs need a valid license to make use of this plug-in.

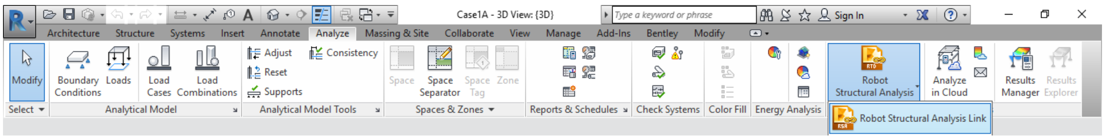


Figure 21: Direct link RSA in analyze tab Revit

If Revit and RSA are installed on different computers, the “Use Autodesk Robot Structural Analysis RTD file” option should be checked by the Revit user. RTD is the native file of RSA and by using this file, the engineer can perform his analysis in Robot while the designer can continue to work in the Revit software. If the option is not available, the model can be saved in an intermediate file (SMXX). The transfer can still be made, but more arrangements between these two parties are necessary.

The user should not bother about the RTD option when the software is installed on the same computer. The additional commands, implemented in the user interface model, will set up a link between the programs and the model will be automatically transferred from Revit to RSA [42].

6.2. Direct link between Revit and SCIA Engineer

Revit developed by Autodesk and is one of the most widespread BIM-modelling programs among the AEC industry. The FEM-software SCIA Engineer is developed by the competitive company SCIA, part of the Nemetschek group. An independent third party, CADS, has designed a plug-in between the two programs, which will establish a bi-directional link (figure 22). Several options are available in the plug-in, for example, there can be opted to ignore the loads, load combinations, etc.

The mode of export can also be chosen, there are two possibilities: a direct exchange or a file exchange. The file exchange will be used when the software programs are installed on different computers. An *.r2s file will be created and can be imported later in SCIA. No matter which mode is chosen, it is important that the correct version of SCIA Engineer is selected.

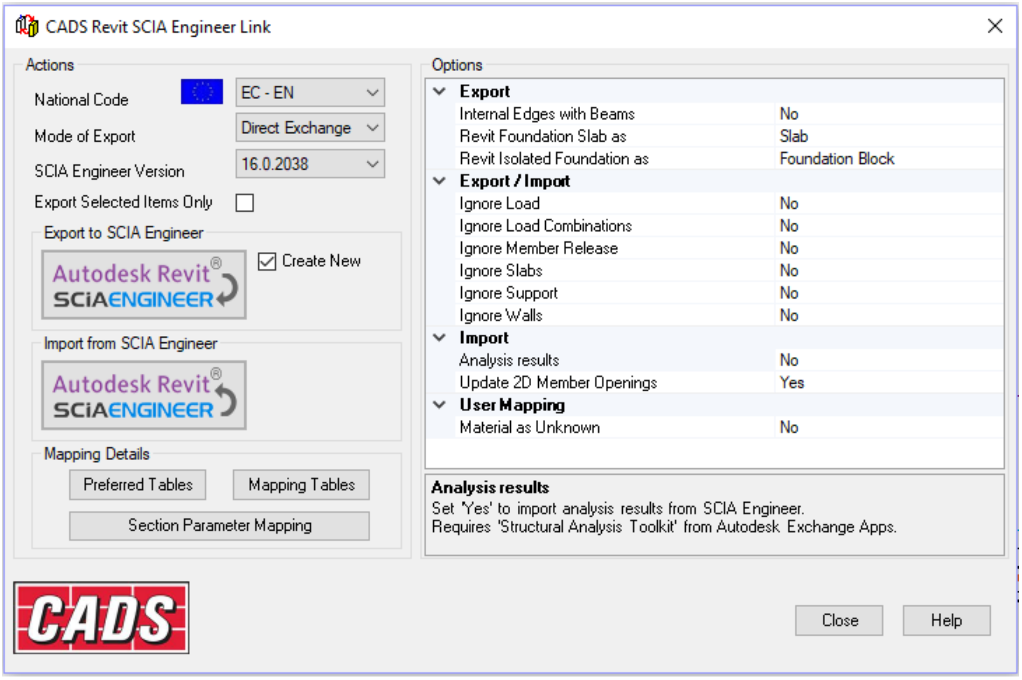


Figure 22: CADS Revit SCIA Engineer Link

In chapter 4 ‘Interoperability’, some of the most common issues that could occur during the conversions process are explained. One of these issues is the mapping process. In most cases, Revit will use another name for the objects, materials, etc. than SCIA Engineer. The plug-in provides the possibility to explicitly link the components of both programs. Only when every component is linked, the conversion will take place. All the links are stored in ‘mapping tables’, which can even be used in the future for other projects.

When the link is used for the first time, a new model will be created. Later on, when adjustments to the architectural model are made, the user has the possibility to create a new model or to just update the existing model. As said, the link is bi-directional, so it is also possible to update the architectural model in Revit with information form SCIA [29].

6.3. Direct link between Revit and RFEM

A direct link from Revit to RFEM can be established thanks to a plug-in. The BIM-model can be directly exported to RFEM, which means only one conversion is necessary and the chances to lose data are smaller. To perform this direct link, both programs need to be installed on the same computer with a valid license.

A couple of settings must be defined before exporting the file. In the general settings, the user has the possibility to modify the orientation of the z-axis and to choose if the entire project must be exported or only the selected elements (figure 23). Other options that can be selected relate to the eccentricities, nodes, lines and the section and material parameters. Some structural settings can also be selected (figure 24). For example, if the structural data is applied or not. When the user wants to export loads, load cases or load combinations defined in Revit, this option should be activated. The self-weight cannot be exported separately, but it can be included in one of the defined load cases.

Finally, the conversion of the boundary conditions of isolated foundations or wall foundations can be chosen. These are shown in figure 3 for the general settings and figure 4 for the structural settings.

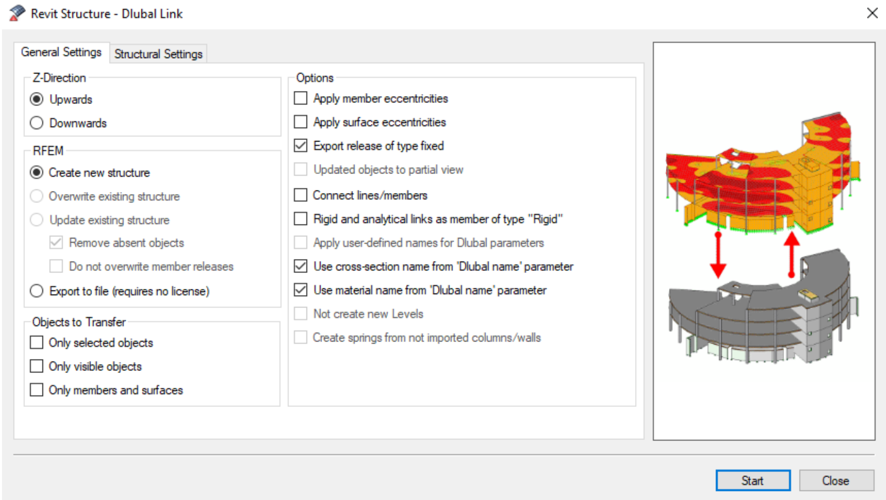


Figure 233: General settings Revit Structure - Dlubal Link

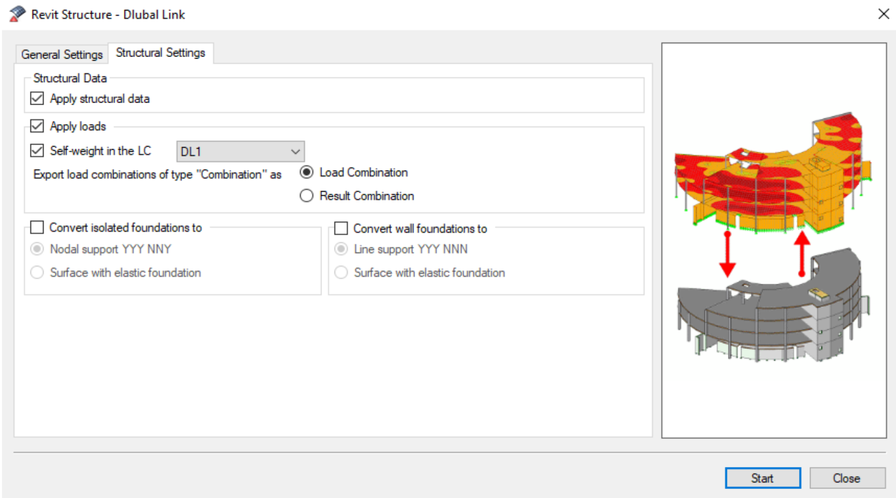


Figure 244: Structural settings Revit Structure - Dlubal Link

6.4. Direct link between Tekla Structures and SCIA Engineer

There is the possibility to establish a direct link between Tekla Structures and SCIA Engineer even though both programs are from different software vendors.

A plug-in similar to the plug-in from Revit to SCIA Engineer was used to create a bi-directional link. Depending on the version of SCIA Engineer, a specific plug-in must be installed. The last version that makes use of this workflow is SCIA Engineer 2010.1. Most engineering companies prefer to use a recent version of SCIA Engineer. Consequently, the plug-in is not supported anymore. Instead, a link based on IFC is employed between the two programs.

6.5. Direct link between Tekla Structures and STAAD.Pro

The native format of STAAD.Pro files have a *.std suffix. Tekla Structures can export the models directly to an STD file. Unfortunately, this link could not be investigated due to only having a student license which does not support this feature.
Another possibility is to export to a CIMsteel analysis model. The exchange happens through CIS/2 file. These files are used to exchange information about steel structures. This link will not be investigated because of the fact that it is not possible to exchange components made of other materials.

6.6. Direct link between Tekla Structures and RFEM

Tekla Structures is able to transfer its models to RFEM with the help of a direct link.
A valid license is necessary to make use of this option. Unfortunately, this license is not available for students and thus cannot be investigated in this thesis. The only other possibility to establish a link between these two programs is by using IFC.

6.7. CSiXRevit

The data exchange between Revit and ETABS, SAP2000 or SAFE is provided by the plug-in CSiXRevit. In this thesis, there will only be focussed on the link between Revit and ETABS. The data will be transferred with an intermediate data exchange file (.EXR). The user can transfer data in both ways, because the link is bidirectional. It is not necessary to transfer the whole model, there is also the possibility to convey a particular set of data. The user has also the ability to express how the data of the equivalent objects of both programs must be mapped. Because of these features, the user has full control over the data transfer [43].

6.8. Integrated Structural Modelling

The transfer to Bentley STAAD.Pro from Bentley AECOsim or Revit is enabled with Bentley's Integrated Structural Modelling (ISM). When ISM is used, not only data can be exchanged between the programs, but the ISM-workflow also provides the possibility to synchronize revisions, track progress, compare alternatives and publish the deliverables.
Structural Synchronizer, a viewing and revision management application is necessary to make the data exchange. It is the core component of an ISM workflow. The application is designed to provide the following features: data synchronization, change management, revision history, and model viewing [44].

Only AECOsim and Revit have the option to export their models as an ISM file. A plug-in must be used in Revit, while it is a standard option in AECOsim. An ISM file can be imported in STAAD.Pro by using the tab 'New from Repository'. To establish a data exchange between the other modelling software programs used in this research and STAAD.Pro, IFC must be used. This process is explained in paragraph 6.8.6 'Links based on IFC; Links to STAAD.Pro'.

The FEM-software RFEM is also capable to import ISM files, which will be used for the models made in AECOsim. Normally, the transfer from Revit to RFEM will not be established by using ISM file because a direct link between these two programs is available.

6.9. StruXML

The StruXML format is used to exchange data from Tekla Structures and Revit to FEM-Design. The format is developed by StruSoft, the provider of FEM-design.
The data transfer from Revit is made possible with the StruXML Revit Add-in, which sets up a bidirectional link. Only the structural elements will be transferred to FEM-Design, because only these elements are relevant for the program. The export will exist of the analytical model of an instance of an element together with its properties.

If the analytical model of the structural elements in Revit is not enabled, the export to FEM-Design will not take place.
The supported elements are all the structural elements, grids, levels, loads or load cases. The link transfers data about the material properties, geometrical aspects, releases of linear elements and boundary conditions of the elements. In some cases, even the eccentricity of the elements will be transferred to FEM-design [45].
Tekla Structures makes use of the Tekla StruXML Export tool, which does not follow the same workflow as the Revit Add-in. The transfer is established by a separate tool and works only in one direction (from Tekla Structures to FEM-Design). The open Tekla model will be translated into an analysis model, this will be exported into a *.struxml file. After this process, it can be opened or imported in FEM-Design. Most of the capabilities of the link are the same. However, it is not possible to transfer the eccentricity of the elements from Tekla Structures to FEM-Design [46].

6.10. Standardized solution: IFC

As said many times before, during the design process many professionals must work together. In the end, all the discipline plans (structural, HVAC, etc.) should come together and provide enough information for the constructor to build the structure. With the technology of today, it is possible to 'simplify' this process. Instead of 2D-plans, 3D-models are made, and the overlaps can be detected with clash detection. By importing one model into other programs, lots of time can be saved because the modelling phase can be skipped for one party. However, this will be only the case when the conversion process is done correctly. To get a reliable conversion process, some difficulties must be overcome, for example the translation of compatible information.

For integrated construction projects, BIM data is mostly exchanged with proprietary formats. As a result, all members of the design team should have software from the same or compatible vendors.

Other exchanges can be performed with a standardized neutral format: Industry Foundation Class (IFC). Even when BIM was not as mature as today, some people saw potential in this open data format. These pioneers believed that in a fragmented project, IFC could fill in the gap between the stakeholders and the different project phases. IFC still has not reached its full potential, but several information exchanges between different software programs are already happening with the help of IFC.

6.10.1 History

IFC was first mentioned in 1994 and has been developed by a private alliance of the following 12 companies:

- Autodesk
- Archibus
- AT&T
- Carrier Corporation
- HOK Architects
- Honeywell
- Jaros Baum & Bolles
- Lawrence Berkely Laboratiory
- Primavera Software
- Softdesk Software
- Timerline Software
- Tishman Construction

These companies laid the foundations of open international standards. They believed that these standards had great commercial potential and more advantages than private of proprietary standards. To reach the full potential of IFC, the alliance had to be expanded. Apart from the 12 original companies, interested parties from all over the world could join in. Eventually, the private alliance became the International Alliance for Interoperability (IAI) in 1996 and had members from North America, Europe and Asia.

To let the development of the standards run smoothly, all the members from a country or in some cases from a region or language area are brought together in a Chapter, for example the IAI Norwegian Chapter, IAI Benelux Chapter or IAI French speaking Chapter. To avoid chaos during the development of the standards, not every member could directly impose requirements. Instead, two representatives from each Chapter were appointed to correspond with the International Council about the needs of the members.

In 2008, the organization replaced its name with BuildingSMART. Up to the present time, BuildingSMART keeps reviewing and improving the standards to achieve the ultimate goal: openBIM. There can only be spoken about openBIM, when everybody follows the same standards. When it comes to open data formats, IFC is the most developed. As a result, it is registered by the 'International Standardisation Organisation' since 2013 under the code ISO16739: 'Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries' [9].

6.10.2 IFC versions

BuildingSMART is constantly improving IFC, which has as a result that there exist multiple versions of the IFC model schema. Every version is capable to handle more problems than the previous one.
More information about these releases is given in table 3, additionally a timeline of the releases is shown in figure 25 [47].

Table 3: IFC releases;based on [48]

IFC version	Release	Improvements	Status
IFC 1.0/ IFC 1.5/ IFC 1.5.1/ IFC2.0	Before 2000	First versions	Outdated and not listed anymore
IFC 2x	October 2000	Providing a stable platform	Listed but no longer maintained
IFC 2x - Add1	October 2001	Fix issues that occurred during the implementation	Listed but no longer maintained
IFC 2x2	May 2003	Several extensions of IFC	Listed but no longer maintained
IFC 2x2 - Add1	July 2004	Fix issues that occurred during the implementation	Listed but no longer maintained
IFC 2x3	February 2006	Quality improvement of IFC 2x2	Listed but no longer maintained
IFC 2x3 TC1	July 2007	Documentation and corrections of IFC 2x3	Maintained, strongly recommended for implementation
IFC 4 (former IFC 2x4)	March 2013	Enriched entities in comparison to IFC 2x3 and obsolete entities are deleted	Replaced by IFC4-Add2
IFC 4 – Add1	July 2015	Fix issues that occurred during the implementation and minor updates on the MVD’s	Replaced by IFC4-Add2
IFC 4 – Add2	July 2016	Necessary improvements to start the IFC4 certification process for the IFC4 Reference View and the IFC4 Design Transfer View	Maintained, baseline for IFC Reference View V1.1 and IFC4 Design Transfer View V1.1
IFC 5	Unknown	full support for various infrastructure domains and more parametric capabilities	Planning phase

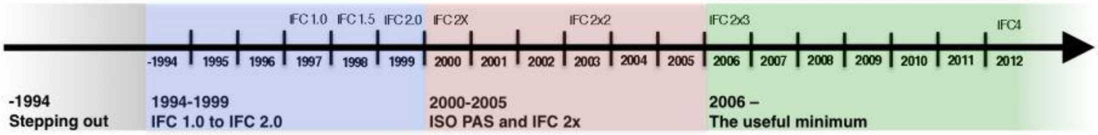


Figure 255: Timeline IFC [49]

IFC 2x2 is supported by the most common software nowadays available. Earlier versions were necessary to reach the maturity level of today. The difference in maturity between the versions of IFC is illustrated in figure 26. IFC is still evolving and every level of maturity unlocks new possibilities. While IFC 2 only had a stable platform, IFC 2x2 had already extensions for several tools. Nowadays, IFC 4 is already achieved, but this is not the final stage as can be seen in the figure 26. In comparison to proprietary schemas, the IFC schema is much more extended. Yet, it is still a challenge to implement the IFC schema into the software, mainly because software vendors prefer their own proprietary solution.

Over time, openBIM will be achieved with the help of IFC. However, this is not the ultimate goal. The goal is to decrease the risks and the maintenance of the security requirements. Which will result in an improvement over time of the usability and the functional level of the data for multiple business needs.[47].

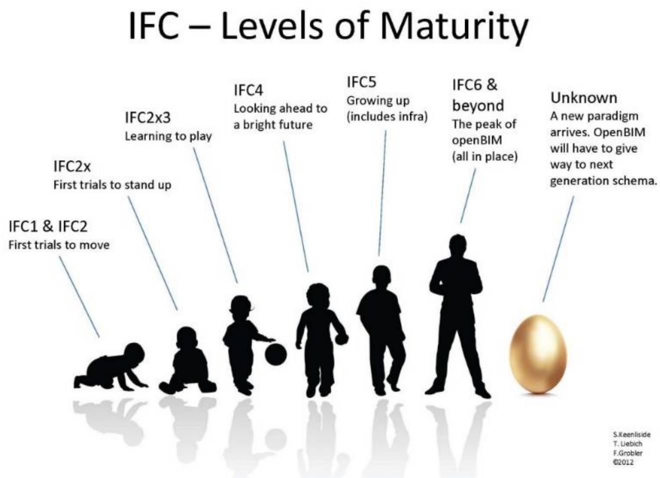


Figure 266: IFC- Levels of maturity [47]

6.10.3 IFC model schema

ISO 16739 describes the neutral data format IFC. However, there is the option to use the following data formats, depending on the various encodings of the underlying data:

- **IFC-SPF**
  The text format defined by ISO 10303-21 is called IFC-SPF (STEP Physical File) and is also the most widely used IFC format. One single object record is used for each line, which makes it readable while it still has a compact size. IFC-SPF can be recognized by the extension “.ifc”.
- **IFC-XML**
  ISO 10303-28 describes the IFC-XML, which has the extension “.ifcXML”. It is used when interoperability with XML tools is required or to exchange partial building models. Normally, building models are quite large, up to 400 % of the ICF-SPF format, which makes this format less common in practice.
- **IFC-ZIP**
  When a IFC-SPF file is embedded in a ZIP compressed format, there can be spoken about IFC-ZIP. An IFC-SPF file can be compressed down by 60 to 80%, while the IFC-XML file can reach an astonishing compression of 90 to 95%.This file format has the extension “.ifcZIP” [50].

Each of these data formats can be used to make an IFC-conversion because they all follow the same data schema. This schema is defined with the EXPRESS language, which maps all the interrelated entities and inheritance relationships. The data schema exists of four conceptual layers (figure 27):

- **Resource layer**

  The resource layer is the bottom layer and contains all the fundamental concepts that are needed in the IFC object model. The concepts are expressed as entity types. One example of an entity type is the geometry, which will define a point, line, etc. All the other layers will make use of these entities or refer to them.

- **Core layer**

  The basic structure of the IFC object model is provided by the core layer. In this layer, the most general concepts will be defined, which will be specified in the higher levels.

  This layer also includes the Kernel and Core Extensions.

  The kernel is the template model. All the other schemata within the model should be developed according to the form defined by this template.

  The framework is very general, to use it in the AEC/FM industry some specialization of the classes defined in the Kernel is necessary, which is executed by the Core Extensions. They also provide the possibility to express the primary relationships and roles of the classes.

- **Interoperability layer**

  This layer is crucial to define the interoperability between different domain extensions. The basic concepts that are used in multiple domains, for example shared building elements (beam, door, roof, etc.), are explained in this layer. All these concepts are necessary to let an inter-domain exchange happen.

- **Domain/application layer**

  The domain/ application layer is the top layer. While other layers were general, this layer will define the model details that should be met in order to speak of the AEC/FM domain process.

  This layer will enable the software to perform intra-domain exchanges and share information. The domains are for example ‘architecture’, ‘HVAC’, ‘FM’, etc. [50], [51].

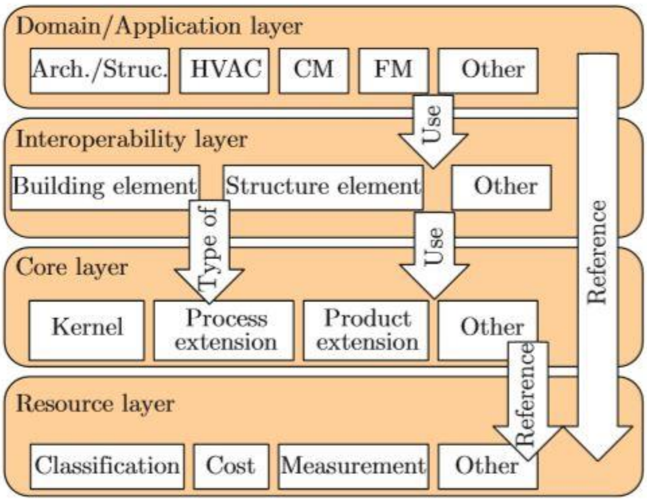


Figure 27: Layering concept of IFC architecture [52]

As can be seen in figure 27, the communication of the IFC schema functions is unidirectional. This 'ladder principle' causes that a particular layer class can refer to the same or a lower layer class, but it is not possible to refer to a higher layer class. Referring to the same layer class is only allowed within the core and resource layer, which are the bottom two layers [50].

The structure of IFC2x3 TC1 and IFC 4 – Add2 is respectively displayed in figure 28 and 29. Immediately, it can be noticed that the core of these two data formats are similar. Both versions use C++ as their programming language and most classes are the same. The main difference between these two versions is that IFC4 focuses on providing new features, while IFC2x3 TC1 main goal was to fix some issues of the stability release IFC2x3. A stability release was necessary because the previous version IFC2x2 had lots of bugs which needed to be fixed with additions and eventually, the data format became chaotic. By releasing IFC2x3, a stabile format was provided and the implementers were able to catch up with the many additions of IFC2x2 [49].

The obsolete entities that were still present in IFC2x3 are no longer implemented in IFC4, which makes the data format more efficient.

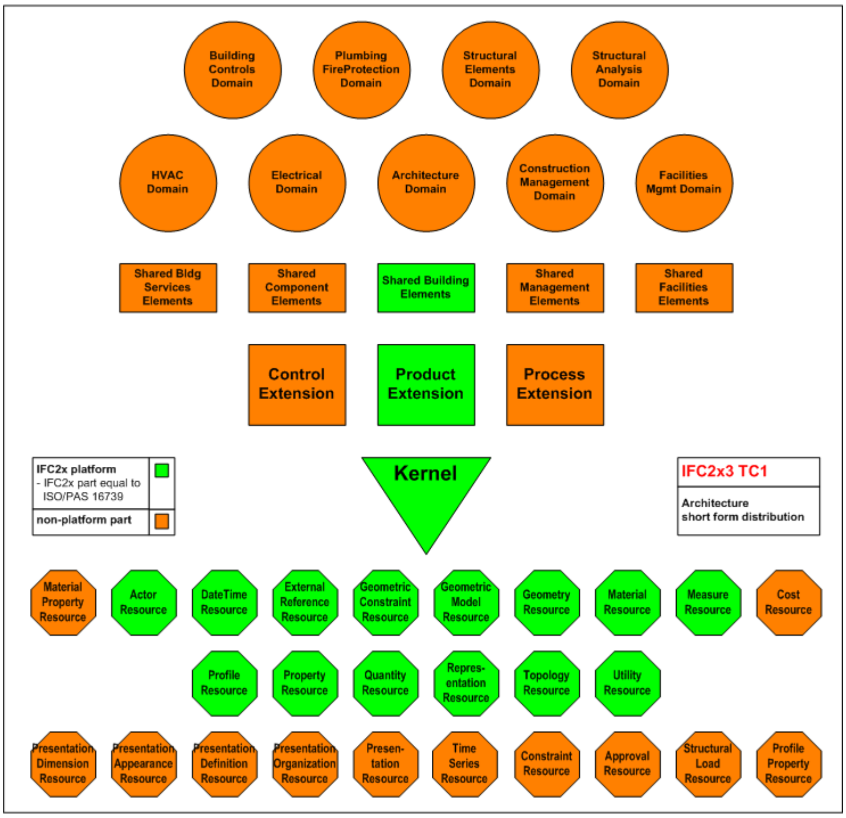


Figure 28: Schema IFC2x3 TC1 [53]

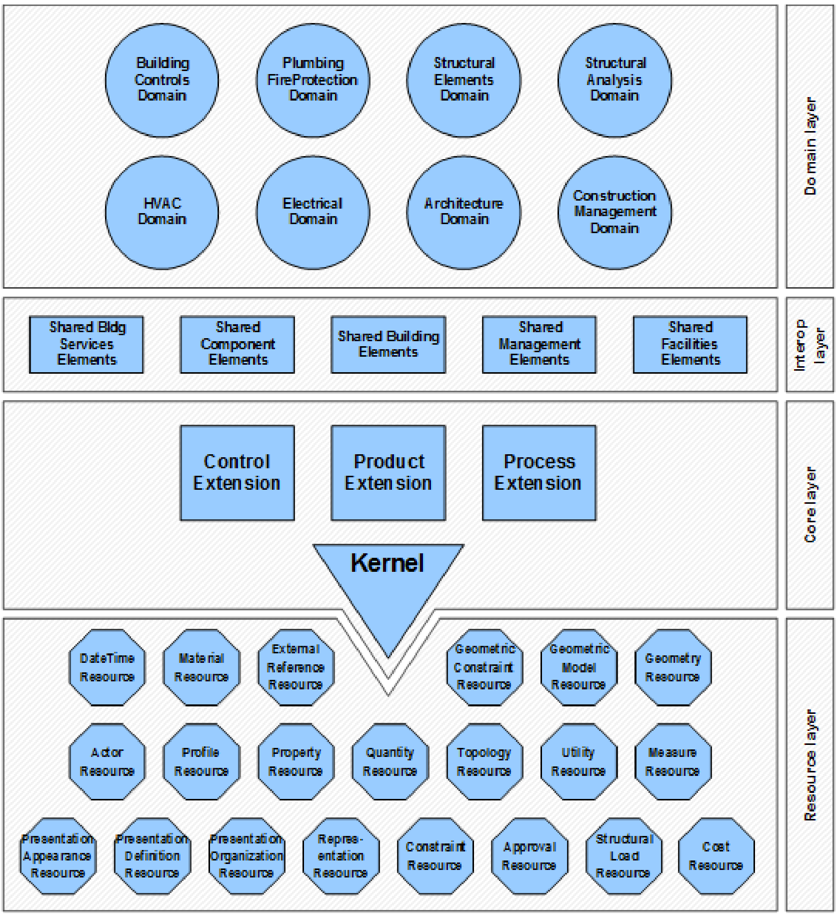


Figure 29: Schema IFC4 [51]

6.10.4 Mapping between the IFC-based BIM and structural FEM

The data structure of an architectural model is completely different from a structural model, which is logical because they are used for different purposes. While the architectural models are used to design and visualize a construction, the structural models are used as a base for the stability study.

The architectural models can be seen as physical models that contain lots of non-structural member information, but also a little bit of structural member information, like material data. The structural models on the other hand are finite element models. The first draft of this model will consist of the structural member provided by the architect together with a vertical and lateral load transferring system. Then, the structural engineer can add new structural members, boundary conditions, different load cases and load combinations, etc. The relationship of information between the architectural and structural models is illustrated in figure 30. Because of the nature of these models, the data structure will be completely different.

However, both models have to provide information about the same building elements. In most cases, the properties in one program will be more extensive than in the other. For example, according to the architectural model, a plate is made in concrete C20/25. The same plate will be used in the structural model and therefore also be made from the same material, but it will contain more properties for example the E-modulus because these are necessary for the FEM-analysis. It is important that the data is mapped correctly, in order to link the equivalent objects and enable the possibility to reuse the information [52].

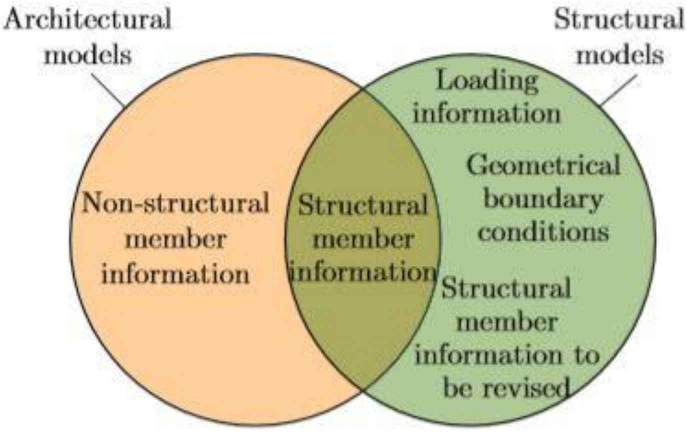


Figure 270: Relationship of information between the architectural and structural models [52]

Only the structural information should be transferred from the BIM-model to the structural model. The other information is irrelevant for the calculations and will make the structural model too heavy.

A part of the interoperability layer of IFC2x3-TC1 schema is shown in figure 31. Lots of building elements are implemented in this layer, but only the elements that contain structural information (for example: IfcBeam, IfcColumn, IfcWall and IfcSlab) will be extracted from the architectural model. Then, they will be implemented in the structural model as preliminary structural members [52].

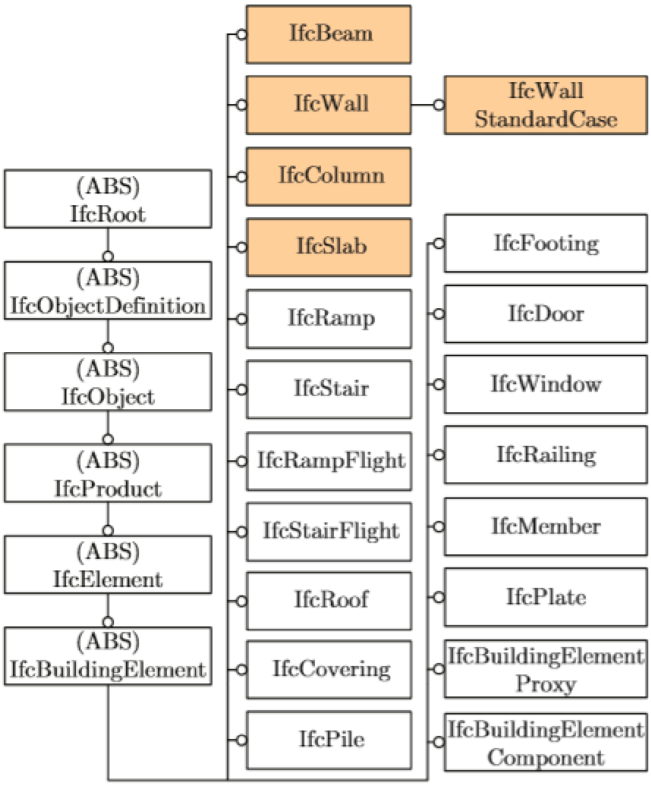


Figure 281: Building elements defined in the IFC2x3-TC1 schema [52]

In chapter 2: BIM and chapter 3: FEM, more information about the functions of the models can be found. The conversion process is a weak point when information between the different kinds of software must be exchanged. As said in paragraph 4.3 ‘Conversions’, some processes will exist of 2 conversions. First from BIM to a neutral data format and afterwards to a file format that is readable by FEM-software. By using viewer software, it is possible to check the model after the first conversion. This check-up will tell us if the conversion went wrong during the first or the second transmission.

The check-up can be done with different software programs: notepad, Solibri Model Viewer, Tekla BIMsight, Autodesk Navisworks Freedom, Autodesk Navisworks Manage and Bentley Projectwise Navigator [54].

Notepad is a general text processor, not an editor. This program can create, open and read plaintext files. It is possible to see the code of the IFC-file. Every line will represent an IFC-class that is assigned to a building element, which makes the file clear and organized. However, most people do not understand code and even the ones who can, will have trouble to visualize the model. Luckily, there are other programs that are able to convert the IFC-file into a visual model.

Solibri Model Viewer (SMV) is developed to open IFC files and Solibri Model Checker files (SMC). While the Solibri Model Checker detect clashes and analyses the quality of the BIM-information, the Solibri Model Viewer will visualize the results. There are also some features that make the communication with other participants of the design team easier. For example, it is possible to share comments with the others in 3D-views [55].

Tekla BIMsight is a free program that combines all the different models from other disciplines into one project model. It is possible to keep this program for free because every user has to register himself, which will open marketing opportunities for Trimble, the provider of Tekla BIMsight.
A second program for clash detection is not needed. [54]

The other software that was previously mentioned will not be used to check IFC-files, because SMV and Tekla BIMsight suffice to do our research.

6.10.5 MVD

Definition

As explained in paragraph 2.6 ‘Open BIM’, Model View Definitions (MVD) are used to define subsets of IFC data and will avoid unnecessary data to be shown. When IFC is used purely to import or export a model, an insufficient process will be created because not all the data attached to the model, is necessary for all the professionals related to the project. Remember the example of paragraph 2.6 ‘Open BIM’, the fire behaviour of the building elements is only interesting for the fire safety engineer and not for the structural engineer. Exchanging data related to the tasks is more sufficient and can be done in model views. To ensure an effective exchange, the Model View Definitions are used. When these are followed correctly, only the necessary data will be accessible by the professional, which means that assumptions about information that does not belong to his field of study cannot be made. By taking away the possibility to interfere with data from other discipline models, mismatches will not be created [2].
MVD’s are used to satisfy the exchange requirements composed by the AEC industry. The content of these exchange requirements depends on the stage of the building process. BuildingSMART uses the Information Delivery Manual (see 2.6 Open BIM) to define these exchange requirements. The MVD’s can collect all the necessary data and exchange requirements for the required phase of the building process from the IDM’s to let the data exchange to a particular discipline happen. A contract between the different parties can indicate which data has to be provided using a specific Model View Definition [56].

Format

The MVD’s define the subsets of IFC data in a format called MVDXML. In the format, the allowable values of particular attributes of particular data types can be found. It basically means that elastic modulus of a material will be found back in the discipline model of a structural engineer, but not in the architectural model. Before MVDXML, a couple of other formats to check data conformance in the AEC industry were already available. The goal of MVDXML is not to replace these formats but to automate their workflow so information requirements at higher levels can be defined, rather than to depend on manual calculations which can have errors.

MVDXML can be used in a statistical or a dynamic manner by software applications. Statically means that the format is created to support a specific model view and dynamically that it is created to support all model views. An example of a dynamic function is when data is exported, it can be filtered automatically so only data relevant to the model view is included [20].

BuildingSMART International has a monopoly when it come to the verification process of MVD's. However, that does not mean that they develop every MVD. The developing process can be done by other organisations or interest groups, which will submit there MVD's to BuildingSMART international. The BuildingSMART TEAMS will review the MVD's and if they are accepted, they will be published and become BuildingSMART MVD's, which are internationally accepted [57].

Views

The general exchange requirement and MVDXML are not reliant on a specific release of IFC, while the realization constructed in the MVD is limited to an IFC release. Following is an overview of all the available official BuildingSMART International Model View Definitions [56].

IFC2x3

Coordination View

The Coordination View was finalized in 2007 but since 2010 outdated due to the release of a new version: Coordination View Version 2.0.

Structural Analysis View

The Structural Analysis View contains the exchange requirements for a model created in a structural design application by the structural engineer to be send to the structural analysis application (figure 31). The following figure shows what data is comprised in the structural analysis model. This view is released in 2008 but is not used anymore due to new, improved releases of MVDs [58].

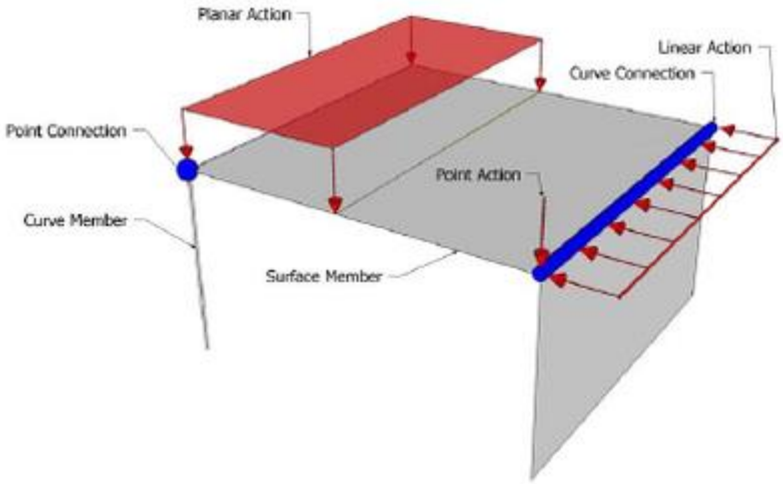


Figure 291: Comprised data Structural Analysis View [58]

Basic FM HandOver View

The Basic Facility Management (FM) Handover View was developed to improve the interoperability between the phases of the building process. Currently, this view is not used anymore [59].

Coordination View Version 2.0

The Coordination View 2.0 has replaced the first Coordination View since 2010 and at this moment, it is BuildingSMART Internationals most implemented MVD. The goal of this view is to improve the coordination between the tasks of the architect, the mechanical (building services) and the structural engineer. This goal can be achieved by making a proper exchange between the models, as shown in the diagram below (figure 32). The models that are shared according to this MVD are re-editable by the receiving application. The spatial structures, building elements, building service elements and possible the non-parametric data will be kept during this transition.

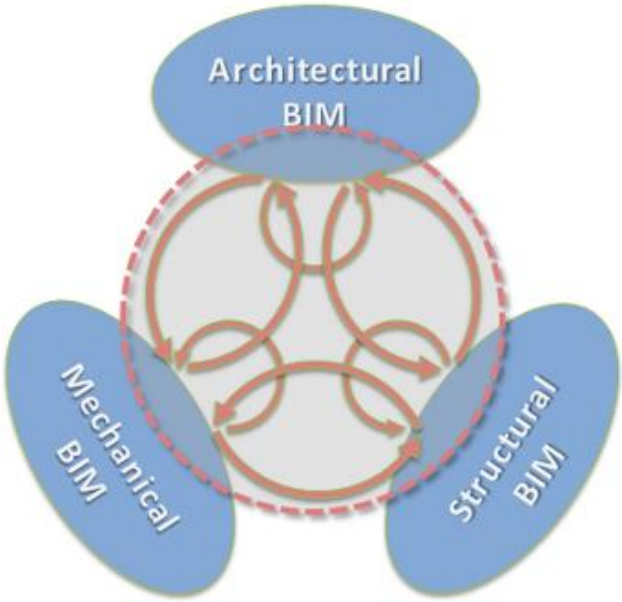


Figure 302: goal Coordination View [60]

IFC4

Reference View Version 1.1

The Reference view Version 1.1 has been a BuildingSMART Final Standard since 2015. The reference view is intended to be used when the exchange of IFC models is mostly one-directional or if a reference model is the base for the BIM workflow. The receivers of the IFC4 Reference View model have access to all the content of the IFC model, but only the original will have the ability to make changes. The IFC model can be used by other disciplines for visual checking and presentation, clash detection, quantity take-off and the construction sequencing. It is not possible to make a round-trip with the this view due to the fact that the receiver cannot make any changes [61].

Design Transfer View Version 1.0

The Design Transfer View Version 1.0 is a BuildingSMART Final Standard since 2015. It can be seen as an expansion of the Reference View due to the ability for both the original author as the receiver to make changes in the IFC model. This view also provides the possibility to transfer the ownership of the complete discipline model, which can be useful for further work or archiving.

The Design Transfer View can integrate an IFC model, generally from a different discipline into another model using references. For example, the load bearing elements of an architectural IFC model can be integrated and edited in a structural model.

Just as the Reference View, it is not possible to make round-trip, meaning the receiver makes changes in the model and sends the full modified model back. It is recommended to use BCF (see 2.6 'Open BIM') to inform the originator of change requests [61].

6.10.6 Links based on IFC

Links from Revit

Many plug-ins to establish a direct link between Revit and FEM-software are currently available. However, there is also the possibility to export the model with IFC. This can come in handy when it is not known which FEM-software will be used or when a direct link between the programs is not supported. There is the option to export the model in IFC2x2, IFC2x3 or IFC4. As seen in table 3 in paragraph 6.10.2 'IFC versions', IFC2x2 is outdated. Depending on the FEM-software, a choice between IFC2x3 and IFC4, each with different MVD's, should be made.

Links from ArchiCAD

Graphisoft is a part of the Nemetschek group who is a forerunner when it comes to openBIM. The data exchange happens with IFC files and some features are provided to make the conversion easier.
When a model in ArchiCAD is exported to an IFC file, several options are available.
There can be chosen for IFC2x3 and IFC4 and different MVD's, but it is does not stop here. When IFC2x3 is chosen, there are several translators available to choose from. When it is not known in which software the IFC file will be imported, there can be chosen for the general translator. It is also possible to choose a specific translator, for example the 'data exchange with SCIA Engineer'. Other translators apply to BIM-software programs and will not be used for our research.

Links from AECOsim

AECOsim is a software program developed by Bentley. The preferred workflow is to exchange data with ISM. However, it is possible to export a model to an IFC data format. Using this, the model can be imported in different FEM-software due to IFC being an exchange format widely used. Two types of IFC formats can be exported, IFC2x3 and IFC4. For IFC 2x3, there are three MVD's available: CV2.0 + QTO & Space Boundaries, CV2.0 and Facilities Management Handover. Only IFC 2x3 CV2.0 is used in this research due to the other options being not relevant for a structural analysis. The QTO & Space Boundaries are interesting for an energy analysis and the Facilities Management Handover are mostly used after the construction is completed to exchange management files together with the BIM-model. The other IFC data format is IFC4. Only one MVD is available: IFC4 Reference View. No differences are detected between the IFC2x3 data format and the IFC4, except for the fact that not all the FEM-software programs are capable of importing IFC4.

When exporting the IFC file from AECOsim, a couple of options are available. The file can be optimized, zipped, the facet tolerance can be chosen between coarse and fine which has an influence on the size of the file. It is also possible to map datagroup types and properties if the corresponding file is available.

Links from Tekla Structures

The models made in Tekla Structures can be exported as an IFC, IFCXML, zipped IFC or zipped IFCXML. All these file formats originate from the IFC2x3 version.

The Coordination View 2.0 and Steel Fabrication View are the only views that are interesting for our research. After some investigation, we noticed that the Steel Fabrication View is used when only the reinforcement bars must be exported, which makes it not usable for the complete model. Only the Coordination View 2.0 will be used our investigation.

Links from Vectorworks

Vectorworks has a lot of export possibilities, from DWG to KLM. However, only one is suitable for the export to FEM: IFC.

Vectorworks has the ability to export different types of IFC and different MVD's available. For IFC2x3, only the Coordination View 2.0 – Architecture and the Extended Vectorworks Model View are an option for the conversion process to FEM-software. A Structural View was not available. Eventually, there was not any difference between the two exported views for our purposes.

When IFC4 was used, the Reference View had to be used because of the lack of other MVD's.

There were several ways to model certain components of the building. A steel beam could be modelled with a structural element, a construction element or with a profile and a concrete beam could be modelled with a structural element or a construction element. Each way of modelling had its effect on the properties and the conversion process.

Links to Robot Structural Analysis

Many direct links are available for Robot thanks to plug-ins. These links are well developed and because of this fact, it became unnecessary to support IFC. Only IFC2x2 can be imported in RSA. As said before, this version is outdated.

Links to SCIA Engineer

Currently, only IFC2x3 can be imported in SCIA Engineer. For this research, we decided to choose the IFC2x3 Coordination View 2.0. More information about the Coordination View 2.0 is provided in paragraph 6.10.5.3 'Views'. Unfortunately, a Structural View was not supported by the architectural programs since this view is outdated.

Links to STAAD.Pro

It is not possible to import an IFC file directly in STAAD.Pro. However, a data exchange from ArchiCAD, Tekla Structures or Vectorworks to STAAD.Pro can be established, but a workflow that also makes use of IFC files must be followed.

The first step consists of exporting the architectural model to an IFC file.
As said, above, these IFC-files cannot be directly imported and must be transformed to the ISM file format. This process is executed by the Structural Synchronizer.
After the conversion from the IFC file to the ISM file in the Structural Synchronizer, the ISM fil can be imported in STAAD.Pro. In total, the model will be converted three times.

As long as a program is able to export models to IFC2x3, a data exchange with STAAD.Pro can take place. Other versions of IFC are not supported by the Structural Synchronizer, which imports and converses IFC to ISM files.
Before importing the IFC-file, the general, profile section and material settings must be defined.
The general settings allow the user to import all the property sets which are defined in the IFC-file, for example the fire resistance (figure 33). The profile section settings make it possible to import the pre-installed Standard Tables. Based on these tables, the matching cross-section in the ISM file can be determined (figure 34). The third and last settings are used to map materials correctly (figure 35). The name of the material in the IFC-file can be equalled to an ISM material. The options are concrete, steel, aluminium, masonry, timber or other. The properties of the materials are in some cases transferred and in others not, more details are given for each conversion in chapter 8: Case studies.
After the file is transferred to an ISM file, all the properties can be seen in the Structural Synchronizer (figure 36). Little changes to the geometry of the profiles and the properties of the elements can be made in this software.

Figure 31/ General import setting

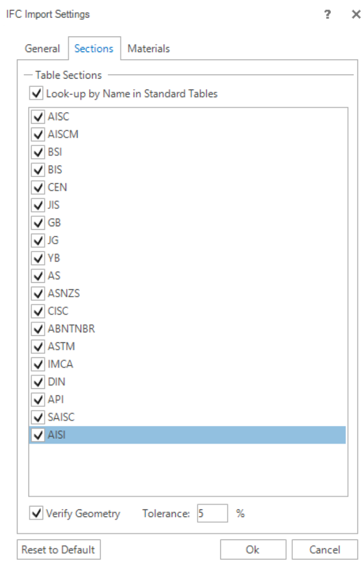


Figure 334: Section import settings

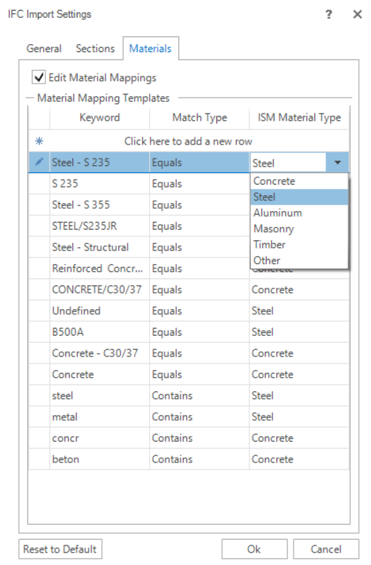


Figure 325: Material import settings

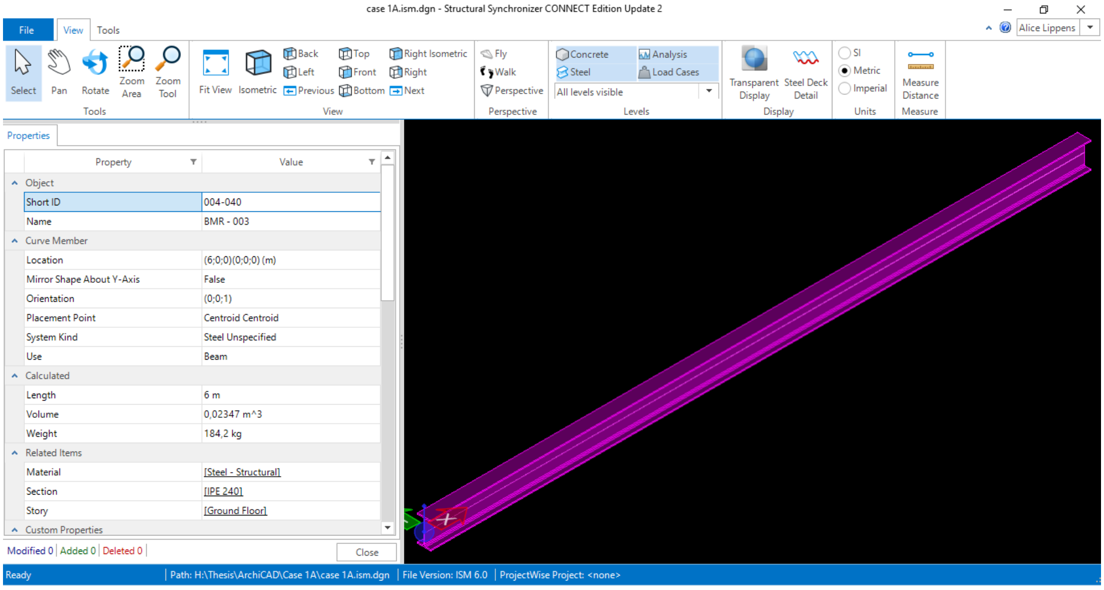


Figure 36: Structural Synchronizer CONNECT Edition

After the IFC-file is conversed to an ISM-file, it is time to open STAAD.Pro. Here, a new file will be created by using the tab ‘new file from Repository’ and the window shown in figure 37 will pop up and again, some settings must be selected.

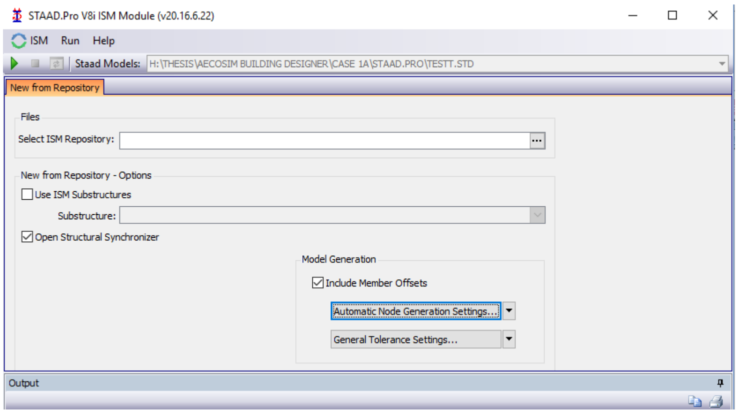


Figure 37: Importing ISM-file

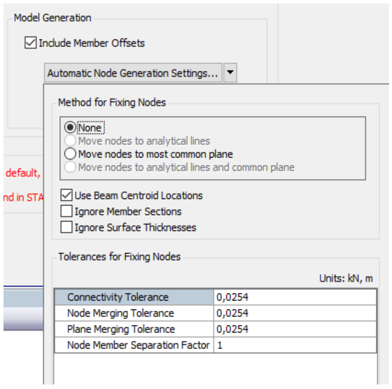


Figure 38: Node settings

For example, it is possible to adapt the properties of the nodes of a beam or surface (figure 38). Tolerances can also be set in this window. After the settings are chosen, the conversion starts. The Structural Synchronizer will open, and the desired structure can be selected and updated. This is interesting for the engineer so final adjustments could possibly be made to make sure that the model is imported correctly. Lastly, the model will be imported in STAAD.Pro, and can be checked and used for analyses.

All in all, the workflow is quite cumbersome. In total, the file is converted three times before the model can be used in the FEM-software. A lot of data can get lost during these transitions, meaning the chances of obtaining decent results when the properties are compared, are low.

Links to RFEM

A wide range of file formats can be imported in RFEM. A direct link is used to import models from Revit and Tekla Structures, ISM for the ones made in AECOsim. Apart from these options, it is also possible to import IFC file2x3. Nowadays, it is not possible to import IFC 4 in RFEM.

Links to ETABS

ETABS, a software of Computers and Software.INC, can import both IFC2x3 and IFC4. The MVD that is used, does not have an influence whether the file can be imported or not.

Links to FEM-design

In FEM-Designer, IFC 2x3 is the only version of IFC that can be imported. There is no limitation to the use of MVD’s, all of the developed MVD’s can be used. The materials of the IFC file can be mapped to the available materials in FEM-Designer. Due to this mapping process, the name of the material and the properties will not be transferred into the FEM-Designer model.

Summary

Table 4 is the summary of the previous paragraphs. It shows which format can be used to enable a link between an architectural program and FEM-software.

Table 4: Summary links from BIM to FEM

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

7 Method

The scope of this thesis is to investigate the interoperability from BIM to FEM. More specifically, the focus lays on the conversion of models in order to save time for the engineer. We take into consideration that not every piece of information will be converted in the right way and that some information will not be converted at all. However, sometimes this is not a problem. For example, in most cases, it should not be a problem that boundary conditions are not transferred. The architect is not focussed on determining the correct boundary conditions because these depend on the choices of the engineer. The connection between a concrete column and beam can be a simple or a continuous joint. The type of joint depends on the used amount of reinforcement and its anchoring length. The type of joint will have its influences on the rest of the construction. Therefore, only people who have full access to all the structural information should be able to make a justified decision about the type of joint that will be used. The same reasoning can be followed for the conversion of the loads, load cases and load combinations.
Other information can be extremely important, for example the coordinates of the objects, the type and material of a beam or column, etc.

It is evident that a structural analysis cannot be made when the geometrical information is not provided correctly. The influence of the length on the moments is quadratic, which means that the length has a bigger impact than difference in loads on the moments in an object.
During our investigation, we will check if the coordinates are transferred correctly, even when the objects are rotated, if the local axes are not in the middle anymore, etc.

The type of the profiles is another important part of the construction. The architect does not have to make the optimal choice for the type of beams, columns, etc. which will be used, but space must be provided to place these structural elements. Most of the time, the architect will make a decent choice, but the elements can always be optimized by the engineer.
If the type of element is not imported and set to a default value, lots of time will be wasted by manually changing each element.

Another situation that can occur is that the name of an object is transferred correctly, but not the information that belongs to these objects. This can be a good thing, as long as the FEM-software can recognize the transferred profile type.
The issues that arise are a combination of the translation of compatible information (see paragraph 4.4.3 ‘Translation of compatible information’) and the difference in level of features (see paragraph 4.4.6 ‘Different level of features’). Every link handles these issues differently, which we will investigate to see the advantages and disadvantages of each method.
Apart from the cross-sections that will be imported in the FEM-software, it is also important that these types are accessible, can be used for calculations and if necessary be modified to another cross-section.

Eventually, the material will be the last thing that has to be transferred correctly. The design team can decide to make use of prefab concrete elements in the structure. There are only few manufacturers who provide these elements. For the standard elements, concrete C50/60 is used and this information can already be implemented in the architectural model. When the conversion to the FEM-software is made, time can be saved by transferring and reusing this information.
There are several ways to map the corresponding materials, but as previously discussed, it is important that the transferred information is accessible and can be modified in the FEM-software.
As said before, the following transfers will be made (figure 39, 40 and 41):

Figure 349: Investigated links ArchiCAD, Vectorworks and Tekla Structures

Figure 40: Investigated links AECOsim

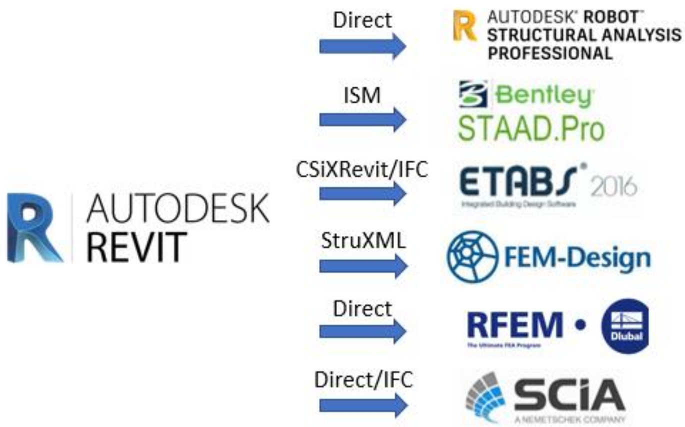


Figure 41: Investigated links Revit

A simple case will be investigated. This case will provide us with the information about the conversion process of all the previously described components. A check will be conducted to verify whether the properties have been transferred correctly. For instance, it would be uninteresting if a transferred property is changed to a default value.

8 Case study

In this case, a typical example will be investigated to get an idea of the quality of the different kinds of links. All the FEM-software has the capability to make calculations for different materials. These materials have different properties, which means that the conversion for steel can be good, while it will not be satisfactory for the conversion with wood. In this thesis, there will be focused on the two most commonly used materials in the AEC industry: steel and reinforced concrete. The conversion of both materials will be examined to form a solid conclusion of the interoperability from BIM to FEM.

8.1. Model properties

A simply supported beam as shown in figure 42 will be used for the first set of conversions. The analytical line will be modelled in the exact centre of the beam.

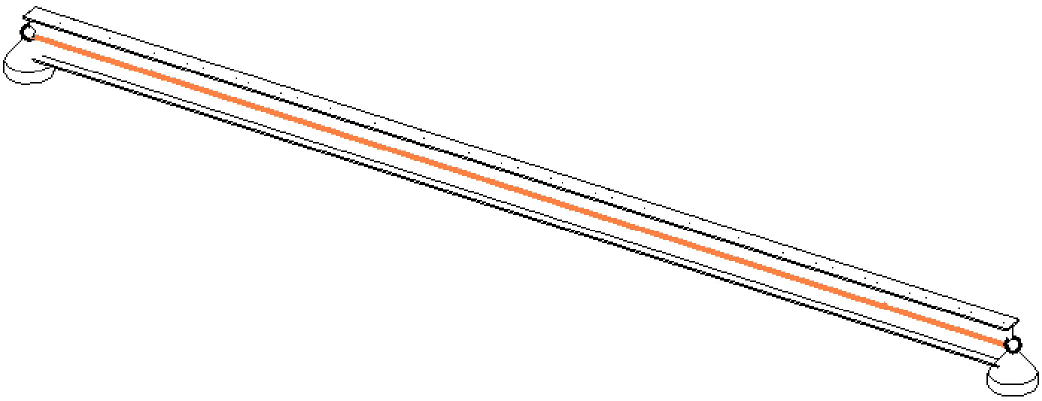


Figure 42: Simply supported beam; case 1A in Revit

The beam has a length of 6 m and the following materials are used:

- case 1A: steel S235,
- case 1B: reinforced concrete C30/37,

In each case, the same loads will be applied to make sure that the different models can be compared. The used loads are fictive, but the sizes of the loads are realistic, even though they are not supported by any calculations. Only the self-weight of the construction, permanent loads, variable loads and wind loads will be applied. For our investigation, it is unnecessary to apply forces because of the snow, etc.

The following loads will be applied (figure 43):

- self-weight of the beam,
- permanent loads: distributed force of q= 4 kN/m, applied over the whole length of the beam,
- mobile loads: concentrated force of P= 5kN in the middle of the beam, x= 3m,
- wind loads: distributed force of q= 1 kN/m, applied over the whole length of the beam.

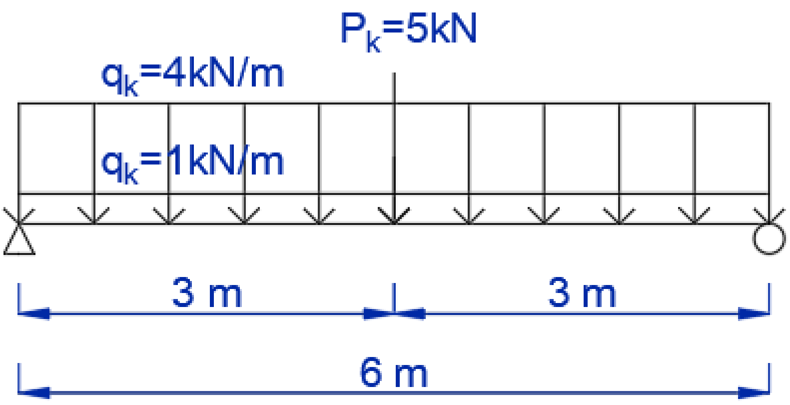


Figure 43: applied loads

There is also the possibility to define load combinations in some BIM-software packages. A random combination in ULS and SLS will be created to see if the conversion to FEM-software is reliable.

- ULS: $1{,}35 \times q_{\text{self-weight}} + 1{,}35 \times q_{\text{dead load}} + 1{,}5 \times P_{\text{live load}} + 0{,}9 \times q_{\text{wind load}}$
- SLS: $1 \times q_{\text{self-weight}} + 1 \times q_{\text{dead load}} + 0{,}3 \times P_{\text{live load}} + 0 \times q_{\text{wind load}}$

The scope of this thesis is to investigate the conversion process, not to determine the most optimal solution for the cross-section of every material or to let the material succumb. For this particular reason, cross-sections that will be able to handle the load are used and have the following dimensions (figure 44 and 45):

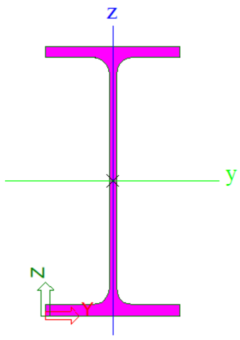


Figure 44: Steel beam: IPE240

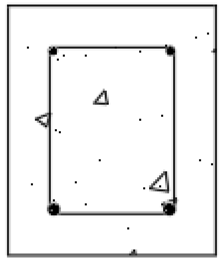


Figure 45: Reinforced concrete beam: 300x250

After the first set of conversions, some adjustments to the models will be made. By rotating the model, changing the material and shifting the position of the local axes, it will be explicitly clear if the conversions are done properly.
All the beams will be modelled in the different BIM-software from scratch, which means that a conversion from BIM to BIM will not take place. The BIM-models will contain information about the section properties and geometry of the profile, the used materials and, if possible, also about the boundary conditions, loads and load combinations.

8.2. Robot Structural Analysis: links and results

8.2.1 Revit to RSA (direct link)

The direct link between Revit and Robot Structural Analysis was accomplished with the help of a specialized plug-in. When the conversion is made, the following window will pop up (figure 46) and there can be chosen which conversion method should be used. A new model can be created (send model), an existing model can be updated (update model) or an existing model where calculations and results are included, can be updated (update model and results). For this research a new model is created. It is also possible to convert the model to an intermediate file, but this option is not chosen due to a better conversion when using a direct link or integration. When the software is installed on different computers, this intermediate file will be the only available option for the transmission of the model.

When choosing the manner of conversion, there are a couple of extra options which can be included, as shown in figure 47. If there are some elements selected in Revit, it is possible to only transfer those objects and their parameters. Of course, it is also possible to transfer the whole Revit project. The self-weight of the model can be integrated in one of the defined load cases, or it can be ignored and therefore not be converted to RSA. If the model is using steel connections or reinforcements, the properties of these components can also be transferred by activating this option.

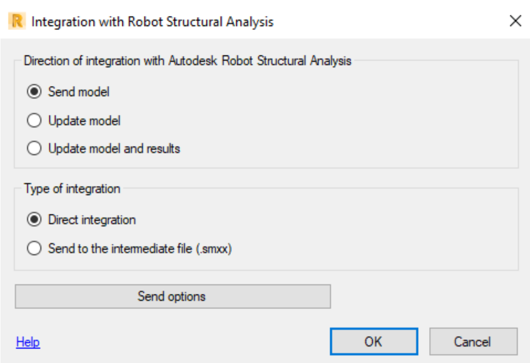


Figure 46: Transfer options Revit to RSA

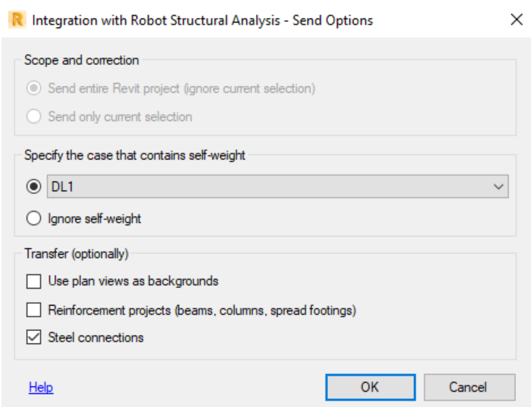


Figure47: Send options direct link Revit to RSA

After choosing the preferred conversion options, the model will be send to RSA. When this is completed, a warning list will be generated in Revit. All the transferred properties and encountered problems during the conversion are shown in this report (figure 48). According to the report of the reinforced concrete model, no problems were detected during this transition. Next, the RSA file automatically opens and shows the calculation messages (figure 49). These warnings are not relevant to this research due to not modelling a panel. The two linear loads (Dead load and Wind load) placed on the model in Revit, are converted to RSA and node 3 is not part of the analysed model. These warnings are a big help to spot mistakes. However, when too little information is given, these warnings become unnecessary. For example, even though our model exists of only one beam between two nodes, the warning says that node 3 is not a part of the analysed model. Therefore, it becomes difficult to estimate the weight of the error.

overzetting naar robot - Kladblok

Bestand Bewerken Opmaak Beeld Help

```
Revit Levels    2018-4-28 16:03:54 - Command execution started.
--> Stage execution time: 1 [seconds]
Revit Bars
--> Stage execution time: 10 [seconds]
Revit Point supports
--> Stage execution time: 1 [seconds]
Revit Load cases
--> Stage execution time: 1 [seconds]
Revit Load combinations
--> Stage execution time: 2 [seconds]
Revit Point loads
--> Stage execution time: 0 [seconds]
Revit Line loads
--> Stage execution time: 36 [seconds]
Robot Nodes
--> Stage execution time: 0 [seconds]
Robot Bars
--> Stage execution time: 25 [seconds]
Robot Point supports
--> Stage execution time: 0 [seconds]
Robot Load cases
--> Stage execution time: 0 [seconds]
Robot Load cases
--> Stage execution time: 0 [seconds]
Robot Loads
--> Stage execution time: 1 [seconds]
Robot Levels
--> Stage execution time: 1 [seconds]
Robot Nodes
--> Stage execution time: 0 [seconds]
Robot Bars
--> Stage execution time: 0 [seconds]
Robot Bars
--> Stage execution time: 2 [seconds]
Robot Point supports
--> Stage execution time: 7 [seconds]
Robot Load cases
--> Stage execution time: 1 [seconds]
Robot Load combinations
--> Stage execution time: 0 [seconds]
Robot Loads
--> Stage execution time: 1 [seconds]
Robot Levels
--> Stage execution time: 31 [seconds]
Update reinforcement
--> Stage execution time: 65 [seconds]
The operation is almost complete.
--> Stage execution time: 1 [seconds]
Completed
16:07:02 - The command was completed. Execution time: 3:07 [minutes:seconds]
```

Figure 358: Transferred properties Revit to RSA

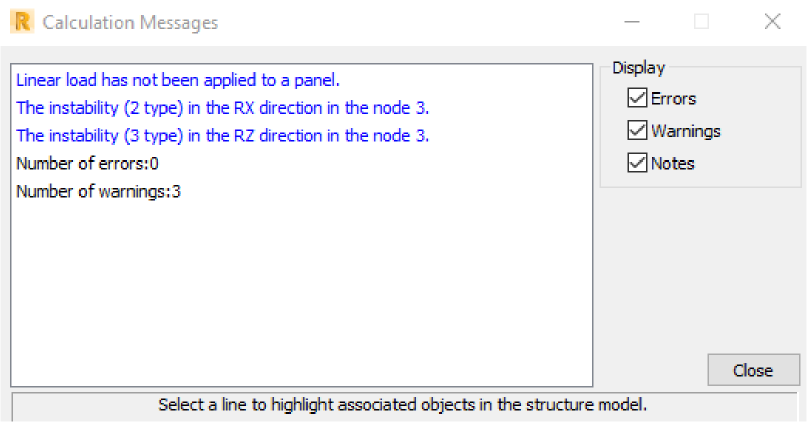


Figure 369: Calculation messages Revit to RSA

The direct link is very easy to use since it is not necessary to map the sections or materials. Both programs are using the same label for standardised sections and materials. The fact that it is possible to choose whether the self-weight of the construction is included in the transition can be an advantage if the self-weight is not relevant to the calculations, for example if only the effect of the applied loads is investigated. The information about the transferred components can be found in appendix 1: table B and C for respectively the steel and the reinforced concrete model. The used symbols in these and the following tables are defined in legend which is shown in appendix 1: table A.

No major problems were detected when comparing the properties of the BIM-model and the FEM-model of both the steel model and the reinforced concrete model. The geometrical properties of the Revit model are correctly transferred to the RSA model. The length of the model, the rotation of the cross section and the global coordinates are the same in both models. These are probably the most important properties to be transferred correctly due to the fact that one of the goals of using a direct link is to make the design process for the analytical model less time-consuming and to make sure the calculations are made for the correct models. Knowing this, the structural engineer does not have to design the complete structure from scratch and consequently needs less time to complete his process.

Another important conclusion is that only the type of profile and name of the material are transferred. This is noticeable due to some properties defined in Revit and not in RSA and the other way around. The properties of the profile are linked to the type but are defined by RSA itself. This means that when the dimensions of a profile are changed in

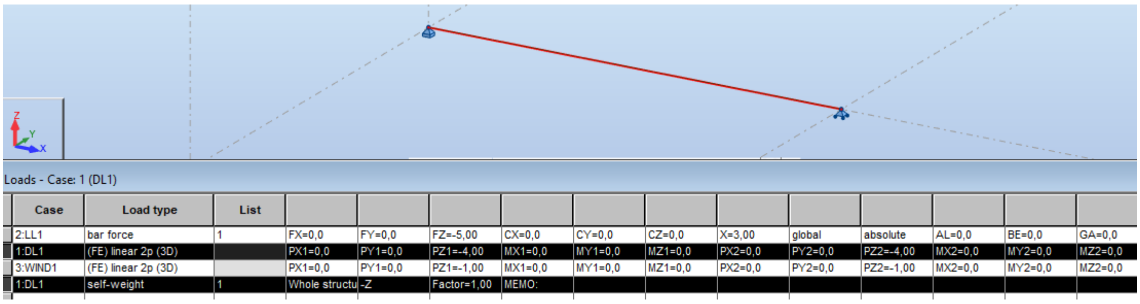
Revit but the name of the profile remains unchanged. Consequently, the dimensions will not be transferred correctly to RSA. In RSA the properties of the profile will be based on the name of the imported profile to avoid doubt amongst the other members of the design team.

The same story can be told regarding the material of the model. When the name is correctly transferred and linked, which is not a problem using this direct link, the properties of the material in RSA will be defined by the material library of RSA. When the designer in Revit wants to define special properties to the material, they will have to notify the structural engineer to adjust this in their RSA model.
An important encountered issue is that the reinforcement designed and modelled in Revit was not transferred to RSA. However, this is probably not a big problem because the reinforcement is normally designed based on the applied loads on the beams and these are generally calculated by the analysis software. It can be a problem when an RSA model is convert to a Revit model and later on back to RSA to make further calculations. The reinforcement will be deleted but can be calculated again later. Figure 50 showed that there was the option to transfer reinforcement. This option is only relevant when a model is updated, not when a new model is created.

The boundary conditions defined in Revit are correctly transferred to RSA even though these are normally not defined by the architect. The structural engineer will define these when preparing the model for analyses. When the structural model is transferred to the design model and then back to a structural model after some adjustments, it is interesting to know that the definition of the boundary conditions will not get lost.

The last properties that are exported according to the notebook file (figure 51), are the load cases and combinations. These are both transferred correctly and the safety factors in the load combinations are also transferred. The self-weight of the model is not transferred, but, as said before, the user can choose in which load case he wants to insert the self-weight. If the user wants to see the self-weight in a separated load case, one can choose to ignore the conversion of the self-weight and create a new load case in the FEM-software.
The concentrated and distributed loads are also imported in RSA. Even though the distributed loads are not visible in the 3D-view, their values are correctly shown in the

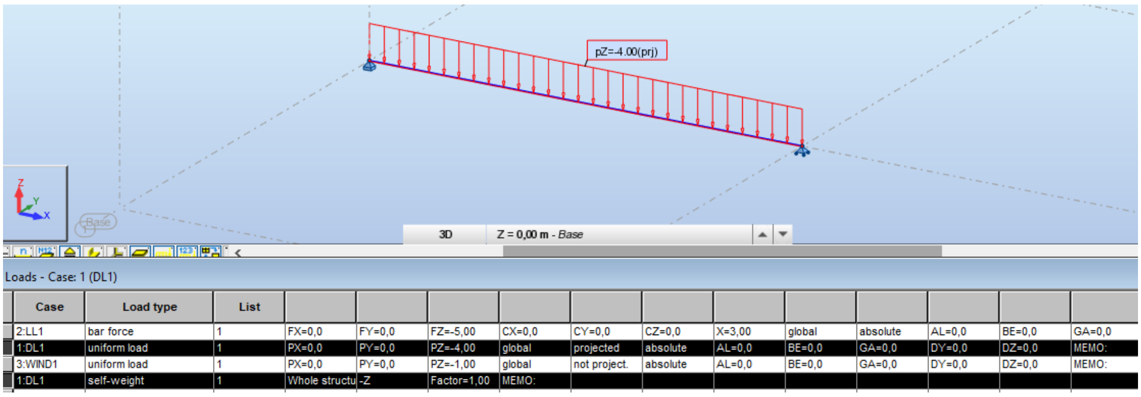
summary table. The type of load is the cause of this issue. The imported distributed loads are typed as ‘(FE) linear 2p (3D)’ (figure 6), if this is changed to the type uniform load, they are visible (figure 7). As stated before, this is not a major problem because this is quickly changed and the loads are generally applied on the structure in the analysis model.



Loads - Case: 1 (DL1)

Case	Load type	List												
2:LL1	bar force	1	FX=0,0	FY=0,0	FZ=-5,00	CX=0,0	CY=0,0	CZ=0,0	X=3,00	global	absolute	AL=0,0	BE=0,0	GA=0,0
1:DL1	(FE) linear 2p (3D)		PX1=0,0	PY1=0,0	PZ1=-4,00	MX1=0,0	MY1=0,0	MZ1=0,0	PX2=0,0	PY2=0,0	PZ2=-4,00	MX2=0,0	MY2=0,0	MZ2=0,0
3:WIND1	(FE) linear 2p (3D)		PX1=0,0	PY1=0,0	PZ1=-1,00	MX1=0,0	MY1=0,0	MZ1=0,0	PX2=0,0	PY2=0,0	PZ2=-1,00	MX2=0,0	MY2=0,0	MZ2=0,0
1:DL1	self-weight	1	Whole structu	-Z	Factor=1,00	MEMO:								

Figure50: Distributed load as '(FE) linear 2p (3D) Revit to RSA'



Loads - Case: 1 (DL1)

Case	Load type	List												
2:LL1	bar force	1	FX=0,0	FY=0,0	FZ=-5,00	CX=0,0	CY=0,0	CZ=0,0	X=3,00	global	absolute	AL=0,0	BE=0,0	GA=0,0
1:DL1	uniform load	1	PX=0,0	PY=0,0	PZ=-4,00	global	projected	absolute	AL=0,0	BE=0,0	GA=0,0	DY=0,0	DZ=0,0	MEMO:
3:WIND1	uniform load	1	PX=0,0	PY=0,0	PZ=-1,00	global	not project.	absolute	AL=0,0	BE=0,0	GA=0,0	DY=0,0	DZ=0,0	MEMO:
1:DL1	self-weight	1	Whole structu	-Z	Factor=1,00	MEMO:								

Figure 51: Distributed load as 'uniform load' Revit to RSA

The direct link between Revit and Robot Structural Analysis is a trustworthy method to transfer a model. The most important properties that are designed by the architect such as the geometry, the section and the material are correctly transferred. It is not an issue that some properties, for example the loads, are not transferred correctly because it is better to model these properties directly in the FEM-software. The workflow is easy to follow and the design process of become more efficient for the engineer.

8.2.2 ArchiCAD to RSA (IFC)

To transfer an ArchiCAD model to RSA, an IFC file is used. In ArchiCAD it is possible to export the model to IFC 2x3 or IFC 4 but RSA is only capable to import data exchange formats of the version 2x or 2x2 [62]. However, it was only possible to import the IFC 2x3 format file, but not ideal. When opening the IFC file in RSA, the file is automatically imported. It is not necessary to map any properties which indicates that the conversion probably is not very specific.

In appendix 1: table B and C for respectively the steel model and the concrete model, it becomes clear that our hypothesis is correct. All the properties are compared and a clear difference between the steel section and the concrete section can be noticed. Next, the difference between the conversed properties will be discussed.

The only property of the models that is imported correctly in both cases, is the geometry. The length, rotation of the cross section and global coordinates are transferred. All the properties are correctly transferred, even though the global coordinates are in sometimes modified. This can be explained by taking a look at the reference line of the profile.

When the reference line is positioned in the middle of the centre, the global coordinates will remain exactly the same after the conversion. However, when the reference line is set at the top or bottom of the profile, the z-coordinate of the nodes will be modified. The nodes will be repositioned to the centre of the beam. Between these nodes, the analytical line will also be created for further calculations. In comparison with the original model, the position of the beam remains the same, which means that the coordinates are indeed transferred correctly.

As for the steel beam, the results for conversion of the type of the profile and material were disappointing. The type of the profile is stated as default in the FEM-model and according to RSA the applied material is concrete, which is the default value of RSA when no material is imported (figure 52 and 53).

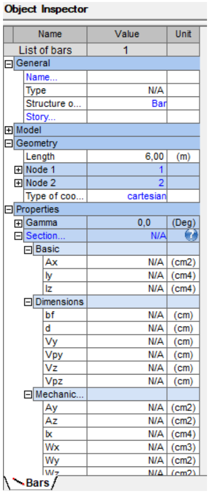


Figure 52: Profile properties steel model ArchiCAD to RSA

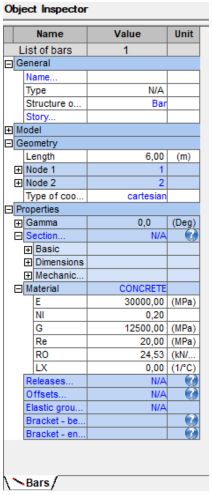


Figure 53: Material properties steel model ArchiCAD to RSA

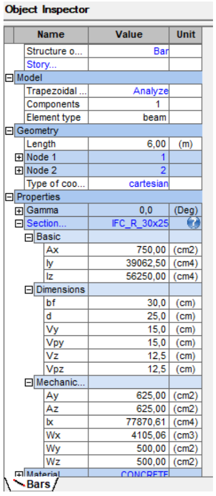


Figure 54: Profile properties concrete model ArchiCAD to RSA

More properties are imported pertaining to the concrete beam. Parameter mapping is used for the conversion of the profile. However, some odd things happened during this process. The height and width in ArchiCAD switched positions in RSA and became respectively the width and height. Still, the conversion is marked as successful because the profile is turned and therefore the cross-section has the same orientation in both programs.

The profile properties were calculated by RSA because the possibility to define these properties is not provided in ArchiCAD (figure 54).

On first sight, the material properties seem to be correct but ‘concrete’ is the default value in RSA. Only the name and class of the material could be defined in ArchiCAD. Defining other properties fall outside the scope of this program. Eventually, RSA will assign all the properties to be beam based on the default material.

In ArchiCAD, it was not possible to define boundary conditions or apply loads on the model, so the conversion of this property cannot be compared. Creating reinforcement bars in the concrete model, was also not an option in this software program. Due to this the transmission of this property cannot be discussed.

When all these concerns are considered, we can conclude that the conversion from ArchiCAD to RSA using IFC2x3 is not ideal. The material is not converted and when using a steel profile, the cross-section could not be transferred. However, the simple concrete profiles could be converted. In all cases, the geometry of the structure was correct. This last property is the most important one to save time for the structural engineer. There are programs on the market that are more mutually compatible. It is not impossible to exchange data, but every single profile must be modified. In the advanced case, it is possible to investigate whether the profiles are connected correctly and make the transfer or whether it is better to build the model from scratch. It is recommended to share the BIM-model together with the drawings where the different materials and sections are described per element.

8.2.3 AECOsim to RSA (IFC)

The conversion of a model in AECOsim to RSA using the IFC data format is quite similar to the conversion from ArchiCAD to RSA. It is possible to export from AECOsim to IFC2x3 and IFC 4. Because of the fact that RSA cannot import IFC4, only the IFC2x3 file will be imported. The results of this conversion are displayed in appendix 1: table B and C for respectively steel and concrete. The differences between this conversion and the one with ArchiCAD (see passage 2 'ArchiCAD to RSA (IFC)') will be discussed in the following paragraphs.

The geometry of the steel model is not very well transferred, only the length of the beam is correct. The x and y-coordinates are the same as in the BIM-file, however, the z-coordinate is wrong. This coordinate is -0,15 as it should be 0,00. This difference can be explained with the help of an IFC viewer. The viewer shows that the elevation of the bottom and the top of the profile are exported and have a value of respectively -0,15m and +0,15m. The coordinates of the centre were not transferred to the IFC file. An attentive reader will notice that the height is 0,30m instead of the desired 0,24m for an IPE240 profile. The reason why another profile was favoured over the European IPE240 is the fact that only American profiles could be modelled in AECOsim and another profile had to be chosen.

When RSA imported the IFC file, no coordinates for the centre of the profile could be found. However, Robot bases the profiles on these coordinates. Since the necessary coordinates were missing, the coordinates of the bottom of the profile were used as the new centre of the profile.

This problem does not occur in the model with the concrete beam. The global coordinates are the same in the BIM-model and the FEM-model as is the position of the reference line. Due to the global coordinates being correct, the length of the beam is also correctly conversed.

There is a difference between the conversion of the steel profile and the concrete profile, which was also the case for the models in RSA converted from ArchiCAD.

The profile of the steel beam (properties seen in figure 55) is not imported in RSA.

While, in case of the concrete beam (properties seen figure 56), the type of the profile, height and width are correct. All the other properties of the section are calculated by RSA. Furthermore, the material of both the beams is not imported and again the default value of ‘concrete’ is given as seen in passage 2 ‘ArchiCAD to RSA (IFC)’.

Name	Value	Unit
Length	1,82	(m)
Node 1	1	
Coordinat...	-0,00 -3,10 -0,15	
Node 2	2	
Coordinat...	1,82 -3,10 -0,15	
Type of coo...	cartesian	
Properties		
Gamma	0,0	(Deg)
Section...	N/A	
Basic		
Ax	N/A	(cm2)
Iy	N/A	(cm4)
Iz	N/A	(cm4)
Dimensions		
bf	N/A	(cm)
d	N/A	(cm)
Vy	N/A	(cm)
Vpy	N/A	(cm)
Vz	N/A	(cm)
Vpz	N/A	(cm)
Mechanic...		
Ay	N/A	(cm2)
Az	N/A	(cm2)
Ix	N/A	(cm4)
Wx	N/A	(cm3)
Wy	N/A	(cm2)
Wz	N/A	(cm2)
Material	CONCRETE	
E	30000,00	(MPa)
NI	0,20	
G	12500,00	(MPa)
Re	20,00	(MPa)
RO	24,53	(kN/...
LX	0,00	(1/°C)

Bars

Figure 55: Properties steel beam AECOsim to RSA

Name	Value	Unit
Length	1,82	(m)
Node 1	1	
Coordinat...	-0,00 -3,04 0,0	
Node 2	2	
Coordinat...	1,82 -3,04 0,0	
Type of coo...	cartesian	
Properties		
Gamma	0,0	(Deg)
Section...	IFC_R_20.3x22.9	
Basic		
Ax	464,52	(cm2)
Iy	20228,86	(cm4)
Iz	15983,31	(cm4)
Dimensions		
bf	20,3	(cm)
d	22,9	(cm)
Vy	10,2	(cm)
Vpy	10,2	(cm)
Vz	11,4	(cm)
Vpz	11,4	(cm)
Mechanic...		
Ay	387,10	(cm2)
Az	387,10	(cm2)
Ix	30139,33	(cm4)
Wx	2031,73	(cm3)
Wy	309,68	(cm2)
Wz	309,68	(cm2)
Material	CONCRETE	
E	30000,00	(MPa)
NI	0,20	
G	12500,00	(MPa)
Re	20,00	(MPa)
RO	24,53	(kN/m3)
LX	0,00	(1/°C)

Bars

Figure 56: Properties concrete beam AECOsim to RSA

In AECOsim, it was possible to define the boundary conditions of the beams and to apply loads. However, these are not converted in the RSA model. As said before in passage 1 ‘Revit to RSA (direct link’, this is not a major problem due to the engineer applying the loads in RSA and not the architect in AECOsim.

The same conclusion as in passage 2 ‘ArchiCAD to RSA (direct link)’ can be made, it is not ideal to use RSA when modelling with AECOsim due to the poor transfer with IFC 2x3. It would not be logical to exchange information between these programs because a solid link exists between AECOsim and STAAD.Pro and between Revit and RSA.

8.2.4 Tekla Structures to RSA (IFC)

To make the conversion possible of a Tekla model to a RSA model the IFC 2x3 data format must be used. As said before, RSA can only import IFC 2x and IFC 2x2 files properly. Importing an IFC 2x3 file is possible, however with data loss and only pertaining the concrete beam. It was not possible to import the IFC file of the steel beam in RSA. There is the possibility to open a ‘*.std’ file (Staad) but this is not a logical option because then the file first must be imported in STAAD.Pro and saved as a staad-file. Next, this staad-file must be imported in RSA. All in all, three conversions must take place, which can result in a lot of data losses. Furthermore, the software must be available which is not very likely to be the case. The result of the conversion can be found for the steel and the reinforced concrete beam in appendix 1: table B and C. However, the transfer from Tekla Structures to RSA was not possible for the steel beam and therefore the column with results will be empty for this conversion in table B.

The geometry is correctly transferred to RSA, except for the rotation of the cross section. This property could not be transferred. The other geometrical properties, which are the length and the global coordinates are correctly conversed.

The conversion of the concrete beam can be compared to the conversions of the beams modelled in ArchiCAD (paragraph X) and AECOsim (paragraph X). Again, the name of the profile and the height and width are correctly transferred. The other profile properties are calculated based on these data instead of importing the properties from the BIM-software.

The material properties are defined for concrete, however, as said in the previous paragraphs, this is the default value that RSA uses and is not imported from the BIM-software.

Tekla Structures is one of the few programs that are capable of modelling the reinforcement bars for the concrete beam. However, the information about the reinforcement was not transferred to the RSA model. Neither the material properties of the steel nor the profile properties of the reinforcement are converted. This is not the biggest issue due to the structural engineer designing the reinforcement and not the architect. But it will not be easy to exchange the information efficiently back and forth between the programs.

Tekla Structures features the possibility to define the boundary conditions, load cases and combinations. These can be exported with an analysis model, but not trough IFC. As a result, these properties are not imported in RSA. Again, as previously mentioned, this is not a major problem due to fact that these are being calculated and defined in the analysis model by the engineer instead of the architect.

The conversion from a Tekla model to an RSA model, using IFC2x3 is most of the time asking for trouble. For a steel model, the conversion is not possible. However, it was possible for the concrete model to transfer the major properties such as the geometry, as long as the profile was not rotated, and the cross-section. The impression could be given that it is possible to make use of this link. Let’s not forget that only a simple case was investigated. When a normal project with many elements is transferred, more problems will arise.

8.2.5 Vectorworks to RSA (IFC)

For the steel beam in Vectorworks, there are three different options to design this element: a construction element, a structural element or a chosen detailed profile. The concrete beam can either be designed as a construction element or as a structural element. The file in Vectorworks can be exported as an IFC 2x3-file or an IFC 4-file, due to RSA only be able to import the IFC 2x3-file, only these files are discussed in this paragraph.

The results of the conversions are shown in appendix 1: table B for steel beams and table C for concrete beams.

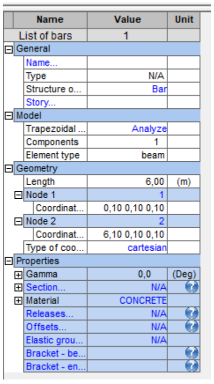


Figure 57: Properties chosen detailed profile steel, Vectorworks to RSA

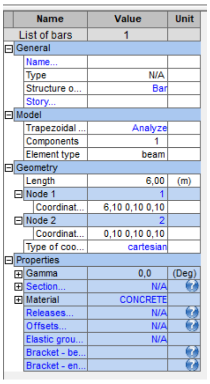


Figure 58: Properties chosen structural profile steel, Vectorworks to RSA

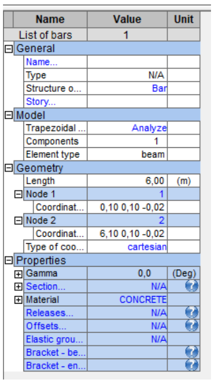


Figure 59: Properties construction element steel Vectorworks to RSA

The results of the conversions of the steel beams are not desirable, only information about the geometrical properties is exchanged and not even all these properties are transferred. The length of the profile is the only property correctly transferred in all three different design options. The rotation of the cross section is in none of the three models converted. The global coordinates are correctly transferred to the RSA model when the model was designed with the construction element or the chosen detailed profile, but this was not the case when the structural element was used.

The global coordinates of the start point of the steel beam in the Vectorworks models are (0,100; 0,100; 0,100)m. The node properties, seen in figures 57 and 58, are correctly transferred for the structural element and detailed profile.

But this is not the case for the z-coordinate of the construction element (figure 59). The value of the z-coordinate is -0.020 m instead of the original 0,1 m.

This mistake can be explained regarding how the beam is transferred when modelled as a construction element. The height of the beam is 240 mm because an IPE240 profile is chosen.

Normally, for the z-coordinate, a value 0,100 m should be assigned to the centre of the beam. When converting the construction element to an IFC data format, the reference line of the model is taken at the bottom of the profile which is positioned at z= -0,02 m.

For the concrete beam, the geometry is properly transferred except for the rotation of the cross-section. The length is still correct as are the global coordinates.

While the conversion of the type of the steel beam could not be executed, the conversion of the concrete profile performed better. The type of the profile, its height and width are imported in RSA and the other properties are calculated by the program based on this data. The material is stated as ‘concrete’, but as said before, this is the default value. It is not even possible to define material properties such as the characteristic cylinder strength in Vectorworks. The value 20 MPa is assigned to this property by Vectorworks. This can be dangerous because it is possible that the engineer performs calculation without adjusting this value. It would be better if the default value was N/A.

To conclude this conversion, when designing a steel beam, it is not recommended to design it as a construction element. The structural element and the chosen detailed profile are also not ideal. However, they are more correct. The architect must be willing to use structural elements and the detailed profiles instead of construction elements, which can make the design process more complicated.

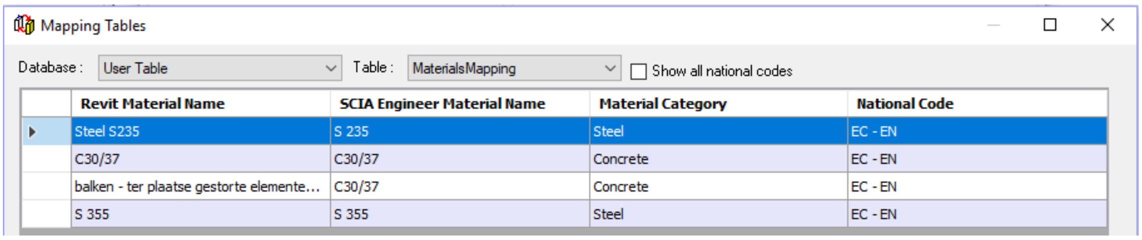
It does not matter if a construction or structural element is used when modelling a concrete beam, the same properties are transferred to RSA.

8.3. Scia Engineer: links and results

8.3.1 Revit to SCIA Engineer (Direct link)

Both Revit and SCIA Engineer were installed on the same computer, which made it evident to choose the direct link instead of a file-based link. When the file-based option is used, the additional license esa.21 for SCIA Engineer is necessary to import the *.r2s file. This license was not at our disposal, which lead to the fact that a file-based link was not possible. There has to be kept in mind that the direct link can only be used when there is a working license for Revit and SCIA Engineer available on the same computer.

The plug-in provides mapping tables that must be used. Every time a material cannot be converted from Revit to SCIA, the table appears and an explicitly link must be made (figure 60). There is also the possibility to map sections. Eventually, a full export report will be generated and SCIA Engineer will open automatically. Materials and sections that were defined in another process are saved in the mapping tables and can be used again. A warning about all the materials that are transferred based on the user mapping will be given together with a summary about the export (figure 61).



Revit Material Name	SCIA Engineer Material Name	Material Category	National Code
Steel S235	S 235	Steel	EC - EN
C30/37	C30/37	Concrete	EC - EN
balken - ter plaatse gestorte elemente…	C30/37	Concrete	EC - EN
S 355	S 355	Steel	EC - EN

Figure 60: Mapping Tables Revit to SCIA Engineer

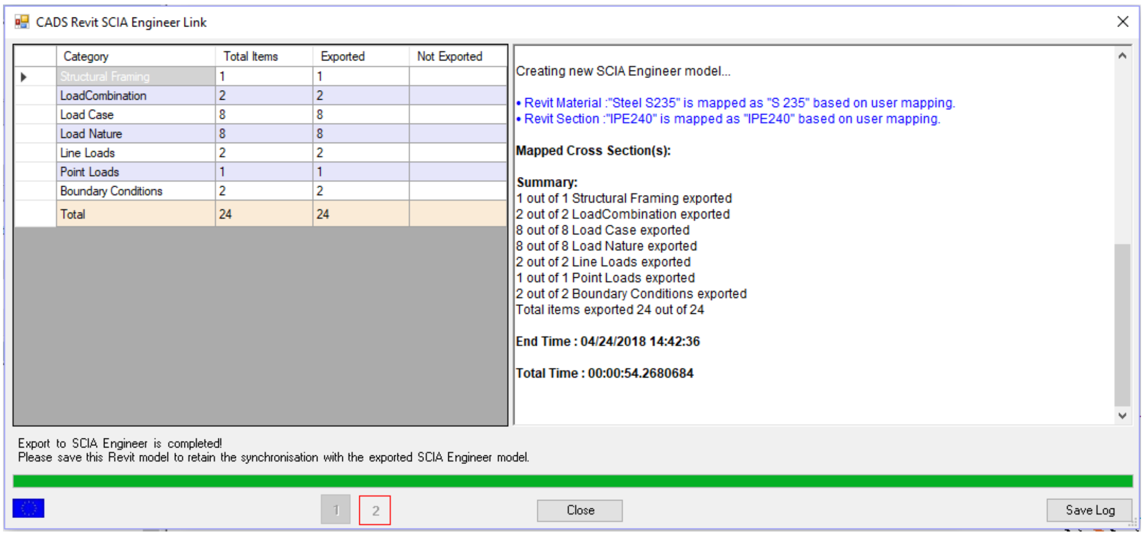


Figure 6137: CADS Revit SCIA Engineer link

The direct link is well developed and is easy to use. Information about each transferred component can be found in appendix 1: table D for steel and table E for reinforced concrete together with the other exchange methods and table A for the legend.

Due to the high quality of this link, no issues were encountered during conversion of the data which is partly due to the fact that the model only consisted of a simply supported beam.

When we take a closer look at the steel beam, we can see that the geometry, which consists of the coordinates and the rotation of the cross-section, was transferred perfectly. Due to the mapping tables, the profile and materials were also transferred correctly, as expected. In SCIA Engineer, the profile and the steel contain more properties than in Revit. Thanks to our steel models, we noticed that this issue is handled by linking the name of the items and then using the associated information that is implemented in the FEM-software, which will lead to some implications.

For example, it is possible in Revit to manually change all the properties without changing the name of the element. When the wrong value for the moment of inertia is used in Revit, there will be no consequence because SCIA Engineer will use its own moment of inertia. However, when the dimensions of the profile are changed without modifying the name, a totally different profile will be used for the analysis. It is not likely that this situation will happen, but it is possible.

The mapping of a standard steel beam is an easy process. The only thing the user must do is choosing the correct SCIA Engineer section from a pre-installed mapping table and link this to the corresponding Revit family.

For concrete sections, such a database does not exist. Another workflow will be used: parameter mapping (figure 62). First, the section type that will be used in SCIA is selected. This will determine which parameters have to be transferred. After that, all the parameters are linked to a Revit property. After the conversion, SCIA Engineer will calculate all the necessary properties for the analysis. The parameters that are explicitly linked are marked in the cross-section menu.

In SCIA Engineer, all the properties of the objects are accessible and can be modified. This sounds evident, but this is not the case for all exports.

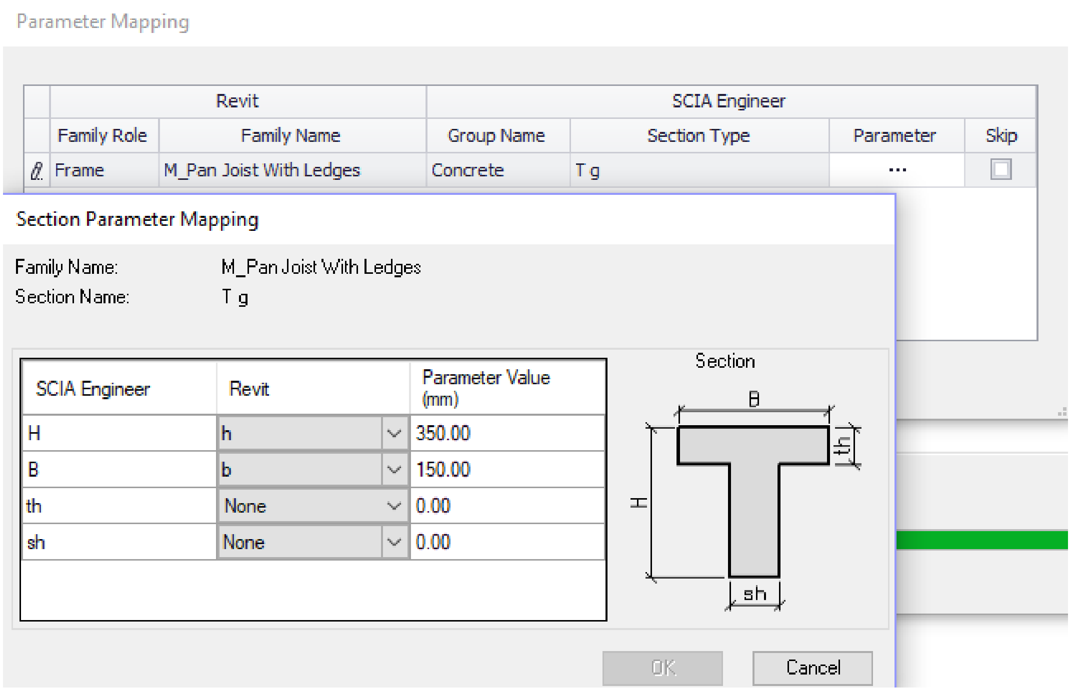


Figure 62: Section parameter mapping: T joist

In both cases the main material was transferred correctly, but when more attention was paid to the reinforced concrete beam, some issues could be found. All the elements of the reinforcement were completely left out. Currently, no solution for this issue is available because the direct link does not support the export of reinforcement bars [63].

Revit is one of the few architectural programs in which boundary conditions can be defined. At first, an architect will not define these because of the lack of knowledge. The type of boundary condition depends on the execution of the support/ connection. The engineer will decide how certain connections must executed and therefore the architect does not have all the necessary information to define the boundary conditions.
However, it is possible that an analysis model is imported in Revit and later exported to SCIA Engineer. In this case, the boundary conditions have been already defined and can be reused or modified.

When we examined the load cases and load combinations, the link looked promising because they were all exported correctly. The only downfall was that creating the combinations in Revit is time-consuming and the value of the safety factors cannot be filled in automatically.
Normally, the load cases will contain loads, but unfortunately, the export of these loads was a disaster. All the line loads were completely gone even though they were exported according to the log file.
It was a different story for the point loads. These were placed at the desired place, with the accurate value in the correct load case. However, it was not possible to perform any calculations with these loads. All in all, only calculations with the self-weight could be made. These were correctly, but only because the self-weight was generated by SCIA Engineer based on the profile and density of the material.
In Revit, an analytical line could be created. After the transfer, the analytical line was gone, which is a positive development because this ensures that SCIA Engineer will define an analytical line at the rightful place of the profile.

All in all, there can be decided that the link between Revit and SCIA Engineer is a solid link for practical purposes. The geometry and boundary conditions transferred correctly and SCIA Engineer will create the cross-sections and materials based on mapping tables and parameter mapping. The transfer for reinforcement bars is not supported and the loads are not exported correctly. However, in the normal workflow, an architect will not provide information about these elements because that is the task of the engineer.

8.3.2 Revit to SCIA Engineer (IFC)

In the previous paragraph, there was spoken about the direct link between Revit and SCIA Engineer that can be used thanks to a plug-in. Apart from that, it is also possible to transfer the data with an IFC2x3 file. Both Autodesk and SCIA are supporters of openBIM, which can be seen when the transferred properties of both links are compared, which is done in appendix 1: table D and E.

All the geometrical, section and material properties that could be mapped with the direct link, can also be mapped with IFC. However, the process requires a little bit more work.

All the geometrical properties are correctly transferred, which was also the case for the direct link.
The standard steel profiles are mapped with standard profile tables based on the Eurocode. This process does not require any extra work. There is no difference between the mapped properties of the direct link and the IFC-file based link. Extra properties, like the buckling curves were also implemented in the pre-installed tables.
The link of the concrete profiles is established with parameter mapping. However, the user does not have to explicitly link the parameters of both profiles. The program is able to link these without external help because the standardized format is used. The linked parameters might be the same, but initially, not all properties have the correct value.
SCIA Engineer has an option '2nd EEM Analysis', which is turned off at first instance when the IFC link is used. Because of this, it is not possible to calculate the torsional moment of inertia and the torsional modulus. This issue can be easily fixed by enabling the '2nd EEM Analysis' and re-reading the cross-section.

The material mapping must be done manually in the material converting table (figure 63), which can be used for all the IFC-files
The export of all the properties is handled in the same way, which means that the steel beams will be mapped based on the name, while the concrete beams are mapped on parameter mapping. The process itself needs more work than when a direct link is used. Instead of just pointing out the correct materials in a pre-installed database, a mapping table for the materials must be manually made. An example of such a database can be

found in figure 63. The first material is the name of the component in the BIM-software, the second is the equivalent in SCIA Engineer.

Good communication between both participants is required, the engineer must know the exact name (including every space) of the materials to establish the link. The material table can always be expanded and reused in other projects.

materiaaltabel - Kladblok

Bestand Bewerken Opmaak Beeld Help

```
[materialen]
;
Concrete - C30/37=C30/37
CONCRETE/C30/37=C30/37
balken - ter plaatse gestorte elementen C30/37=C30/37
S235=S 235
STEEL/S235JR=S 235
Steel S355=S 355
Steel - S 355=S 355
B500A=B 500A
Steel Rebar - B500A, B or C=B 500A
```

Figure 6338: material table SCIA Engineer

The direct link was not able to transfer any information about the reinforcing bars and the same was expected from the export with IFC. However, it was a pleasant surprise to see that the rebars with the correct position, shape, diameter and materials appeared in the model. All the reinforcement bars are imported as longitudinal reinforcement but can be manually changed to stirrup reinforcement if necessary. Even though all necessary components are there to make a control calculation, when this calculation is performed, an error occurs. It is better to implement the reinforcement structure directly in the FEM-software.

The IFC-file was not able to export the boundary conditions, loads and load combinations. None of these items is transferred, which would appear to be a safe choice. The engineer will have to make a conscious decision to implement each of these components, which makes it less likely that during the defining process, one of these boundary conditions or loads is accidentally skipped and therefore has the wrong properties.

Recurring exchanges are also not a problem for the link. The adjusted IFC-file can be reread in the '*.esad' file (the format that SCIA Engineer uses). The program will automatically seek for the adjustments and make changes to the model after the confirmation of the user. The boundary conditions and loads that were already implemented will remain the same as long as their analytical line exists. When a beam is deleted in the architectural model, it will also be deleted in the analytical model and the boundary conditions belonging to this beam are therefore no longer needed. But when only the cross-section of the beam is changed, SCIA Engineer will keep these properties because the analytical model itself is not modified.

IFC is a good alternative for the direct link. The most important components of the model for the structural analysis are transferred correctly. The model can be expanded with boundary conditions and loads. These components are not lost when the IFC-file is reread in the software, provided that the analytical line is maintained.

8.3.3 ArchiCAD to SCIA Engineer

The only possibility to exchange data between ArchiCAD and SCIA Engineer is through IFC2x3. ArchiCAD provides several translators and one is especially designed for SCIA Engineer: ‘data exchange with SCIA Engineer’. It only makes sense that this option is chosen. In appendix 1: table D and E, the results of the conversion of respectively the steel and concrete beam can be found.

Taking a closer look to the beams, there can be noticed that the only property of the models that is imported correctly in both cases, is the geometry. The length, the rotation of the cross section and the global coordinates are transferred. We could notice that the z-coordinate of global coordinates is slightly modified in some cases. The coordinates in ArchiCAD are defined by the reference line, which can lay at the top, centre or bottom of the profile. SCIA Engineer uses will model the profiles between two nodes, which represent the centre of the beam. This difference in the modelling approach results in the modification of the coordinates. However, when compared to the BIM-model, the position of the beam remains the same and therefore the global coordinates are marked as correctly transferred. This explanation can be made more concrete with an example. In ArchiCAD, the reference line of the concrete beam was placed at the top of the profile and the coordinates of node 1 were (0,500; 0,500; 0,500)m. The coordinates were modified in SCIA Engineer and node 1 was placed on (0,500; 0,500; 0,350)m. It appeared that the coordinates were incorrect. However, when a closer look was taken at the beam, it was clear that the top of the profile still had the same coordinates.

For the steel beam, there can be seen that not all the properties are the same. ArchiCAD has a database with national standards for a wide range of profiles and can be imported with the ‘import steel profiles’ function. Normally, the architect will use this function instead of drawing his own profiles because it is less complicated. When the IPE240 profile in ArchiCAD is compared to the one in SCIA Engineer, there can be seen that not every property is the same. For example, in ArchiCAD the value of the radius of the fillet is 0 mm while in SCIA this is 15 mm. This is explainable because the level of detail is lower in ArchiCAD for these elements, simply because for these objects a high level of detail is not required in the modelling phase.

For steel, SCIA Engineer has a pre-installed database with cross-sections. Every one of these cross-sections has a specific code based on the building codes, which means that the profiles can be mapped correctly. Then, SCIA Engineer will use the properties provided in its database for further calculations.

When the cross-section of the concrete beam was investigated, it became clear that the values of the parameters ‘height’ and ‘width’ were switched. When the model was examined in the Solibri Model Viewer, we could see that the modification happened during the export to the IFC model. As a result of this modification, all the values of depending parameters that SCIA Engineer had calculated were also changed. However, the cross-section was turned thanks to the settings of the local axes and therefore had the same position as in the BIM-model. The conversion of the profiles was marked as successful, because when calculations are made, SCIA Engineer uses the rightful properties, which was concluded after a testcase. For the test, a beam with a clear difference in dimensions was created to make sure that the rotation of the cross-section (0 or 90°) could be determined without relying on the values of the properties. Two control beams were also modelled, one with exactly the same parameters (height and width) as the beam after the transfer and one with the desired parameters (figure 64 and 65). Eventually, the beams had the same orientation because one them was rotated over 90° (figure X and X). The deflection of both control beams was determined and the value of the deflection of the transferred beam was the same as the beam with the desired parameters, which means that the conversion of the profile is satisfying.

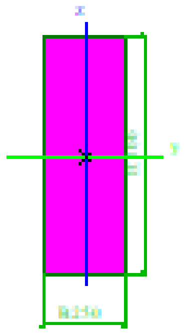


Figure 64: Cross-section desired beam

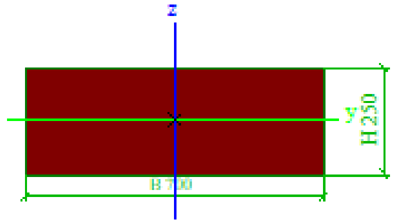


Figure 65: Cross-section rotated beam

The materials are mapped with the material table. The process is exactly the same as the link between Revit and SCIA Engineer, described in the previous paragraph. The only downfall is that in ArchiCAD, it is only possible to define 'Steel – Structural', which means that it is not possible to map different kinds of steel. Normally, the architect will indicate which beams are made from steel, but their properties will not be defined. Basically, this is not a major issue, because most of the time, only steel S235 is used and it is possible to map one material to 'Steel – Structural'. When several kinds of steel are used, it becomes undesirable to create new models when the IFC file is imported. However, SCIA Engineer also provides the possibility to update the existing model. The user can choose which entities and properties are imported and which are not.

Reinforcement bars, boundary conditions, loads, loads cases and combinations could not be modelled in ArchiCAD and therefore these properties must be created in the FEM-software by the engineer.

As said, the software vendors of ArchiCAD and SCIA Engineer both favour openBIM and this can be seen in the quality of their link. Both programs are more than capable to import and export IFC files. The transferred information is handled correctly, even though some properties switched places in case of the concrete beam, the orientation of the beam remained the same and calculations were executed correctly.

8.3.4 AECOsim to SCIA Engineer

The only possibility to import a model from Bentley AECOsim in SCIA Engineer is with IFC2x3. The export from the BIM-software to IFC is no problem. However, the data in this model is not supported by SCIA Engineer, even though IFC is a neutral data format. The following error appears when trying to import the file: 'not supported data: ENDSEC;END-ISO-10303-21'. This means that the header of the file cannot be closed and the process is stopped. There cannot be spoken of interoperability between these two programs.

8.3.5 Tekla to SCIA Engineer

Both Tekla and the Nemetschek group are proponents of openBIM and invested lots of time in making their software suitable for IFC. The efforts can be seen in the conversion process that leaves little room for error as can be seen in appendix 1: table D and E.

The beams in SCIA Engineer have the exact same position as the ones in Tekla Structures. The coordinates of the reference line are modified to the coordinates of the centre of the beam. The rotation of the cross-section is also correctly handled.

In Tekla, there can be chosen to base the primarily profile mapping on the name of the profile or on the dimensions. A standard format of a pre-installed database must be chosen for the steel beams, which makes it impossible to modify the properties. Every time, the mapping happens based on the profile name and SCIA Engineer uses its own properties. This is not the case for the concrete profiles, because the name cannot be recognized by SCIA Engineer, the mapping happens based on the dimensions. The '2nd EEM Analysis' has to be manually activated to get the correct torsional moment of inertia and torsional constant, which was not necessary for the steel beams.
The name of the concrete beams cannot be recognized and will not be transferred. The cross-section is based on parameter mapping. Only when the '2nd EEM Analysis' is activated, the correct values of all the properties will be available. Otherwise, some values will be simplified or set on the default value.

The mapping process of the materials is the same as for the conversion from Revit to SCIA Engineer, which means that the materials are mapped based on their names. The properties implemented in Tekla will be ignored and only those provided by SCIA Engineer will be used.

The IFC file based link is capable of transferring the reinforcement bars created in Tekla Structures. The position and shape of the bars is correct, but the original diameter was not maintained. The bars of 8 mm and 12 mm became respectively 10 mm and 14 mm. In SCIA Engineer, all the bars are defined as longitudinal reinforcement, to get stirrup reinforcement, the property must be manually modified. The last property that has an influence on the reinforcement is the concrete cover, which was not transferred. Instead SCIA Engineer uses a method to calculate the minimum concrete cover, which is set as default value. Results about the reinforcement cannot be generated, an error occurs every time. Again, it is a better option to model the reinforcement directly in the FEM-software instead of the BIM-software.

The boundary conditions, loads and load combinations can be defined in Tekla Structures, but they can only be exported with an analysis model. With the provided license, it was not possible to export this model. However, even though this functionality is not available, there can still be concluded that both software programs are capable of handling IFC-files and good results were obtained.

8.3.6 Vectorworks to SCIA Engineer

As said before, there are several ways to model certain elements in Vectorworks. The concrete and steel beam can both be modelled with a construction or a structural element. For the steel beam, there is even a third possibility: a chosen detailed profile. The results of the conversion of every case can be found in appendix 1: table D and E.

First, a closer look is taken at the geometry. Normally, the global coordinates are always transmitted correctly, but in this case, it goes horribly wrong. Only the coordinates from the detailed profile remained the same. The other elements had problems with the conversion of the axes, which resulted in slightly different results. It was not a problem for this model, but when a big 3D model is made and all the elements are slightly off, big mistakes can happen. All the components would have to be set back correctly, which is a time-consuming job.

The middle of the construction element had in all cases (0,100; 0,100; 0,100)m as coordinates. Even for the simplest case, the z-coordinate changed. When the reference line was in the middle of the element, top or bottom, the coordinates became respectively (0,100; 0,100; -0,020)m, (0,100; 0,100; -0,020)m and (0,100; 0,100; 0,220)m. It was odd that even when the reference line was positioned in the middle of the element, the element repositioned itself and the new middle line used the coordinates of the bottom of the profile. The structural element performed slightly better. As long as the axes were positioned in the centre of the element, the conversion goes perfect. When they do not lay in the centre, the coordinates of the axes in Vectorworks will be used as the centre of the profile, which means that the whole profile will be moved.

The rotation of the cross-section also gives problems. While the rotation of the detailed profile goes perfectly, the other two elements are rotated in the wrong direction.

The following component is the cross-section of the profiles. In case of the structural steel element and the concrete beam, the type is not transferred, but the form of the profile is. Because of this, SCIA Engineer was able to make calculations for some properties. The area, moment of inertia, etc. were available for further calculation. However, there were also some major shortcomings:

- Only the graphical from was transferred, which mend that the initial form was not available and that the geometrical properties (height, width, etc.) were hidden.
- Some properties were not calculated or simplified. This problem could be fixed by enabling the option ‘2nd EEM Analysis’ and re-reading the cross-section.
- The default buckling curves were used, which is safe but incorrect. For the buckling analysis, the correct curves must be used. They can be modified by hand.

With some help of the user, SCIA Engineer can collect all the necessary properties for the analysis. Because the name was not transferred and the geometrical data was hidden, the engineer does not have a clue about which profile is used. All in all, it would be easier to change the cross-section to a profile pre-installed in SCIA Engineer instead of making all these adjustments.

The same story applies to the steel construction elements and the detailed profiles. The only difference is that the type will be transferred. SCIA Engineer will still use the properties derived from Vectorworks instead of mapping the profiles. For the concrete profiles, the cross-section was simple and parameter mapping could be used. The height and width are correctly linked and all the corresponding properties are calculated. To get the correct properties, the option ‘2nd EEM Analysis’ should be manually activated, just as in the other cases.

To make a steel profile, there is a fourth option. The detailed profile can be modified to the wishes of the user. The name of the profile is maintained in Vectorworks, but in SCIA Engineer it is changed to ‘CUSTOM’, which is a good thing. But the custom-made profile is not accessible, which means that lots of information disappears and the engineer must guess which properties are used. It is not even possible to control if all the dimensions of the profile are correct.

If a mistake happened during the implementation of the profile, all the calculated properties in SCIA Engineer will be incorrect and they cannot be corrected in the FEM-software. It is better to communicate about the details of the profile and create a new profile in SCIA Engineer.

Thanks to the mapping table, not a single problem occurred for the conversion of the materials. It was not possible to create reinforcement bars in Vectorworks. Consequently, they could not be transferred to SCIA Engineer.

Boundary conditions, loads and load combinations could not be created in Vectorworks and therefore not be exported, which means that the engineer will have to make a conscious decision for each component of the analysis model.

The biggest issue is that every element is handled differently. A model will be a combination of structural and construction elements, but even the geometrical properties of these elements are converted in different ways.
When somebody else has made the architectural model, which we are assuming in this investigation, not all details will be known and therefore it is difficult to spot mistakes that happened during the conversion. Even when it is your own model, it can be a difficult task. It is safer to interpret the data and make a model from scratch instead of using IFC.

8.4. STAAD.Pro: links and results

Only ISM files can be imported in STAAD.Pro. Some architectural programs, like Revit and ArchiCAD, are capable to directly export their models to ISM, while others need an extra step.

8.4.1 Conversion with ISM (Revit and AECOsim)

The conversions from Revit and AECOsim to STAAD.Pro with ISM are quite similar. The same issues were encountered for both links and will be discussed together in passage C 'results'. The only difference is the followed workflow for the conversion. Both workflows will be explained in the passages below.

a. Workflow from Revit

As said before, a model designed in Revit can be directly exported as an ISM file when the ISM Revit Plugin is installed. The plug-in let the user define some settings to improve the quality of the link.

Before a conversion can take place, the Revit families must be mapped to the ISM families. If this is not done, it will not be possible to map the components, profiles, materials, etc. of the structure in a later stage of the process.

First, as seen in figure 66, all the necessary section families must be inserted in the software to make sure every element can be correctly linked. These families are based on the material group of the element and the type of section. In the first case, the families 'concrete', 'steel' and the used sections were added to the project.

Next, the ISM section properties must be mapped to the Revit section properties. The properties depend on the type of profile.

For steel, only I-profiles are featured, meaning only these profiles must be mapped (figure 67). The concrete profiles are rectangular and are mapped based on their parameters (figure 68).

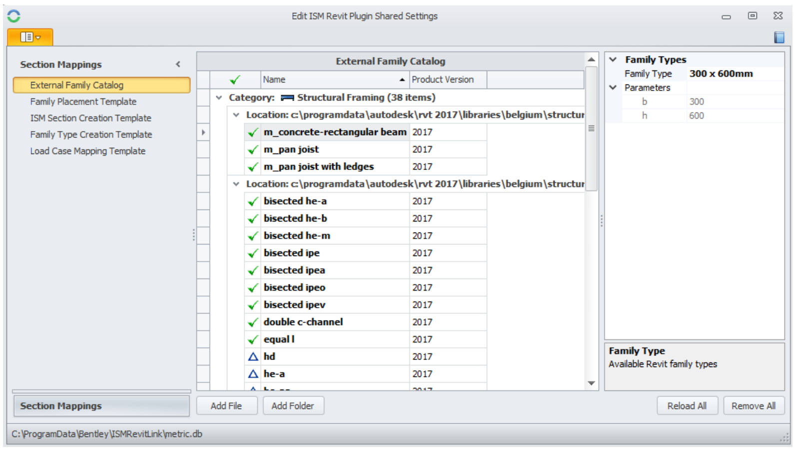


Figure 67: External families Revit

The third property setting are the complementing properties of the previous setting. Now the properties of the elements in the families defined in Revit are mapped to the corresponding ISM property. Once again, a report will be generated which shows the mapped properties. This report can be seen in figure 70 for the steel IPE profile and in figure 71 for the concrete rectangular profile.

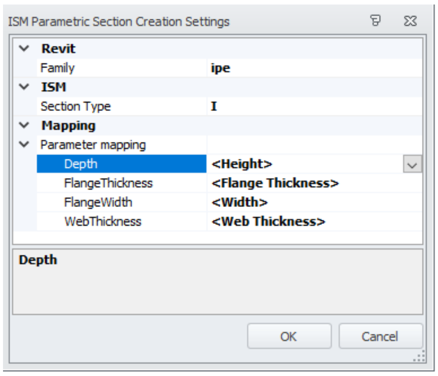


Figure 68: ISM section settings steel

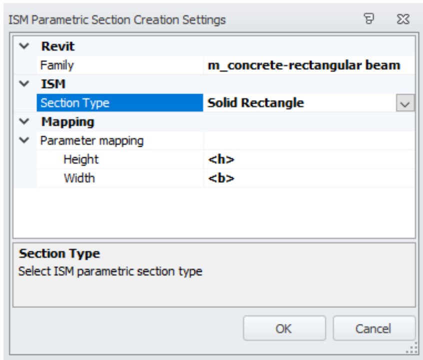


Figure 69: ISM section settings concrete

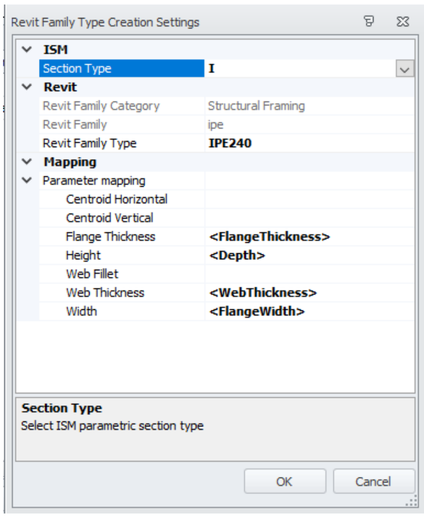


Figure 70: Revit section settings steel

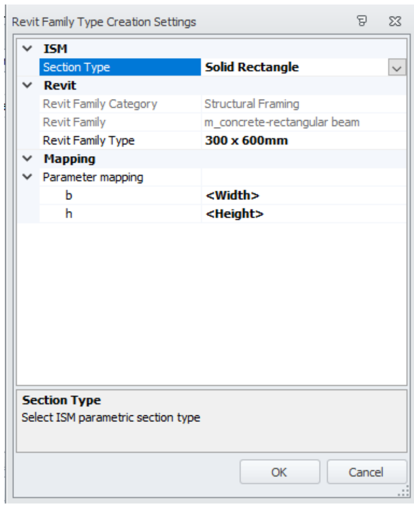


Figure 71: Revit section settings concrete

The loads are the last settings that can be defined. The load cases designed in Revit can be mapped to the corresponding ISM load cases to enable a proper transfer (figure 72). This will be further discussed if the load cases are indeed transferred or not.

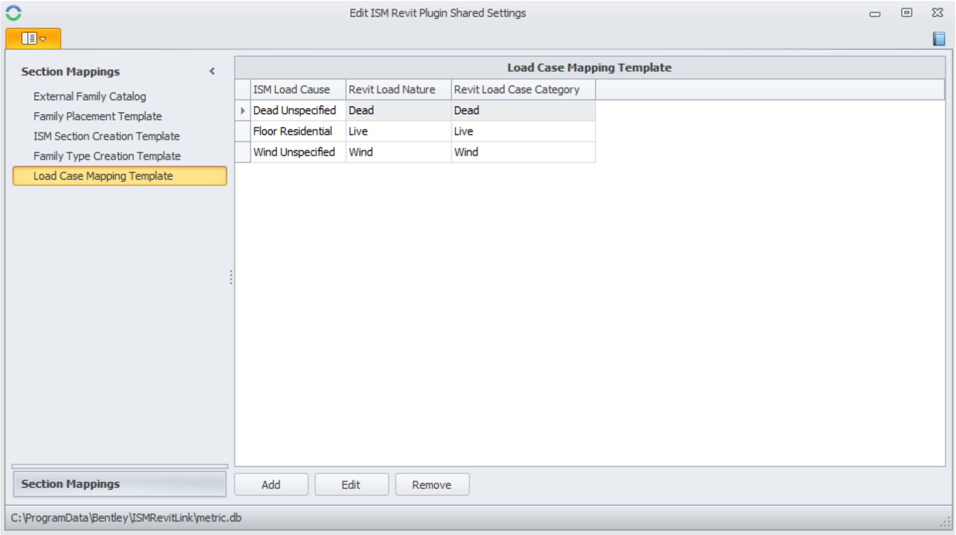


Figure 72: Settings load cases Revit to STAAD.Pro

After the families are mapped, the repository can be created. First, the user has the option to activate the following advanced operation settings:

- The coordinates which correspond with the coordinate system origin in STAAD.Pro can be chosen, as seen in figure 73. For our cases, this is set to (0,0; 0,0; 0,0)m so the global coordinates can be compared in a later stage of the investigation.
- There can be chosen to export only the selected elements instead of the whole model.
- Another interesting feature is to activate the 'Model Cleanup', which means that all the properties of the element and the file, which are not referred to in the export, will be deleted.
- The last option is to whether export the reinforcement or not. The Rebar Detailing Code can be defined and it is possible to export only the desired reinforcement of a particular element.

For this project, the properties that were not used, were not removed to make sure that the comparison could be performed properly. For example, not a single load was implemented in the load case 'snow'. This load case was also not used in any combination, which means that it was not necessary to transfer this load case. By keeping it, we could determine if the load case was indeed transferred of not. Otherwise, it would be a guess, which is not reliable. This will be further discussed in this passage C.

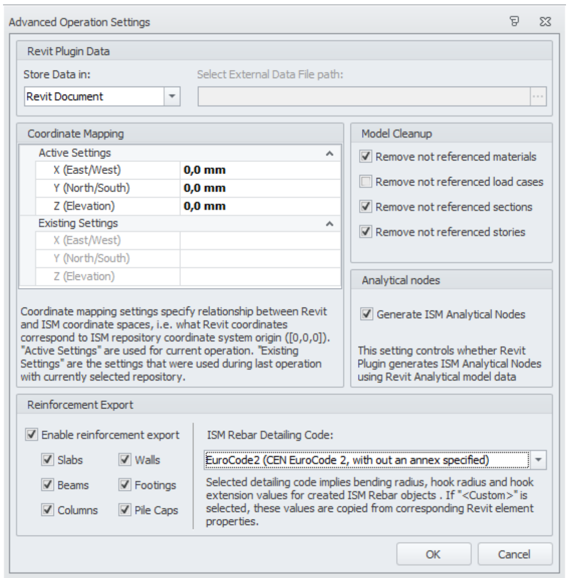


Figure 73: Export options Revit to STAAD.Pro

The second step is to map the load cases, materials and sections, starting with the load cases. If the previously mentioned settings are correctly determined, this will be an easy process. When the button 'match all' is activated, all the load cases should be linked to the corresponding Revit load case due to comparing the names, mapped to the ISM load case and, if necessary, new corresponding ISM load cases will be created (figure 74).

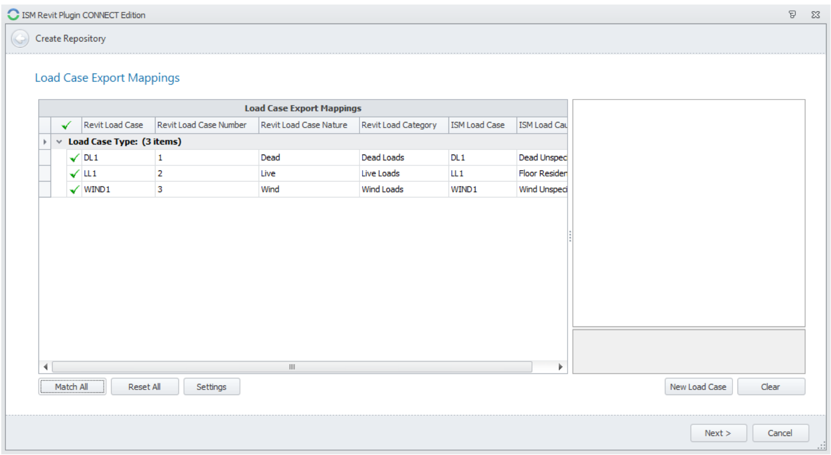


Figure 74: Load Case Export Mappings Revit to STAAD.Pro

The same procedure is followed to map the materials. Again, this is a simple process thanks to the settings that were made in the beginning. The names of the materials and the parameters are compared and linked to ISM materials and a new ISM component is created with these properties.

The last property that is matched before the file is exported is the section. The section in Revit is be compared to the sections available in the ISM Repository and in the Section Tables from the chosen code. Next, a new ISM Parametric Section will be created with the same parameters as the Revit section.

After this step, the process can be finalized and the ISM file will be created. An operation report (figure 75) can be generated. This states that the line loads are not correctly converted, which means the results will probably not be correct. This will be discussed later in the results.

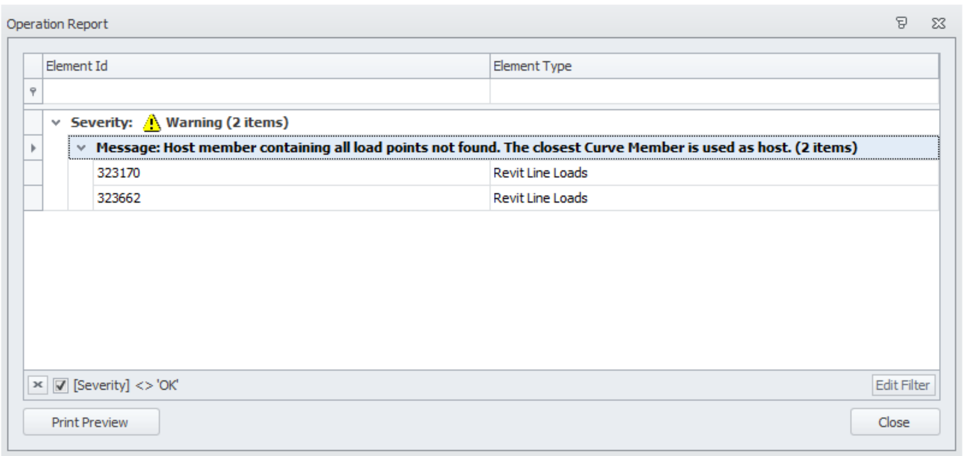


Figure 7539: Operation Report Revit to STAAD.Pro

b. Workflow from AECOsim

Exporting an AECOsim file to an ISM file is a simple process and can be quickly executed because both programs are from the same software vendor. Only the type of the elements needs to be mapped. The possibility to only export a selected element is also available, which is mostly used when a model has to be updated. Default materials can be defined but these do not have an influence on the conversion of the materials (figure 76).

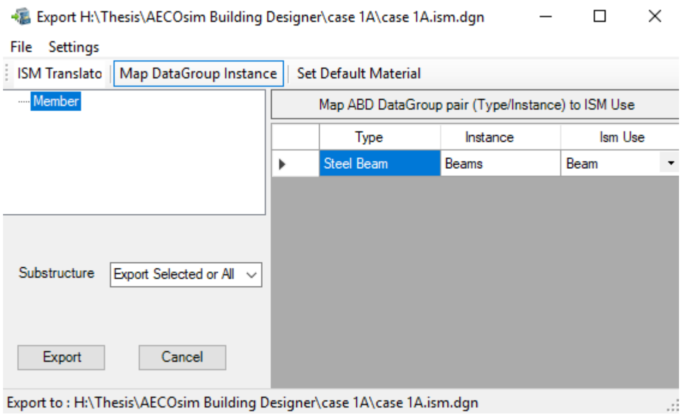


Figure 7640: AECOsim export to ISM

c. Results

As previously mentioned in paragraph 6.8 'Integrated Structural Modelling', it is only possible to export the BIM-file directly to an ISM file in AECOsim and Revit. The results of these exchanges can be found in appendix 1: table F and G for respectively the steel and the concrete beam.
The results of the steel and concrete elements in both the programmes are quite similar and will be discussed in this passage.

All the properties of the geometry of the beams are perfectly transferred. However, it was not possible to model a rotated beam in AECOsim which means this property could not be transferred or checked. The orientation of the y- and z-axis is also switched, this however does not change anything to the position of the beam.

Most of section properties of the steel beam are properly imported in STAAD.Pro. However, there is a difference between the two programs. The section properties in the FEM-model converted from AECOsim are not all transferred. Only the type of the section is transferred from AECOsim to the FEM-software. The other properties are cannot be modified in AECOsim. However, they are available in STAAD.pro, which means that they are defined by STAAD.Pro based on the type of the section instead of being transferred. A similar conversion happens with the Revit file although most of the properties of the section are transferred from the Revit-file thanks to the mapping tables instead of being defined by STAAD.Pro.
Revit and AECOsim both use parameter mapping to link the cross-section of the concrete beam to the corresponding section in STAAD.Pro. The type, height and width are transferred from the BIM-software to the FEM-software. All the other properties are defined by STAAD.Pro based on the measurements of the sections.

Reinforcement was modelled in Revit but neither the steel nor the rebar properties could be found in STAAD.Pro. In AECOsim, the reinforcement could not be implemented in the model. Consequently, the properties could not be exchanged.

The conversion of the material properties is similar to the one of the section properties. Again, the class of the material, is properly transferred.

The name of the material is transferred in the AECOsim-exported-model and all the other properties are defined by STAAD.Pro based on the class of the material.

The properties of the Revit-exported-model are correctly transferred thanks to the mapping tables, except for the density of steel. The default value for steel is assigned to this property instead of the defined value in Revit. For concrete, this property is correctly transferred.

Both BIM-software programs are capable of implementing boundary conditions, loads, load cases and load combinations. Only in the case of the concrete beam modelled in AECOsim, the loads, load cases and load combinations could be transferred to STAAD.Pro. Even this transfer is not ideal, because the loads are only visible in the tables, but not in the views. Calculations cannot be made with the imported model, which is the reason why the conversion of the loads is marked as unsuccessful even though the values of the loads are available in load tables.

In the other cases, none of the features was converted. It was to be expected that the line loads in Revit were not exported correctly due to the given warning during the export of the file. Features to support detailed mapping between Revit and STAAD.Pro were available, which is the reason that these results were not expected. However, normally the engineer will decide which boundary conditions and loads should be applied. It is not a big issue that these properties cannot be transferred.

The import of ISM files, which are directly exported from a BIM-software, are relatively good. The geometry, the sections and the materials are always imported. In every case, the global coordinates are transferred correctly, which is the most important part of the conversion. The conversion of the steel beam had some flaws, because not all the properties were transferred. However, these did not occur for the conversion of the concrete beam. Boundary conditions and loads should not be modelled in the BIM-software but directly in STAAD.Pro.

8.4.2 Conversion with IFC

As said in paragraph 6.10.6 ‘Links based on IFC; Links to STAAD.Pro’, it is not possible to import IFC files directly into STAAD.Pro. To establish a data exchange, the IFC files must be converted to an ISM file using the Structural Synchronizer. Then, they can be imported in STAAD.Pro. The results of all the links with the different IFC-exported models will be discussed in this passage and the results are also shown in appendix 1: table F and G.
The models made in ArchiCAD, Tekla Structures and Vectorworks were exported as IFC2x3 file. In Vectorworks, there were three different models designed as earlier explained. They were all exported for the steel beam, for the concrete beam only the structural element and the construction element were available.

First, the results of the steel elements will be discussed. Already for the geometry, a difference between the links of the different programs can be spotted because not all the properties of the geometry are correctly transferred from all the different BIM-software. Only the geometry of the ArchiCAD model and the Tekla model is correctly transferred. This conclusion could be made because the global position of the profile, rotation of the cross-section and coordinates of the elements remain the same, even though the y- and z-axis are switched.
The Vectorworks models were capable of exporting the length and the rotation of the cross section correctly. Only when a structural element was used to model the beam, the global coordinates were transferred correctly. For construction element and the detailed profile, the reference line was not imported correctly, which lays at the base of the explanation of the modification of the z-coordinates. The reference line was assigned to the centre of the section. However, during the export, it has been placed at the bottom of the profile which results to the z-axis coordinate -0,02m (centre coordinate was 0,10m and half of the profile is 0,12m, which leads to -0,02m at the bottom of the profile). In STAAD.Pro the reference line is positioned in the centre of the profile. Consequently, the global position of the element and the global coordinates were not correctly transferred.

The types of the sections are all correctly transferred except for the one of the structural element in Vectorworks. All the other properties are not imported in STAAD.Pro, but they are defined by the program based on the type of the section. Standard sections are used for these elements meaning these could be easily mapped in the Structural Synchronizer

Due to the mapping of the material when transferring the IFC-file to the ISM-file, the class of the material, and with the ArchiCAD also the name of the material, are correctly transferred. Again, the structural element in Vectorworks is the only exception. In this case, the properties of the material are not correctly transferred and the default values are given by STAAD.Pro.

Only in Tekla Structures it was possible to define boundary conditions and load, load cases and load combinations. However, none of these were imported in the STAAD.Pro model.

The results of the concrete elements are a slightly disappointing. The length and the global coordinates are correctly transferred to the STAAD.Pro models. However, the y- and z-axis are switched again but this does not change the global position of the model. Only in the Tekla model, it was possible to rotate the axes and was this property correctly transferred.

While the geometry was transferred quite good, the transfer of the profiles and materials were a downfall.

The type of the profile, the height and the width are only transferred from the Tekla model. The other properties are however not imported but calculated by STAAD.Pro based on this data. ArchiCAD and Vectorworks did not export any of the properties of the section. Only in Tekla structures, it was possible to model reinforcement bars, but these are not transferred to STAAD.Pro. However, this only becomes a problem when the data is exchanged several times.

The class of the elements, concrete, could be mapped when conversing the IFC file to an ISM file. An exchange of the class for the models made in Tekla Structures and Vectorworks was properly done, but not for the model made in ArchiCAD.

Again, the properties are not imported from the BIM-models and the default values are defined by STAAD.Pro. These are either the standard concrete values defined in STAAD.Pro or default values.
Just as for the steel beams, it was again only possible to define boundary conditions and the loads in Tekla Structures. However, these could not be exported to STAAD.Pro.

Using an IFC data format to import in STAAD.Pro, after conversing it to ISM, is clearly not ideal. It is a cumbersome method and a lot of data gets lost during the process. Even the geometry, which is in almost every other case correct, is not properly transferred. When data has to be exchanged with STAAD.Pro, it is better not to make use of IFC.

8.5. RFEM: links and results

8.5.1 Revit to RFEM (direct link and IFC)

The direct link between Revit and RFEM can only be used when both programs are installed on the same computer, which is often not the case. The other option to transfer the models is by using IFC, which will be discussed together with the direct link in this passage. The results of the transitions can be found in appendix 1: table H and I for respectively the steel and concrete beam.

Whether the direct link or IFC link was used, every time the geometrical properties of the steel and concrete beams were correctly transferred. Not a single difference could be found in the properties in RFEM compared to those in Revit.

None of the properties of the steel profile were transferred when using the IFC-file. However, the direct link is capable to export the type of the profile. Then, the other properties of the section will be calculated by RFEM based on the type of the profile.
The properties of the concrete beam were exchanged thanks to parameter mapping. The profile type, name, height and width were imported in the RFEM-model. The other properties are calculated by RFEM based on these properties.
The reinforcement designed in Revit could not be transferred. Neither the material properties of the steel, nor the profile properties of the rebars are imported.

In case of the steel beam, the class of the material was implemented correctly in RFEM for both links, although some differences between the direct link and IFC can be noticed for the other material properties.
The material has the same name as in the BIM-model when the beams are transferred with the direct link, but the other depending properties are not correctly transmitted and differ from the properties in Revit.

For the IFC link, the values of the material properties are similar to the ones in Revit because this time but are not transferred. Instead, instead of mapping the names of the material, the mapping process happened based on the class of the material This means

that it is not possible to transfer a specific material. For example, steel S235 and S355 will be seen as the same material because the class is the same.
The results of the IFC link in case of the steel beam, were not obtained for the concrete beam. Both links were capable of transferring the name of the material correctly. However, not a single property could be linked to this name and the default values were used.

The last properties that were investigated, are the boundary conditions, loads, load cases and load combinations.
The direct link could convert all these features correctly, but the IFC link could only transfer the boundary conditions. However, even this transfer did not come up to expectations. In RFEM, both nodes are hinged instead of one node hinged and one roller as modelled in Revit. This can give the wrong impression to the structural engineer. He might think that the boundary conditions are defined in this way since they have a value. However, these are incorrect.

It can be concluded that the direct link between Revit and RFEM is a solid conversion. All the properties except for the material are properly converted. The class of the material is converted which means the structural engineer knows which material is used and can define the properties on his own to obtain the most economical and efficient result.
The model obtained from the conversion from the IFC data format is far from ideal. However, the geometry and the class of the material are converted, which are the major priorities for the structural engineer in order to make calculations due to him normally defining the cross sections of the elements.

8.5.2 AECOsim to RFEM (ISM)

As said in paragraph 6.10.6 'Links based on IFC, Links to RFEM', it is possible to import an ISM-file into RFEM. Due to the common export file in AECOsim, ISM will be used to import the models from AECO. The results of the conversion of the steel beam are discussed in appendix 1 table H, and these from the concrete beam in table I.

The conversed properties of the geometry are the same for both the steel and the concrete beam. All the properties are correctly imported from the AECOsim-model.

All the properties of the steel profile are defined by RFEM based on the profile type, which is converted from the BIM-model. This process is made possible thanks to the standard tables.
For the concrete, the type, height and width are transferred. RFEM calculates the other properties based on the profile type. Reinforcement could not be designed in AECOsim, which means this could not be checked if it would be converted or not.

The material name is converted in both cases. However, only for the steel beam the class of the material is transferred. Based on this class, RFEM creates the other properties for the material. The used values are default values and apply for steel S235. When another material is implemented in Revit, it will not be converted to the FEM-software. In first instance, this is not a problem because all the materials have to be defined by the engineer. However, when the model is exchanged back and forth, issues can arise.
No material properties are defined for the concrete beam. These can however be defined by searching in the database of RFEM for the name of the material which is converted. This workflow is safe because the engineer must make a conscious choose for each material, however, it asks more work than parameter mapping.

The boundary conditions and the properties of the loads are not converted to neither one of the FEM-models. This is not a major problem due to the structural engineer defining these properties as discussed earlier.

The conversion from AECOsim to RFEM is a proper way to transfer the BIM-model to the FEM-model. Most of the properties are transferred. If they are not transferred, for example the properties of the material, they can be defined by searching the database of RFEM.

8.5.3 Conversion with IFC

Before importing the file, detail settings can be chosen, for example the orientation of the axes can be set and the option ‘plausibility check’ can be activated. After importing the file, the correct code can be selected for the calculations and checks.

No direct links or specific conversion files were available for ArchiCAD and Vectorworks. A direct link was available for Tekla Structures but due to only receiving a student license, this link could not be used. The results of the conversions from the three programmes will be discussed in the upcoming paragraph. In appendix 1: table H and table I the results are shown of respectively the steel beam and the concrete beam.

The results the transfer of the geometry depend on the used software and the kind of beam. It was not possible to form a general conclusion. For the steel beams, ArchiCAD and Tekla export all the possible properties correctly.
The geometrical properties of the concrete beam are also correctly transferred for the Tekla-exported-model. However, this is not the case for the ArchiCAD model. Here only the length is correct. The position of the reference line is not correctly exported according to the Solibri Model Viewer and thus are the global coordinates of the profile not correct. In Vectorworks, the results vary depending on the used material and type of beam.
None of the geometrical properties of the steel beam are correctly transferred in any of the cases (structural element, construction element and detailed profile). The opposite results are obtained from the concrete beams. Here all the geometrical properties are correctly transferred from the structural and construction element.

For the conversion of the section properties, there is again a noticeable difference of the capabilities of the different links between the steel and concrete beams.
None of the steel section properties are converted in any of the cases. However, better results are obtained for the conversion of the concrete beams. The type of the section, the height and the width are properly transferred for the concrete beams for every IFC link with a BIM-programs. Again, the other properties are again by RFEM based on these parameters. Only one conversion is not completely perfect. The values for the height and the width of the profile are switched in the model converted from ArchiCAD. This can lead to major problems during the construction but since this is still in the designing phase, the structural engineer will probably change the value of the parameters, so this is not a major problem. However, updating the model should be handle with great care to avoid mistakes.

Only Tekla Structures has the capability to model reinforcement bars and export them to IFC. However, when importing the IFC-file from Tekla Structures in RFEM, a warning is given that the reinforcement is not imported.

The conversed material properties are similar between the steel and concrete beam, however not for every BIM-software. The model conversed from ArchiCAD could transfer the name of the material. Nevertheless, the other material properties are not imported from the BIM-software and are not defined by RFEM. In the models, created by importing the Vectorworks-models, the name of the material and the class, these are the only properties that could be defined in Vectorworks, are both imported correctly for the construction element.

Lastly, the boundary conditions and properties of the loads, these could only be defined in Tekla Structures, are not imported in RFEM. This is not a major problem as discussed earlier

Overall, it depends on the BIM-software if the conversion is usable or not. For the steel elements, only the geometry is properly exported from ArchiCAD and Tekla, which can be enough for the engineer. However, the conversion from Vectorworks is not satisfying due to none of the properties exporting. The properties of the sections are better converted for the concrete beams. The only properties that are not transferred are the material properties. However, the names of the materials are transferred for the models made in ArchiCAD and Tekla Structures and can be used to search for the material in the database of RFEM.

8.6. ETABS: links and results

ETABS is a software developed to design and calculate concrete elements. Therefore, it is not expected that the results for the steel beam will be successful.

8.6.1 Revit to ETABS (CSiXRevit)

A direct link between Revit and ETABS is available thanks to a plug-in, which can be downloaded from the CSi America site and is called CSiXRevit. To make use of the plug-in an additional license is necessary.

The creation of the link begins with activating or deactivating the export of the following components: the grids, frame, point loads, line loads and load combos. Depending on what is modelled in the project, other settings can also become available. For example, 'export no walls' is an option that could not be modified in our case because there were no walls modelled (figure 77). However, when walls are implemented in a model, this option will become available.

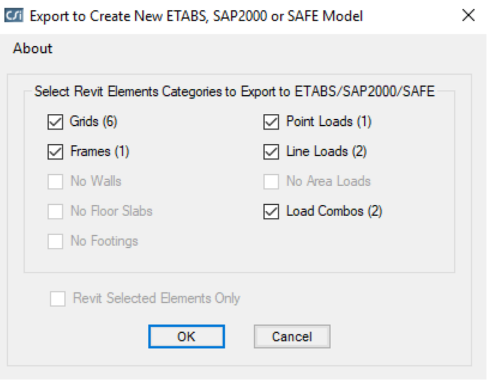


Figure77: Export to Create New ETABS, SAP2000 or SAFE Model

After the export is completed, a Revit Structure '*.exr' file will be saved on the chosen location. Later, this can be opened in ETABS and during the import the desired mapping file can be picked.

However, there is a downside to this direct link. It is not possible to import the '*.exr' file in ETABS when the structure is too small. Consequently, this link could not be used for case 1A and 1B.

8.6.2 Conversion with IFC

ETABS is capable of importing IFC2x3 and IFC4 files. No differences are discovered between the two data formats when analysing the results. The exchange from Revit is also performed with an IFC-file due to the model being too small to convert. All the conversions are executed using an IFC-file, the results, shown in appendix 1: table J for the steel model and table K for the concrete model, are discussed in the following passages.

The results of the conversion of the steel model are not satisfying. The only property that are transferred in every case, is the length of the beam. Even more, this is also the only property that can be imported from the construction model in Vectorworks, which makes this conversion a total disaster. For the construction element in Vectorworks, the global coordinate of the z-axis is wrongly imported. It has a value of -0,02m instead of 0,10m. This fault also appeared in the other FEM-programs where the construction model is imported.

In contrast to the construction element in Vectorworks, the conversion of the structural element and the detailed profile, performed slightly better. For these two profiles, the global coordinates could be transferred properly.

Even though the conversion of the models made in Vectorworks with IFC was a failure, in most cases the geometry is properly transferred. The desired results were obtained for the conversions of the model imported from ArchiCAD, AECOsim and Tekla Structures. For the model in Revit, all the properties are also accurately converted except for the rotation of the beam. This property could not be checked in ETABS because it was not implemented in the software.

The type of the profile could only be imported when the IFC link with Revit or Tekla Structures was used. The other properties concerning the section are defined by the pre-installed database in ETABS based on the name of the profile. In none of the other conversions the profile type is imported. The default value is assigned to these elements, which is HEM1000. This can lead to mistakes due to the section indeed having a value but not an incorrect one. However, as said before, the engineer will probably change the section to become the most economical and efficient result, but this process is not time efficient.

In the model converted from ArchiCAD and AECOsim, the name and the class of the materials are both converted correctly. The other properties are defined by ETABS based on the class of the material. Due to not knowing the parameters of the material in the two architectural models, the ETABS had to create the values for the parameters of the materials based on the class of the materials.
The names of the materials in the other models are all correctly transferred except for the one from the detailed profile from Vectorworks.
The class of the material on the other hand was not converted in any of the models, except for the models derived from ArchiCAD and AECOsim as previously mentioned. The default value ‘other’ was assigned to the models made in Revit, Tekla Structures and Vectorworks. Consequently, the elements had the correct name, but not the corresponding material properties.

Boundary conditions, loads, load cases and load combinations are defined in AECOsim, Revit and Tekla. However, none of these properties and their values are exported to the FEM-model in ETABS. In the model which is obtained by exporting the Revit model, the nodes do have a property, but they are both hinged instead of one hinged and one fixed. Which is even worse than no results due to the structural engineer possibly interpreting these wrong. When the FEM-model is created, this will not be a big issue, because it is normal that all the boundary conditions are checked. However, when the model is exchanged back and forth, the engineer must check if the boundary conditions are unwillingly modified or not.

Better results are obtained with the conversions of the concrete models, at least for the section properties. For Vectorworks two different model types were imported into ETABS, a structural model and a construction model. From the structural model, only the geometrical properties could be reused in the FEM-software. The ETABS models modelled with construction elements can also import the correct profile type, height and width, and the name of the material. In all other cases, profile type, height and width of the profile was exchanged properly, except for the IFC link with the Revit model. In this case it was not possible to transfer the profile type. However, the dimensions were exchanged. ETBAS created the other section properties based on the transferred dimension.

The length and global coordinates were in all cases of the concrete beam correctly imported. The rotation of the axes cannot be checked due to this not being features in ETABS.

In the model imported from AECOsim and the Vectorworks construction file, all the geometrical properties are correct, so the length, the position of the axes, the position of the analytical line and the global coordinates.
In the model from ArchiCAD, the position of the reference line is not properly converted. This can be noticed by the z-coordinate. This value is set on 0,35m while it should be 0,5m. The reference line was modelled on the top of the profile but is moved to the centre of the profile during the transformation. However, the global position of the model is still the same, so the global coordinates are correct.

The type, height and width of the section are converted in every case. However, in the transferred ArchiCAD model and Revit model, the height and the width are switched. The reason for these changes is unknown to us. These two models are the only ones where the name of the profile is correctly imported. All the other properties are defined by ETABS using the type, height and width. These properties are only correct for the construction model of Vectorworks and not for the structural model.

The conversions of the materials were also not satisfying. Only the name of the material is converted from the ArchiCAD, Revit, Tekla and Vectorworks construction model. However, the other properties are not converted. As seen with the steel beams, again the class of the material is seen as ‘other’ which leads to completely different results. In the AECOsim transferred model, even the name is not converted so the engineer will not know which material is used for this beam. It could however be inferred from the type of profile used.
In Revit and Tekla reinforcement was designed. This did partly convert to the ETABS-models. Only the name of material used for the reinforcement is converted but none of the other properties. The material is again seen as ‘other’ which means the values are not similar to these in Revit or Tekla.
Lastly, the boundary conditions and the properties of the loads are in none of the cases exported. The boundary conditions in the model imported from AECOsim and Revit are

all defined as hinged instead of one hinged and one fixed. This was also the case for the steel beam as earlier discussed.

None of the models in ETABS are perfect for all the properties. Overall it can be concluded that the concrete beams are better transferred than the steel beams due to the type of the profile, the height and the width correctly converted. None of the materials are imported from the BIM-files which means if the material has adapted properties (speciale eigenschappen) the structural engineer cannot know this unless the architect informs him about this. Again, the geometrical properties are sufficiently transferred which is the most important.

8.7. FEM-Design: links and results

8.7.1 Revit to FEM-Design (StruXML)

To set up a bidirectional link between Revit and FEM-Design, a specialized add-in for StruXML from StruSoft must be installed. The plug-in provides some tools to check the analytical model, the materials and the nodes of the model. After the model is checked, it can be exported to an '*.stuxml' file.

There is no need for both programs to be installed on the same computer. The result for the steel beam can be found in appendix 1: table L for the steel beam and table M for the concrete beam.

The results for the steel and concrete beam are quite similar. In both models, the geometrical properties are correctly transferred from the Revit model. Considering the properties of the profile, only the type of the profile is transferred, which could be mapped in Revit during the exporting process to the '*.struxml' file. The other section properties are defined by FEM-Design based on the mapped type of the profile.
None of the properties of the reinforcement are exported from Revit to FEM-Design using the StruXML add-in. However, the materials of the profiles are correctly transferred. The class and type of material could be mapped, the other properties are further defined using the library in FEM-Design based on the name of the material. Due to not being able to transfer the reinforcement, the properties of the used steel could not be mapped.

The last possibly transferred properties are the boundary conditions, loads, load cases and load combinations, the results of these conversions are the same for both the steel and concrete beam. Not all of these are converted from the BIM-model. The type of the boundary conditions and their properties are properly imported. The concentrated forces, distributed forces and load cases are also transferred from the Revit model. Only the load combinations, the corresponding safety factors and the self-weights of the construction are not imported in the FEM-Design model. This link is one of the few that can transfer the boundary conditions and loads correctly. There is only one downfall to this feature. When the boundary conditions or loads are modified in the architectural model without the notice of the engineer, these incorrect properties can be imported in the FEM-software. Therefore, the engineer should always check these properties after the exchange of the model.

Overall, the conversion from Revit to FEM-Designer, using a ‘*.struxml’ file, is a decent method to export a BIM-model to a FEM-model. The reinforcement not being exported is the only major problem because, as previously mentioned, the structural engineer will most likely design this, so it will probably not be needed to export this. The properties of the profile and the material are likewise not imported but defined based on the type of it. This will only be a problem if the designer of the BIM-model used different properties than the standards defined in the libraries, although this is not likely to occur.

8.7.2 Conversion with IFC

The results derived from the conversions of the IFC-files from ArchiCAD, AECOsim, Tekla and the two of the three made in Vectorworks, for the steel beam and concrete beam respectively, are shown in table L for steel and table M for concrete from appendix 1. The conversions are relatively similar but will be discussed separately in the following paragraph.

First of all, it was not possible to import the structural element from Vectorworks into FEM-Design using an IFC data format. This was the case for the steel beam and the concrete beam. Thus, only the construction element and the detailed profile will be discussed for the steel beam and only the construction element for the concrete beam.

For the steel beams, all the geometrical properties are correctly transferred, except for the global coordinate of the z-axis in the Vecorworks models and the position of the analytical line in the model imported from ArchiCAD. Here the analytical line was defined on top of the profile. However, FEM-Design models it in the centre of the profile but the global position of the beams stays the same. The other properties not correctly transferred, are the z-coordinates for the models from both the elements in Vectorworks. These are again defined as -0,02 instead of 0,1. This problem has occurred in previously mentioned conversions from these models to STAAD.Pro and RFEM, see paragraph ‘STAAD.Pro:

links and results' and 'RFEM: links and results'. This mistake can be explained by the position of the analytical line during the conversion. If this is placed at the bottom of the profile, the z-coordinate is indeed -0,02. However, this is seen as the centre of the profile in FEM-Design leading to a wrongly positioned profile.

The profile of the steel beams is in most cases correctly transferred but not by transferring the type of the section and the FEM-software defining the other properties based on that. The height, width, web thickness and flange thickness are converted from the BIM-software to the FEM-software and the other properties are defined and probably calculated based on these data. These results are not for the models converted from Vectorworks, here none of the properties of the profile are correctly transferred.

The material of the model could be mapped when importing the IFC-file into FEM-Design. Therefore, all the materials and their properties are correct. Only the name of the material can be different due to FEM-Design using its own defined material names. However, when mapping the materials, the original name is shown from the IFC-file. The material used in the AECOsim model could not be mapped due to FEM-Design being developed for European codes and the AECOsim model is designed with American codes. However, this could probably be mapped when the correct mapping file is in the structural engineer's disposal.

The last properties of the steel beam that are discussed are the boundary conditions and the properties of the loads. These are defined in the AECOsim and Tekla Structures model but are in neither one of the cases converted.

The results of the conversions of the concrete beams are similar to these of the steel beams. Now all the geometrical properties are correctly transferred, only the position of the analytical line is again placed in the centre of the profile and not on top of it as it is modelled in ArchiCAD. The global position of the profile is still correct which means the conversion satisfies.

As previously mentioned, the type of the profile of the steel beam was not exported but the dimensions were. This only occurred for the concrete beam in the case of the AECOsim transferred model. Here the height and the width of the element are imported

but the type of the profile and the name of the profile not. The opposite occurred in the models imported from ArchiCAD, Tekla Structures and the construction element of Vectorworks. The type of the profile is here imported. All the other properties are in every model defined by FEM-Designer based on either the type of the profile or on the dimensions.
In Tekla it was possible to design the reinforcement for the beam. However, the profile properties and the material properties are not converted to the FEM-Designer model. Again, this is not a major problem due to the structural engineer calculating and designing this.
The materials of the beams could be mapped as previously explained. Therefore, the results are sufficient and all of the materials, if available in the Eurocode, thus in FEM-Design, are correctly transferred. The concrete defined in the AECOsim model is not available in the European codes thus this is not correctly converted. This problem could be solved if the corresponding code is available or a different material, obtainable from the Eurocode, is used.

Lastly, the properties of the boundary conditions and loads are not converted from the AECOsim and Tekla Structural models. This is similar to the steel beams.

It can be concluded that these conversions are sufficient. Except for the models from Vectorworks for the steel beam, all the profiles are transferred. Due to the option of mapping the materials, these are all correctly in the FEM-Design model if the material is available to map. The geometrical properties are, except for the Z-coordinate of the steel Vectorworks models, properly converted. Only the boundary conditions, load properties and the reinforcement are not exported. However, overall it can be said that the use of an IFC-file to import a model in FEM-Design, is a decent way to transfer it and the structural engineer can most certainly use these models efficiently.

9 Conclusion

In the AEC industry, a Building Information Model or Building Information Modelling is gaining acknowledgement. The possibility to attach information to a 3D model is an improvement compared to the old CAD software, which has not been unnoticed.
Nowadays, more and more architectural, structural, etc. models are designed in BIM as this became the standard in a timespan of only a few years.
Many different software programs are available on the market and due to these being widely used, it is important that the interoperability between the programs is sufficient. This can only be accomplished with ongoing research.

In Europe, every construction needs to be calculated and checked according to the Eurocodes. This process is executed by the structural engineer with the help of FEM-software. FEM, the finite element method performs the desired calculations and eventually, the most efficient structure will be obtained.

In the days when no interoperability between BIM-models and FEM-models was available, the structural engineer started his designs from scratch and lost valuable time doing this. Now, having the possibility to use a model that is transferred from the already made BIM-model, Time can be saved and used more efficiently during the calculations, so the most efficient model can be designed. However, the properties transferred from BIM to the FEM-model are variable from software to software. In this research, quality of the different links between BIM and FEM-software was investigated. Different methods of conversions were used; a direct link, IFC data format, intermediate formats, and this for a steel and a reinforced concrete model.

Before modelling a structure and testing the conversions, some theoretical research was done. Here it could be concluded that IFC data format is a widely used conversion method. IFC is an open-source neutral data format that enables the conversion between software programs even when they are developed by different companies, and lays at the base of openBIM. Many companies support openBIM, helped to develop IFC and put it in use. IFC has not reached its limit and BuildingSMART continues to develop this data format. Apart from this conversion method, a couple of direct links were also available, for example from Revit to RSA. It was also possible to use an intermediate file.

Our case study brought to light that the property formats, which enables direct links, are performing better than the open-source format IFC. Especially when there is a direct link and IFC link available between two programs, the difference in the quality of the conversion can be noticed. The quality mostly depends on the willingness of the software developer to support this format.

Autodesk does not fully support IFC. Even though their BIM-software Revit can export to IFC and this link is quite good in general, most exchanges happen with direct links thanks to specialized plug-ins. In all cases, when a direct link is available, it performs better than IFC thanks extra features, such as mapping tables. The FEM-software developed by Autodesk, Robot Structural Analysis, was only capable of importing the outdated IFC2x2 version. A trustworthy link could be established when a direct link to RSA was used, which was only available for Revit. An IFC link to RSA is possible but is mainly asking for trouble. It is better to make the model from scratch or use a different FEM-software program.

In contrast to Autodesk, other software developers are fully supporting IFC. For ArchiCAD, no direct links for structural purposes were even available. The results of the IFC links depend on the used FEM-software. The link with SCIA Engineer, which also favours IFC, is reliable while there is still room for improvement for the link to RFEM and STAAD.Pro. Only when both parties are willing to invest in the development of IFC, a successful link can be established.

Bentley’s AECOsim was not the best student in the class. The exported IFC files could not be imported in SCIA Engineer. When using the ISM file, some properties are exported, however, this does not perform as good as the property formats used in Revit.
There must be kept in mind that AECOsim is an American software that does not support the Eurocode, which means that our standard steel profiles could not be modelled. Transferring the American profiles is difficult because the mapping tables cannot be used.

Tekla Structures uses best of both worlds. The IFC link is well developed but many direct links are also available. The IFC link proved to be satisfying for the geometry and section properties. In some cases, the material could even be mapped correctly, which was the case for the link from Tekla Structures to SCIA Engineer. Other times, the material could not be mapped and must be manually defined by the user. The only link that was unsatisfying was the one to RSA due to RSA not being capable of importing IFC2x3. The concrete beam could be imported with data losses, but a normal project exists of several components and therefore is recommended to build the model from scratch or make use of another FEM-software program. The direct links for Tekla Structures could unfortunately not be investigated.

The last BIM-software on our list is Vectorworks Architect. As the name says, this modelling package is especially designed for architects. This was noticeable during our research. The different kinds of elements that could be modelled in Vectorworks were all handled differently. A model will exist of a combination of these elements and therefore chaos will occur. Some global coordinates will be transferred correctly, while others will not. All in all, Vectorworks is a good architectural program but the interoperability to FEM-software is not satisfying.

We did not have all the licenses to investigate all the possible conversion methods, mostly the links with Tekla Structures to FEM-software were not investigated using direct links. It would be possible to investigate the causes of the wrongly converted properties. Due to not having enough time or the sufficient knowledge of the programs, a thoroughly research for these causes could not be executed. The previously two subjects could be investigated in the future.

Overall, the conversions from BIM to FEM could be used in the construction world, however there is still a lot of room for improvement of the interoperability from BIM to FEM. As a user of the software, it is important to know which properties are correctly imported from the BIM-model and which are created by the FEM-software in order to be able to create a FEM-model efficiently with the help of the BIM-model.

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APPENDICES

Appendix 1. Results of the conversions

Table A: Legend

Legend	
V	The properties are correctly transferred from BIM to FEM.
A	The properties are not transferred, but defined by the FEM-software.
X	The properties are not transferred/ have an incorrect value.
D	The default value of the FEM-software is assigned to this property
C	The property cannot be defined in the BIM-software. The FEM-software creates the correct value based on other properties.
O	The property can be defined in the BIM-software, but not in the FEM-software.
	The property cannot be found in both software programs.

Table B: Results of the conversion to RSA: properties steel

Robot Structural Analysis: Steel							
BIM-program	**Revit**	**ArchiCAD**	**AECOSIM**	**Tekla Structures**	**Vworks structural element**	**Vworks construction element**	**Vworks detailed profile**
Transfer	**Direct link**	**IFC2x3**	**IFC2x3**	**IFC 2x3**	**IFC 2x3**	**IFC 2x3**	**IFC 2x3**
Section properties							
Profile name	C	X	X		X	X	X
Profile type	V	X / D	X		X	X	X
Height	A	X / D	D		X	X	X
Width	A	X / D	D		X	X	X
Web thickness	A	X / D	D		X	X	X
Flange thickness	A	X / D	D		X	X	X
Web fillet/ Radius	A		D		X	X	X
Centroid horizontal	A	D	C		D	D	D
Centroid vertical	A	D	C		D	D	D
Section area	A	D	X		D	D	D
Moment of inertia strong axis	A	D	D		D	D	D
Moment of inertia weak axis	A	D	D		D	D	D
Elastic modulus strong axis	A	D	D		D	D	D
Elastic modulus weak axis	A	D	D		D	D	D
Plastic modulus strong axis	A	D	D		D	D	D
Plastic modulus weak axis	A	D	D		D	D	D
Torsional moment of inertia	A	D	D		D	D	D
Torsional modulus	A	D	D				
Warping constant	A	D	D				
Shear area strong axis	A	D	D		D	D	D
Shear area weak axis	A	D	D		D	D	D
Radius of gyration	A	D	D				
Geometry							
Length	V	V	V		V	V	V
Rotation of the cross section	V	V			X	X	X
Global coordinats	V	V	X		V	X	V
Material properties							
Name material	V	X / D	X / D		X	X	X
Class (steel/ concrete/ ...)	V	X / D	X / D		X	X	X
Behaviour (elastic/ isotropic)	O						
Secant modulus of elasticity	A	D	D		D	D	D
Poisson's ratio	A	D	D		D	D	D
Shear modulus	A	D	D		D	D	D
Density	A	D	D		D	D	D
Yield strength	O						
Tensile strength	O						
Thermal dilatation coefficient	A	D	D		D	D	D
Boundary conditions							
Boundary conditions type	V		X				
Supports: state	V		X				
Degrees of freedom	V		X				
Loads							
Self-weigth	V		X				
Concentrated force	V		X				
Distributed force	V		X				
Load cases	V		X				
Load combinations	V		X				
Safety factor	V		X				

Table C: Results of the conversion to RSA: properties concrete

Robot Structural Analysis: Concrete					
BIM-program	**Revit**	**ArchiCAD**	**AECOSIM**	**Tekla Structures**	**Vectorworks structural element**
Transfer	**Direct link**	**IFC 2x3**	**IFC 2x3**	**IFC 2x3**	**IFC 2x3**
Section properties					
Profile name	C	X	X	X	X
Profile type	V	V	V	V	V
Height	A	V	V	V	V
Width	A	V	V	V	V
Centroid horizontal	A	C	C	A	C
Centroid vertical	A	C	C	A	C
Section area	A	C	C	A	C
Reinforcement number	X			X	
Reinforcement position	X			X	
Reinforcement shape	X			X	
Reinforcement diameter	X			X	
Hook at the start/ end	X			X	
Bending radius	X			X	
Concrete cover	X			X	
Moment of inertia strong axis	A	C	C	A	C
Moment of inertia weak axis	A	C	C	A	C
Elastic modulus strong axis	A	C	C	A	C
Elastic modulus weak axis	A	C	C	A	C
Torsional moment of inertia	A	C	C	A	C
Torsional modulus				O	
Warping constant				O	
Shear area strong axis				O	
Shear area weak axis				O	
Radius of gyration				O	
Geometry					
Length	V	V	V	V	V
Rotation of the axes (local)	V	V		X	V
Global coordinates	V	V	V	V	V
Material properties concrete					
Name material	V	X / D	X / D	X / D	X / D
Class (steel/ concrete/ …)	V	V / D	V / D	V	V
Behaviour (elastic/ isotropic)	O	O			
Characteristic cylinder strength	D	D	D	D	D
Characteristic cube strength	O				
Secant modulus of elasticity	A	D	D	D	D
Poissons's ratio	A	D	D	D	D
Density	A	D	D	D	D
Yield strength	O				
Tensile strength	O				
Thermal dilatation coefficient	A	D	D	D	D
Material properties steel					
Name material	X			X	
Class (steel/ concrete/ …)	X			X	
Yield strength	X			X	
Tensile strength	X			X	
Secant modulus of elasticity	X			X	
Poisson's ratio	X			X	
Shear modulus	X			X	
Density	X			X	
Thermal dilatation coefficient	X			X	
Boundary conditions					
Boundary conditions type	V			X	
Supports: state	V			X	
Degrees of freedom	V			X	
Loads					
Self-weigth	V			X	
Concentrated force	V			X	
Distributed force	X			X	
Load cases	V			X	
Load combinations	V			X	
Safety factor	V			X	

Table D: Results of the conversion to SCIA Engineer: properties steel

SCIA Engineer: Steel								
BIM-program	**Revit**	**Revit**	**ArchiCAD**	**AECOSIM**	**Tekla Structures**	**Vectorworks structural element**	**Vectorworks construction element**	**Vectorworks Detailed profile**
Transfer	**Direct link**	**IFC 2x3**	**IFC2x3**	**IFC2x3**	**IFC 2x3**	**IFC 2x3**	**IFC 2x3**	**IFC 2x3**
Section properties								
Profile name	C	C	V		V	V	V	V
Profile type	V	V	V		V	V	V	V
Height	A	A	A		A	X	X	X
Width	A	A	A		A	X	X	X
Web thickness	A	A	A		A	X	X	X
Flange thickness	A	A	A		A	X	X	X
Web fillet/ Radius	A	A	A		A	X	X	X
Radius 2 (web)	C	C			A	X	X	X
Centroid horizontal	V	V	C		A	D	D	D
Centroid vertical	V	V	C		A	D	D	D
Section area	A	A	C		A	V	V	V
Moment of inertia strong axis	A	A	C		A	V	V	V
Moment of inertia weak axis	A	A	C		A	V	V	V
Elastic modulus strong axis	A	A	C		A	V	V	V
Elastic modulus weak axis	A	A	C		A	V	V	V
Plastic modulus strong axis	A	A	C		A	C	C	C
Plastic modulus weak axis	A	A	C		A	C	C	C
Torsional moment of inertia	A	A	C		A	X	X	X
Torsional modulus	A	A	C		A	X	X	X
Warping constant	A	A	C		A	C	C	C
Shear area strong axis	A	A	C		A	V	V	V
Shear area weak axis	A	A	C		A	V	V	V
Radius of gyration	C	C	C		A	V	V	V
Geometry								
Length	V	V	V		V	V	V	V
Rotation of the cross section	V	V	V		V	X	V	V
Global coordinats	V	V	V		V	X	V	X
Material properties								
Name material	V	V	V		V	V	V	V
Class (steel/ concrete/ …)	A	A	V		V	V	V	V
Behaviour (elastic/ isotropic)	A	A	C		A			
Secant modulus of elasticity	A	A	C		A			
Poisson's ratio	A	A	C		A			
Shear modulus	A	A	C		A			
Density	A	A	C		A			
Yield strength	A	A	C		A			
Tensile strength	A	A	C		A			
Thermal dilatation coefficient	A	A	C		A			
Boundary conditions								
Boundary conditions type	V	C			C			
Supports: state	V	C			C			
Degrees of freedom	V	C			C			
Loads								
Self-weigth	C	C			C			
Concentrated force	X	X			X			
Distributed force	X	X			X			
Load cases	V	X			X			
Load combinations	V	X			X			
Safety factor	V	X			X			

Table E: Results of the conversion to SCIA Engineer: properties concrete

SCIA Engineer: Concrete						
BIM-program	**Revit**	**Revit**	**ArchiCAD**	**AECOSIM**	**Tekla Structures**	**Vectorworks structural element**
Transfer	**Direct link**	**IFC 2x3**	**IFC 2x3**	**IFC 2x3**	**IFC 2x3**	**IFC 2x3**
Section properties						
Profile name	C	C	V		C	V
Profile type	V	V	V		X	V
Height	V	V	V		V	V
Width	V	V	V		V	V
Centroid horizontal	C	D	D		D	D
Centroid vertical	C	D	D		D	D
Section area	C	C	C		A	C
Reinforcement number	X	V			V	
Reinforcement position	X	V			V	
Reinforcement shape	X	V			V	
Reinforcement diameter	X	X			X	
Hook at the start/ end	X	X				
Bending radius	X	X			X	
Concrete cover	X	X			X	
Moment of inertia strong axis	C	C	C		C	C
Moment of inertia weak axis	C	C	C		C	C
Elastic modulus strong axis	C	C	C		C	C
Elastic modulus weak axis	C	C	C		C	C
Plastic modulus strong axis	C	D	C		C	D
Plastic modulus weak axis	C	D	C		C	D
Torsional moment of inertia	C	D	D		C	X
Torsional modulus	C	D	D		C	X
Warping constant	C	C	C		C	C
Shear area strong axis	C	C	C		C	C
Shear area weak axis	C	C	C		C	C
Radius of gyration	C	C	C		C	C
Geometry						
Length	V	V	V		V	V
Rotation of the cross -section	V	V			V	X
Global coordinates	V	V	V		V	X
Material properties concrete						
Name material	V	V	V		V	V
Class (steel/ concrete/ …)	A	A	A		C	V
Behaviour (elastic/ isotropic)	A	A	A		C	C
Characteristic cylinder strength	A	A	A		C	C
Characteristic cube strength	O	O				
Secant modulus of elasticity	A	A	A		A	
Poissons's ratio	A	A	A		A	C
Density	A	A	A		A	C
Yield strength	A	A	A		C	C
Tensile strength	A	A	A		C	C
Thermal dilatation coefficient	A	A	A		A	C
Material properties steel						
Name material	X	V			V	
Class (steel/ concrete/ …)	X	A			A	
Yield strength	X	A			C	
Tensile strength	X	A			C	
Secant modulus of elasticity	X	A			C	
Poisson's ratio	X	A			C	
Shear modulus	X	A			C	
Density	X	A			C	
Thermal dilatation coefficient	X	A			C	
Boundary conditions						
Boundary conditions type	V	X			X	
Supports: state	V	X			X	
Degrees of freedom	V	X			X	
Loads						
Self-weigth	C	C			C	
Concentrated force	X	X			X	
Distributed force	X	X			X	
Load cases	V	X			X	
Load combinations	V	X			X	
Safety factor	V	X			X	

Table F: Results of the conversion to STAAD.Pro: properties steel

STAAD.Pro : Steel							
BIM-program	**Revit**	**ArchiCAD**	**AECOSIM**	**Tekla Structures**	**Vectorworks structural element**	**Vectorworks construction element**	**Vectorworks detailed profile**
Transfer	**ISM**	**IFC2x3 + ISM**	**ISM**	**IFC2x3 + ISM**	**IFC2x3 + ISM**	**IFC2x3 + ISM**	**IFC2x3 + ISM**
Section properties							
Profile name	O	O	O	O	O	O	O
Profile type	V	V	V	V	X	V	V
Height	V	A	A	A	X	A	A
Width	V	A	A	A	X	A	A
Web thickness	V	A	A	A	X	A	A
Flange thickness	V	A	A	A	X	A	A
Web fillet/ Radius	X	C		O			
Radius 2 (web)	X						
Centroid horizontal	V		V	A			
Centroid vertical	V		V	A			
Section area	A	C	C	A	D	C	C
Moment of inertia strong axis	V	C	C	A	D	C	C
Moment of inertia weak axis	V	C	C	A	D	C	C
Elastic modulus strong axis	O						
Elastic modulus weak axis	O						
Plastic modulus strong axis	O						
Plastic modulus weak axis	O						
Torsional moment of inertia	A	C	A	A	D	C	
Torsional modulus	O						
Warping constant	O						
Shear area strong axis	O						
Shear area weak axis	O						
Radius of gyration	O						
Geometry							
Length	V	V	V	V	V	V	V
Rotation of the cross section	V	V		V	V	V	V
Global coordinats	V	V	V	V	V	X	X
Material properties							
Name material	V	V	V	V	X	X	X
Class (steel/ concrete/ ...)	V	V	V	V	V	V	V
Behaviour (elastic/ isotropic)	O						
Secant modulus of elasticity	V	D	D	D	D	D	D
Poisson's ratio	V	D	D	D	D	D	D
Shear modulus	O						
Density	A	C	C	C	C	C	C
Yield strength	V	D	D	D	D	D	D
Tensile strength	V	D	D	D	D	D	D
Thermal dilatation coefficient	V	D	D	D	D	D	D
Boundary conditions							
Boundary conditions type	X		X	X			
Supports: state	X		X	X			
Degrees of freedom	X		X	X			
Loads							
Self-weigth	X		X	X			
Concentrated force	X		X	X			
Distributed force	X		X	X			
Load cases	X		X	X			
Load combinations	X		X	X			
Safety factor	X		X	X			

Table G: Results of the conversion to STAAD.Pro: properties concrete

STAAD.Pro: Concrete					
BIM-program	**Revit**	**ArchiCAD**	**AECOSIM**	**Tekla Structures**	**Vectorworks structural element**
Transfer	**ISM**	**IFC2x3 + ISM**	**ISM**	**IFC2x3 + ISM**	**IFC2x3 + ISM**
Section properties					
Profile name		O	O	O	O
Profile type	V	X	V	V	X
Height	V	X	V	V	X
Width	V	X	V	V	X
Centroid horizontal	A	X	A	A	X
Centroid vertical	A	X	A	A	X
Section area	A	X	A	A	X
Reinforcement number	X			X	
Reinforcement position	X			X	
Reinforcement shape	X			X	
Reinforcement diameter	X			X	
Hook at the start/ end	X				
Bending radius	X			X	
Concrete cover	X			X	
Moment of inertia strong axis	A	D	D	A	D
Moment of inertia weak axis	A	D	D	A	D
Elastic modulus strong axis	O				
Elastic modulus weak axis	O				
Torsional moment of inertia	A	D	C	A	D
Torsional modulus	O				
Warping constant	O				
Shear area strong axis	A	D	C	A	D
Shear area weak axis	A	D	C	A	D
Radius of gyration	O				
Geometry					
Length	V	V	V	V	V
Rotation of the cross -section	V			V	V
Global coordinates	V	V	V	V	V
Material properties concrete					
Name material	V	X	V	V	X
Class (steel/ concrete/ …)	V	X	V	V	V
Behaviour (elastic/ isotropic)	O				
Characteristic cylinder strength	V	D	X	D	D
Characteristic cube strength	O				
Secant modulus of elasticity	V	D	A	X / D	D
Poissons's ratio	V	D	A	X / D	D
Density	O	D	A	X / D	D
Yield strength	O				
Tensile strength	O				
Thermal dilatation coefficient	V	D	A	X / D	D
Material properties steel					
Name material	X			X	
Class (steel/ concrete/ …)	X			X	
Yield strength	X			X	
Tensile strength	X			X	
Secant modulus of elasticity	X			X	
Poisson's ratio	X			X	
Shear modulus	X			X	
Density	X			X	
Thermal dilatation coefficient	X			X	
Boundary conditions					
Boundary conditions type	X		V	X	
Supports: state	X		V	X	
Degrees of freedom	X		V	X	
Loads					
Self-weigth	X		X	X	
Concentrated force	X		X	X	
Distributed force	X		X	X	
Load cases	X		V	X	
Load combinations	X		V	X	
Safety factor	X		V	X	

Table H: Results of the conversion to RFEM: properties steel

RFEM : Steel								
BIM-program	Revit	Revit	ArchiCAD	AECOSIM	Tekla Structures	Vectorworks structural element	Vectorworks construction element	Vectorworks detailed profile
Transfer	**Direct link**	**IFC2x3**	**IFC2x3**	**IFC2x3**	**IFC2x3**	**IFC2x3**	**IFC2x3**	**IFC2x3**
Section properties								
Profile name			O	O	O	O	O	O
Profile type	V	X	X	X	X	X	X	X
Height	A	X	X	X	X	X	X	X
Width	A	X	X	X	X	X	X	X
Web thickness	A	X	X	X	X	X	X	X
Flange thickness	A	X	X	X	X	X	X	X
Web fillet/ Radius	A	X	X	X	X	X	X	X
Radius 2 (web)	O	O						
Centroid horizontal	A	X			X			
Centroid vertical	A	X			X			
Section area	A	X			X			
Moment of inertia strong axis	A	X			X			
Moment of inertia weak axis	A	X			X			
Elastic modulus strong axis	O	O						
Elastic modulus weak axis	O	O						
Plastic modulus strong axis	O	O			X			
Plastic modulus weak axis	O	O			X			
Torsional moment of inertia	A	X			X			
Torsional modulus	O	O						
Warping constant	O	O			O			
Shear area strong axis	A	X						
Shear area weak axis	A	X						
Radius of gyration	O	O			O			
Geometry								
Length	V	V	V	V	V	V	V	V
Rotation of the cross section	V	V	V	V	V	X	V	X
Global coordinats	V	V	V	V	V	V	X	V
Material properties								
Name material	V	V	V	V	X	X	V	V
Class (steel/ concrete/ …)	V	V	X	X	X	X	V	X
Behaviour (elastic/ isotropic)	V	A	X	D	X	D	A	D
Secant modulus of elasticity	X	A	X	D	X	D	A	D
Poisson's ratio	X	A	X	D	X	D	A	D
Shear modulus	X	A	X	D	X	D	A	D
Density	X	A	X	D	X	D	A	D
Yield strength	X	A	X	D	X	D	A	D
Tensile strength	X	A	X	D	X	D	A	D
Thermal dilatation coefficient	X	A	X	D	X	D	A	D
Boundary conditions								
Boundary conditions type	V	X / D		X	X			
Supports: state	V	X / D		X	X			
Degrees of freedom	V	X / D		X	X			
Loads								
Self-weigth	V	X		X	X			
Concentrated force	V	X		X	X			
Distributed force	V	X		X	X			
Load cases	V	X		X	X			
Load combinations	V	X		X	X			
Safety factor	V	O		X	X			

Table I: Results of the conversion to RFEM: properties concrete

RFEM: Concrete						
BIM-program	**Revit**	**Revit**	**ArchiCAD**	**AECOSIM**	**Tekla Structures**	**Vectorworks construction element**
Transfer	**Direct link**	**IFC2x3**	**IFC2x3**	**ISM**	**IFC2x3**	**IFC2x3**
Section properties						
Profile name			O	O	O	O
Profile type	V	X	V	V	V	V
Height	V	V	V	V	V	V
Width	V	V	V	V	V	V
Centroid horizontal	A	A	A	A	A	C
Centroid vertical	A	A	A	A	A	C
Section area	A	A	A	A	A	C
Reinforcement number	X	X			X	
Reinforcement position	X	X			X	
Reinforcement shape	X	X			X	
Reinforcement diameter	X	X			X	
Hook at the start/ end	X	X				
Bending radius	X	X			X	
Concrete cover	X	X			X	
Moment of inertia strong axis	A	A	C	C	C	C
Moment of inertia weak axis	A	A	C	C	C	C
Elastic modulus strong axis	A	A	C	C	C	C
Elastic modulus weak axis	A	A	C	C	C	C
Torsional moment of inertia	A	A	C	C	C	C
Torsional modulus	A	A	C	C	C	C
Warping constant	O	O				
Shear area strong axis	A	A	C	C	C	C
Shear area weak axis	A	A	C	C	C	C
Radius of gyration	A	X	C	C	C	C
Geometry						
Length	V	V	V	V	V	V
Rotation of the cross -section	V	V			V	V
Global coordinates	V	V	X	V	V	V
Material properties concrete						
Name material	V	V	V	V	V	X
Class (steel/ concrete/ …)	D	D	X	X	X	X
Behaviour (elastic/ isotropic)	X	X	D	D	D	D
Characteristic cylinder strength	X / D	X / D		D	D	D
Characteristic cube strength	X / D	X / D		D	D	D
Secant modulus of elasticity	X / D	X / D		D	D	D
Poissons's ratio	X / D	X / D		D	D	D
Density	X / D	X / D		D	D	D
Yield strength	X / D	X / D		D	D	D
Tensile strength	X / D	X / D		D	D	D
Thermal dilatation coefficient	X / D	X / D		D	D	D
Material properties steel						
Name material	X	X			X	
Class (steel/ concrete/ …)	X	X			X	
Yield strength	X	X			X	
Tensile strength	X	X			X	
Secant modulus of elasticity	X	X			X	
Poisson's ratio	X	X			X	
Shear modulus	X	X			X	
Density	X	X			X	
Thermal dilatation coefficient	X	X			X	
Boundary conditions						
Boundary conditions type	V	X			X	
Supports: state	V	X			X	
Degrees of freedom	V	X			X	
Loads						
Self-weigth	V	X			X	
Concentrated force	V	X			X	
Distributed force	V	X			X	
Load cases	V	X			X	
Load combinations	V	X			X	
Safety factor	V	X			X	

Table J: Results of the conversion to ETABS: properties steel

ETABS : Steel							
BIM-program	**Revit**	**ArchiCAD**	**AECOSIM**	**Tekla Structures**	**Vectorworks structural element**	**Vectorworks construction element**	**Vectorworks detailed profile**
Transfer	**IFC2x3**	**IFC2x3**	**IFC2x3**	**IFC2x3**	**IFC2x3**	**IFC2x3**	**IFC2x3**
Section properties							
Profile name		V		V	V	V	X
Profile type	V	X / D	X	V	D	D	D
Height	A	X / D	X	A	D	D	D
Width	A	X / D	X	A	D	D	D
Web thickness	A	X / D	X	A	D	D	D
Flange thickness	A	X / D	X	A	D	D	D
Web fillet/ Radius	A	X / D	X	A	D	D	D
Radius 2 (web)	O						
Centroid horizontal	A	D	V	A	D	D	D
Centroid vertical	A	D	V	A	D	D	D
Section area	A	D	X	A	D	D	D
Moment of inertia strong axis	A	D		A	D	D	D
Moment of inertia weak axis	A	D		A	D	D	D
Elastic modulus strong axis	A	D		A	D	D	D
Elastic modulus weak axis	A	D		A	D	D	D
Plastic modulus strong axis	A	D		A	D	D	D
Plastic modulus weak axis	A	D		A	D	D	D
Torsional moment of inertia	A	D		A	D	D	D
Torsional modulus	A	D		A	D	D	D
Warping constant	A	D		A	D	D	D
Shear area strong axis	A	D		A	D	D	D
Shear area weak axis	A	D		A	D	D	D
Radius of gyration	A	D		A	D	D	D
Geometry							
Length	V	V	V	V	V	V	V
Rotation of the cross section	O	O					
Global coordinats	V	V	V	V	V	X	V
Material properties							
Name material	V	V	V	V	V	V	X
Class (steel/ concrete/ ...)	X	V	V	X	X	X	X
Behaviour (elastic/ isotropic)	D	C	C	X	D	D	D
Secant modulus of elasticity	X	C	C	X	D	D	D
Poisson's ratio	X	C	C	X	D	D	D
Shear modulus	X	C	C	X	D	D	D
Density	X	C	C	X	D	D	D
Yield strength	O						
Tensile strength	O						
Thermal dilatation coefficient	X	C	C	X	D	D	D
Boundary conditions							
Boundary conditions type	X / D		X	X			
Supports: state	X / D		X	X			
Degrees of freedom	X / D		X	X			
Loads							
Self-weigth	X		X	X			
Concentrated force	X		X	X			
Distributed force	X		X	X			
Load cases	X		X	X			
Load combinations	X		X	X			
Safety factor	X		X	X			

Table K: Results of the conversion to ETABS: properties concrete

ETABS: Concrete					
BIM-program	**Revit**	**ArchiCAD**	**AECOSIM**	**Tekla Structures**	**Vectorworks construction element**
Transfer	**IFC2x3**	**IFC2x3**	**ISM**	**IFC2x3**	**IFC2x3**
Section properties					
Profile name		V	X	V	V
Profile type	X	V	V	V	X
Height	V	V	V	V	X
Width	V	V	V	V	X
Centroid horizontal	A	A	A	A	X
Centroid vertical	A	A	A	A	X
Section area	A	C	C	A	X
Reinforcement number	X			X	
Reinforcement position	X			X	
Reinforcement shape	X			X	
Reinforcement diameter	X			X	
Hook at the start/ end	X				
Bending radius	X			X	
Concrete cover	X			X	
Moment of inertia strong axis	A	C	C	C	D
Moment of inertia weak axis	A	C	C	C	D
Elastic modulus strong axis	A	C	C	C	D
Elastic modulus weak axis	A	C	C	C	D
Torsional moment of inertia	A	C	C	C	D
Torsional modulus					
Warping constant	A	C	C	C	D
Shear area strong axis	A	C	C	C	D
Shear area weak axis	A	C	C	C	D
Radius of gyration	A	C	C	C	D
Geometry					
Length	V	V	V	V	V
Rotation of the cross -section	O				
Global coordinates	V	V	V	V	V
Material properties concrete					
Name material	V	V	X	V	X
Class (steel/ concrete/ …)	X	X	X	X	X
Behaviour (elastic/ isotropic)	D	D	D	D	D
Characteristic cylinder strength					
Characteristic cube strength	O				
Secant modulus of elasticity	X	X	D	D	D
Poissons's ratio	X	X	D	D	D
Density	X	X	D	D	D
Yield strength	O				
Tensile strength	O				
Thermal dilatation coefficient	X	X	D	D	D
Material properties steel					
Name material	V			V	
Class (steel/ concrete/ …)	X			X	
Yield strength	X			X	
Tensile strength	X			X	
Secant modulus of elasticity	X			X	
Poisson's ratio	X			X	
Shear modulus	X			X	
Density	X			X	
Thermal dilatation coefficient	X			X	
Boundary conditions					
Boundary conditions type	X / D		X / D	X	
Supports: state	X / D		X / D	X	
Degrees of freedom	X / D		X / D	X	
Loads					
Self-weigth	X		X	X	
Concentrated force	X		X	X	
Distributed force	X		X	X	
Load cases	X		X	X	
Load combinations	X		X	X	
Safety factor	X		X	X	

Table L: Results of the conversion to FEM-Design: properties steel

FEM-design : Steel							
BIM-program	**Revit**	**ArchiCAD**	**AECOSIM**	**Tekla Structures**	**Vectorworks structural element**	**Vectorworks construction element**	**Vectorworks detailed profile**
Transfer	**StruXML**	**IFC2x3**	**IFC2x3**	**IFC2x3**	**IFC2x3**	**IFC2x3**	**IFC2x3**
Section properties							
Profile name		O	O	O		O	O
Profile type	V	X	X	X		X	X
Height	A	V	V	V		X	X
Width	A	V	V	V		X	X
Web thickness	A	V	V	V		X	X
Flange thickness	A	V	V	V		X	X
Web fillet/ Radius	O			O			
Radius 2 (web)	O						
Centroid horizontal	A	V	V	V		X	X
Centroid vertical	A	V	V	V		X	X
Section area	A	A	X	X		X	X
Moment of inertia strong axis	A	C	C	A		X	X
Moment of inertia weak axis	A	C	C	A		X	X
Elastic modulus strong axis	A	C	C	A		X	X
Elastic modulus weak axis	A	C	C	A		X	X
Plastic modulus strong axis	A	C	C	A		X	X
Plastic modulus weak axis	A	C	C	A		X	X
Torsional moment of inertia	A	C	C	A		X	X
Torsional modulus	A	C	C	A		X	X
Warping constant	A	C	C	A		X	X
Shear area strong axis	A	C	C	A		X	X
Shear area weak axis	A	C	C	A		X	X
Radius of gyration	A	C	C	A		X	X
Geometry							
Length	V	V	V	V		V	V
Rotation of the cross section	V	V	V	V		V	V
Global coordinats	V	V	V	V		V	V
Material properties							
Name material	V	A	X	V		A	A
Class (steel/ concrete/ …)	V	V	V	V		V	V
Behaviour (elastic/ isotropic)	O						
Secant modulus of elasticity	A	A	C	A		C	C
Poisson's ratio	A	A	C	A		C	C
Shear modulus	O						
Density	A	A	C	A		C	C
Yield strength	O						
Tensile strength	O						
Thermal dilatation coefficient	A	A	C	A		C	C
Boundary conditions							
Boundary conditions type	V		X	X			
Supports: state	V		X	X			
Degrees of freedom	V		X	X			
Loads							
Self-weigth	X		X	X			
Concentrated force	V		X	X			
Distributed force	V		X	X			
Load cases	V		X	X			
Load combinations	X		X	X			
Safety factor	X		X	X			

Table M: Results of the conversion to FEM-Design: properties concrete

FEM-design: Concrete					
BIM-program	**Revit**	**ArchiCAD**	**AECOSIM**	**Tekla Structures**	**Vectorworks construction element**
Transfer	**StruXML**	**IFC2x3**	**ISM**	**IFC2x3**	**IFC2x3**
Section properties					
Profile name		O	O	O	O
Profile type	V	V	X	V	V
Height	A	A	V	A	A
Width	A	A	V	A	A
Centroid horizontal	A	A	A	A	C
Centroid vertical	A	A	A	A	C
Section area	A	A	C	A	C
Reinforcement number	X			X	
Reinforcement position	X			X	
Reinforcement shape	X			X	
Reinforcement diameter	X			X	
Hook at the start/ end	X				
Bending radius	X			X	
Concrete cover	X			X	
Moment of inertia strong axis	A	C	C	A	C
Moment of inertia weak axis	A	C	C	A	C
Elastic modulus strong axis	A	C	C	A	C
Elastic modulus weak axis	A	C	C	A	C
Torsional moment of inertia	A	C	C	A	C
Torsional modulus	A	C	C	A	C
Warping constant	A	C	C	A	C
Shear area strong axis	A	C	C	A	C
Shear area weak axis	A	C	C	A	C
Radius of gyration	A	C	C	A	C
Geometry					
Length	V	V	V	V	V
Rotation of the cross -section	V			V	V
Global coordinates	V	V	V	V	V
Material properties concrete					
Name material	A	V	X	V	V
Class (steel/ concrete/ …)	V	V	X	V	V
Behaviour (elastic/ isotropic)	O				
Characteristic cylinder strength	A	C	D	C	C
Characteristic cube strength	O				
Secant modulus of elasticity	A	C	D	C	C
Poissons's ratio	A	C	D	C	C
Density	A	C	D	C	C
Yield strength	O				
Tensile strength	O				
Thermal dilatation coefficient	A	C	D	C	C
Material properties steel					
Name material	X				
Class (steel/ concrete/ …)	X				
Yield strength	X				
Tensile strength	X				
Secant modulus of elasticity	X				
Poisson's ratio	X				
Shear modulus	X				
Density	X				
Thermal dilatation coefficient	X				
Boundary conditions					
Boundary conditions type	V		X		
Supports: state	V		X		
Degrees of freedom	V		X		
Loads					
Self-weigth	X		X		
Concentrated force	V		X		
Distributed force	V		X		
Load cases	V		X		
Load combinations	X		X		
Safety factor	X		X		