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BIM Software Capability and Interoperability Analysis

An analytical approach toward structural usage of BIM software (S-BIM)

Master thesis in Building Technology
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PREFACE

In the name of Allah, the most gracious, the most merciful, are the best words ever which I start this thesis with. All praise and thanks belongs to Allah, the Lord of the worlds, and peace and blessings of Allah be upon the last Prophet "Mohammed" and upon his pure and generous family.

This research presented in this thesis was carried out at the department of civil and architectural engineering at the royal institute of technology (KTH) 2015.

I would also like to express my thanks and sincerest gratitude to my supervisors; Professor Folke Björk, with the inestimable advice and guidance of associate professor Kjartan Gudmundsson, to whom I want to thank for providing valuable reviewing, thoughtful feedback and comments the final report to present this master programme thesis.

I am particularly thankful to a number of people who do not work with me but have been friends for the last three years of my life in Sweden, for your support and for all those nice moments, we have spent together: Dr. Saif Wahid Jasim, Dr. Ahmed M.Qasim, Basil Jawad, Mohamed Ameen, Firas Jawad, Safa Alkhazraji & Khalid Agha. I apologize to those whose names I did not mention, but who should also be here.

Last but not least of course, I wish to express my deepest appreciation to my beloved mother, for her infinite love, devotion, encouragement and support that words cannot truly express, my kind brothers and sisters and their families, for their endless encouragement and support, and finally to my father, a great man whom we all missed.

Stockholm, March 2016

Ali Abdulhasan Taher

ABSTRACT

Over the past few decades, major advances have occurred in computer technology to optimize technical solutions. BIM is more than drawings it has played a major role in building design and modelling, construction and maintenance information. Thus, BIM established itself as an alternative to CAD technique, where BIM can be used for views, sections, elevations, and quantity takeoff. . Because of its advantages and the ease and simplicity of modelling process, the use of BIM is growing rapidly and becoming more popular than CAD. Nowadays BIM has no specific standard common platform and number of competitors, compatibility issues occur since every provider of BIM software such as Autodesk Revit, and Rhino BIM that have a common platform namely IFC, CIS/2 and ISM. This study focused on the structural analysis of BIM models. Different commercial software (Autodesk products and Rhinoceros) are presented through modelling and analysis of different structures with varying complexity, section properties, geometry, and material. Beside the commercial software, different architectural and different tools for structural analysis are evaluated (dynamo, grasshopper, add-on tool, direct link, indirect link via IFC).

Keywords: BIM, S-BIM, Autodesk Products, Revit, Robot Structural Analysis, Dynamo, STAAD pro, Rhinoceros, Grasshopper, Tekla, Karamba, IFC, ISM, CIS/2.

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LIST OF ACRONYMS

Item	Description
2D	Two dimensions, length and width
3D	Three dimensions, includes depth
4D	Three dimensions, includes depth + Cost
5D	Three dimensions, includes depth + Cost + Time
BIM	Building Information Modelling
S-BIM	Structural Building Information Modelling
IFC	Industry Foundation Classes
CIS/2	CIMSteel Integration Standards
ISM	Integrated Structural Modeling
FEM	Finite element method
FEA	Finite element analysis

LIST OF COMMERCIAL SOFTWARE USED IN THIS THESIS

Description	Acronyms	Version	Release Date
BIM – Commercial software			
Autodesk AutoCAD 2016	ACAD	M.49.0.0	
Autodesk Revit 2015	RVT	Build: 20140606_1530	2014
Autodesk Robot Structural Analysis 2015	RSA	28.0.0.5335	2014
Autodesk Dynamo	DYN	0.8.2	2015
STAAD Pro V8i	SPro	20.07.10.65	2014
Rhinoceros	Rhino	5.0 SR11	10/2015
Tekla Structures 20	TEK	20.0 Service Release 1	3/2014
Structural BIM – (S-BIM Tools)			
Structural Analysis for Dynamo	-	0.2.1	7/2015
Revit Extensions for Autodesk Revit 2015	Extensions	3.0.8.0	2014
CIS/2 Import-Export 2015 for Revit	CIS/2	9.0.0	5/2015
ISM Revit Link V8i (SELECTseries 7)	ISM	8.11.12.3	8/2015
Grasshopper WIP	GH	0.9.0076	8/2014
Karamba 3d	K	1.1.0	

CHAPTER 1

INTRODUCTION

The construction industry such as automotive and aeronautics is undergoing a revolution. In recent years, Building Information Modeling[1] (BIM) has had an impact on the traditional construction process (Eastman, 2011; Granroth, 2008) and has played a major role in the transition to more industrial construction methods, which has reduced time and costs based on the digital modeling and management of information. Some countries such as Denmark, Singapore and the United Kingdom have decided and mandate this integrated approach toward the Building Information Modeling and European Parliament has already released a call for proposal with the main objective of the development of "a common European strategy for the introduction and specification of Building Information Modelling (BIM) in Europe's public works"[2]. Member States have until April 2016 to reflect the new rules of the guidelines related to public procurement (EUPPD[3], 2014) into national law. The European Parliament recommends the use of digital processes such as BIM in public contracts to improve efficiency and quality of the interchanges in the phases of bidding and competitions for public projects.

The use of BIM or information management model for the design and construction of a building is already widely applied in Sweden (mostly in the architectural design process) including the academic support toward providing a platform for the Building Lifecycle Management (BLM)[4]. BIM can be described as a process to generate and manage information on buildings throughout their lifecycle and enables the integration of dynamic information of the building [an integrated approach toward different branches of information such as architectural and structural information in the design phases of a building]. The software

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[1] (2014). What Is BIM | Building Information Modeling | Autodesk. Retrieved August 14, 2015, from http://www.autodesk.com/solutions/building-information-modeling/overview.
[2] (2015). Support of a common European network aiming at aligning ... Retrieved August 14, 2015, from
http://ec.europa.eu/DocsRoom/documents/10423/attachments/1/translations/en/renditions/native.
[3] (2014). BIM And The New EU Public Procurement Directives: An ... Retrieved August 17, 2015, from http://www.mondaq.com/x/315484/Building+Construction/BIM+And+The+New+EU+Public+Procurement+Directives+An+Update.
[4] (2010). AIA Guide to Building Life Cycle Assessment in Practice. Retrieved August 14, 2015, from http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab082942.pdf.

system is based on a digital 3D presentation of the building (Azhar, 2011). However, it is not necessary that all users apply the 3D digital model and the level of information and detail of the model depends on the projects and context. The implementation of information exchange in construction is not only a technical decision but also a business decision in order to achieve better communication and an improved decision process as well as reduced construction time and costs (Smith & Tardif, 2012). BIM[5] is a new concept in the construction industry and is defined as a collection of programs with different tools used in the design, production and finally in the management of buildings; it contains the object-oriented models that contain information about the building during the construction process (Shamloo & Mobaraki, 2011). Effective strategy for implementing BIM software must not only be based on adapting the construction design process to the corresponding technology, but also through an extensive technical understanding of the capability of different related software and applications.

The use of BIM in structural design involves the choice of appropriate platform. Beside the BIM softwares' internal capabilities characteristics, the interoperability, data standards and communication between softwares must also be taken into consideration (Pazlar & Turks, 2008; Grilo & Jardim-Goncalves, 2010). For instance, the IFC[6] format (Industry Foundation Classes) is a data model/standard that describes objects, their characteristics and their relationships. The IFC is a part of the international standard STEP (Pratt, 2001) or "Standard for Exchange of product data" (ISO 10303). Since March 2013, the IFC are certified ISO 16739 (Liebich, 2012). IFC aim to ensure the interoperability of BIM software. As we intend to show in this thesis, the import and export capability of IFC from one application to another is not completely satisfactory.

[5] (2009). Building information modeling – BIM software and ... Retrieved August 14, 2015, from http://www.bim.construction.com/.
[6] (2012). Industry Foundation Classes Whitepaper - Bentley. Retrieved August 15, 2015, from http://ftp2.bentley.com/dist/collateral/docs/bentley_institute/White_paper_IFC.pdf.

1.1 RESEARCH AIM AND OBJECTIVES

The aim of this thesis is to illustrate how BIM can be used in structural design and calculations. The objective is particularly to compare some of the available tools for structural analysis and design. This comparison has been done by first establishing a platform of reference cases that could then be used to compare the results as well as the capabilities and interoperability of the software and the different data formats.

According to the literature review, there is not any specific integrated differentiating analytical platform to compare different components in BIM software and the related data standards.

In accordance to the main objective, several structures (2D and 3D) with various serviceability in different software and data standards were used. Ultimately, the results could be used for making a "BIM execution plan" in structural analysis and design.

1.1.1 RESEARCH QUESTIONS

The aim is to describe various aspects of BIM and S-BIM to compare them in a manner that may help improve the structural design process and to describe their strengths and weaknesses. This involves:

- The analysis of different structural capabilities of the common BIM software and compare them.
- The examination of different data models and standards in accordance with the interoperability.
- The evaluation of the S-BIM tools as a plug-in for commercial software modeling.

1.1.2 HYPOTHESES & EXPECTED CONTRIBUTION TO KNOWLEDGE

There is a traceable trend of standardization in the international construction industry in both the determination of BIM models and the interoperability of different BIM applications.

We believe that there is a lack of proper communication between different BIM software and the open source file format of IFC containing some practical deficiencies capability. In order to examine this hypothesis, this study compares a selection of current BIM applications through the modeling both simple and more advanced structures. The BIM applications have also been tested with common FEA structural software and their structural add-Ins (plug-ins) tools in both normal BIM (Revit) and algorithm way (Dynamo and Rhino Grasshopper).

Finally, this study attempts to describe the reliability of different BIM software and data standards including the S-BIM, BIM and related data models.

1.2 THESIS OUTLINE

The first chapter is a general introduction to the study followed by a second chapter that provides a comprehensive literature review on the specifications of different software and data standards, such as IFC, CIS/2, ISM and Revit, STAAD Pro (BIM SOFTWARE & DATA MODELS). Chapters 3 and 4 include the comparative case study of BIM, S-BIM and the related add-ins and data standards with simple and more advanced models. The third chapter describes the applicability of structural BIM for simple 2D structures with different section properties and different materials; various properties and different materials have been investigated in the applicability of the structural BIM and with different materials (steel and timber), geometries (column and beam) and different physical section properties (rectangle and I section). In the fourth chapter the applicability of S-BIM tools are tested with the three dimensional steel structure from.

Dynamo and Rhino Grasshopper software beside the current BIM application such as Revit during these two chapters have also been used to differentiate the subjects and evaluate them. S-BIM (Carrasco & Navarro, 2013) is a new concept of in sense of structural integrity of BIM; for S-BIM the Autodesk RSA (Robot structural Analysis) has been tested to assess the links and capability of RSA in various structural design analysis. Furthermore this study includes the application of a well-known reliable structural design software, STAAD Pro, and compared the results with RSA. The efficiency of data models standards such as IFC, CIS/2 and ISM have also been examined during the third and fourth chapters.

1.3 LITERATURE REVIEW

The term BIM has a contextual meaning the interpretation of which depends on disciplines (Granroth, 2008). According to the literature study of the author, no comparative studies have been done on the reliability of structural BIM and structural add-ins for BIM. The focus of this literature study is on the literature on the specifications of different software and data standards (for example IFC, CIS/2, ISM and Revit, STAAD Pro). The literature used may be categorized according to the following topics:

- BIM origins and elements.
- BIM data standards and models.
- The related analysis methods according to the research objectives.

1.3.1 THESIS BACKGROUND LITERATURE STUDY AT A GLANCE

In general, the theoretical framework of BIM (Lu & Li, 2011), there seems to be a lack of research on the effective integration of sense of technical requirements to facilitate the technology and its application (Singh et al., 2011).

In most of the published studies, BIM models are associated with un-unified data[7]. BIM and CAD models were developed in parallel where a productivity improvement of 57% was demonstrated with BIM software (Sacks et al., 2010) concerning the design of a building facade. However, problems of the study of this thesis emerged in the IFC exchange data model was incomplete that technically confirmed the need for the data standard improvement. There are also interdisciplinary studies (Aram et al., 2013) to flow the information with BIM.

1.4 RESEARCH METHODOLOGY

The core methodology of the study of this thesis is based on an analytical approach [software capability comparing] by analyzing the key factors of software performance differentiation; the final evaluation relies heavily on the comparison criteria of the performances. All these comparisons would advocate our conclusion about the subjects (software or data model) performances and the results would emphasis the significance of developing such an “analysis platform”.

This research is focused on the comparison on the software and software standards of BIM and structural design and the formalization of the associated results based on the experimental approach to evaluate different common BIM software and interoperability data models mostly by analyzing different criteria and investigate the capabilities of the cases. This research focused on the comparison on the software standards of BIM and structural design, based on the experimental approach to evaluate different common BIM software and interoperability data models through the modeling simple and more advanced structures. An overview of the BIM software and structural BIM tools is shown in table 1.1. This study includes:

[7] (2014). Re-use of structural elements | S-BIM & Sustainability for ... Retrieved August 20, 2015, from http://oliebana.com/2014/12/23/re-use-of-structural-elements/.

- Using indirect link Structural Analysis for Dynamo between DYN and RSA.
- Using indirect link (CIS/2 Import and Export 2015) from Revit to RSA via CIS/2.
- Using indirect link (ISM Revit plug-in) from Revit to SPro via ISM.
- Using indirect link Karamba between DYN and RSA.
- Using Autodesk direct link (Robot Structural Analysis link) from Revit to RSA.
- Using indirect link (ISM Revit plug-in) from Revit to SPro via ISM.

Table 1.1: List of commercial software used in the thesis.

Description	**Acronyms**	**Version**	**Release Date**
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Autodesk Dynamo	DYN	0.8.2	2015
STAAD Pro V8i	SPro	20.07.10.65	2014
Rhinoceros	Rhino	5.0 SR11	10/2015
Tekla Structures 20	TEK	20.0 Service Release 1	3/2014
Structural BIM – (S-BIM Tools)			
Structural Analysis for Dynamo	-	0.2.1	7/2015
Revit Extensions for Autodesk Revit 2015	Extensions	3.0.8.0	2014
CIS/2 Import-Export 2015 for Revit	CIS/2	9.0.0	5/2015
ISM Revit Link V8i (SELECTseries 7)	ISM	8.11.12.3	8/2015
Grasshopper WIP	GH	0.9.0076	8/2014
Karamba 3d	K	1.1.0	

1.4.1 STRATEGY OF INQUIRY & STEP ANALYSIS

In general, the main methodic approach is similar to the Grounded Theory (Dick, 2002) except that our categorization does not become a basis of any new theory. Furthermore, this study aims to explain different aspects of BIM and S-BIM with IFC, ISM and CIS/2 with a data gathering strategy in order to develop the needed platform for the hypothesis examination. Since our “substantive area” has been identified (Douglas, 2003), we have collected the needed data through the practical tests (chapters 3 & 4), to eventually link and visualize them and through the final chapter our “theoretical sampling” (Eisenhardt & Graebner, 2007) shapes the structure of a prospect software adaptation policy and an enhancement proposition.

1.4.2 TOWARD A COMPARING PLATFORM OF ANALYSING

An experimental context based on the comparing processes of different components in BIM software and the related data standards (chapters 3 & 4) is the basis of the assessment of the performance evaluation based on our developed criteria in order to facilitate the structural design agents in the transitional phase to develop a deliverable structural phase design. The lack of interoperability between different software would be recognizable regarding the associated data elements models. This interoperability is necessary for the collaboration of agents working on the same model.

1.4.2.1 EXPERIMENTAL MAPPING & VISUALIZATION

The possibility of developing algorithms of BIM structure modelling through Dynamo and Rhino Grasshopper software can bring about a new possibility for visualization and mapping and is discussed in chapters three and four.

1.5 RESEARCH SCOPE AND LIMITATIONS

The BIM software has been becoming more sophisticated by progressively integrating a growing number of features and there are still progresses to be made. A very important part of this progress is related to the software interoperability and data standards and communication between software. As we mentioned in the hypothesis, the import and export in the BIM application need to be more developed in order to make the operations automatic. This study is related to a practical assessment of the common BIM software and their compatibility to data standards for structural design. This thesis is also an attempt to develop a platform for comparison of structural BIM software.

CHAPTER 2

BIM SOFTWARE & DATA MODELS

"CAD helps people to draw. BIM helps people to construct." - Richard Saxon

Previous studies show that the cooperation between professionals during the process contains the average of seven times re-entering the information (Grosrey, 2013) because the non-unified approaches of different members of a design team; the lack of coherence, effectiveness and interoperability cause waste of time and money. The solution that has been ordinated since about twenty years ago is the use of BIM[1]. The construction industry has shown an increased willingness to apply BIM to reach significant potential gains in projects. As mentioned in the first chapter of this thesis, the European Union has recently applied new guidelines and "Procurement Directive"[2] to encourage member states according to the usage of digital tools. The definition of BIM varies and often has been explained depending on the activity that uses it (Jongeling, 2008). The "US National Building Information Model Standard Project Committee"[3] has defined BIM as:

"Building Information Modeling (BIM) 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."

BIM improves the processes of design and construction and stage-based operational approach regarding the information exchange; eventually, it is an introduction to the age of information and communications technology in the building sector (Fountain, 2004) at the heart of the

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[1] (2011). NBS National BIM Library - free-to-use BIM objects. Retrieved August 27, 2015, from http://www.nationalbimlibrary.com/.
"The National BIM Standard-United States® (NBIMS-US™) provides consensus based standards through referencing existing standards, documenting information exchanges and delivering best business practices for the entire built environment. With open BIM standards we can build detailed models then deliver accurate products that can be used during commissioning and operation to ensure facility functionality throughout the life of the facility and to deliver high performance, carbon neutral, and net zero energy based facilities."
[2] (2014). European Directive Officially Opens Public Procurement to ... Retrieved August 27, 2015, from http://www.bimtaskgroup.org/european-directive-officially-opens-public-procurement-to-use-bim/.
[3] (2015). National Building Information Modeling Standard Version 1 ... Retrieved August 27, 2015, from https://www.wbdg.org/pdfs/NBIMSv1_p1.pdf.

technological and economic control revolution (Beniger, 2009) integrating digital tools to the process of construction design and life-cycle and facilitating the market development. However, the effective application of BIM contains the implicit interoperability between the related software and data format standards. In other words, BIM is a working method or a process[4] mostly based on the collaboration around a digital information model (Hading & McCool, 2015) in which each contributor uses the model, deriving and feeding an updating the information toward a final virtual object. BIM is a collective concept of how to formulate, implement, and store the information in a systematic and quality assured manner (Jongeling, 2008).

There is controversy regarding the influences of BIM as a powerful tool providing a real leap in terms of quality and productivity in the construction sector[5] reducing time, decreasing cost and contributing to the sustainability values[6]. As Pontus Bengtson, BIM expert at WSP (Winroth, 2012), emphasizes, BIM is primarily not about new technology, but about an attitude. The information-based approach would eventually reduce the level of risk (Jannadi & Almishari, 2003) and increase the quality of design and implementation. Moreover, the digital model would have a better economic performance with optimized management costs (Bryde et al., 2013). The mentioned Information-based approach requires the standardization of data formats and interoperability.

In a broader view, BIM is valuable in terms of the generation of reliable and quality information that preserve the investments in sense of asset management[7].

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[4] (2011). Building Information Modeling (BIM) - InfoComm. Retrieved August 28, 2015, from http://www.infocomm.org/cps/rde/xbcr/infocomm/Brochure_BIM.pdf.

[5] (2013). improving efficiency and productivity in the construction ... Retrieved August 28, 2015, from http://www.cefrio.qc.ca/media/uploader/Improving_efficiency_and_productivity_in_the_construction_sector_final.pdf.

[6] (2014). Integration of BIM and Business Strategy - The Whole ... Retrieved August 28, 2015, from https://www.wbdg.org/pdfs/integratebim_harris.pdf.

[7] (2015). Leveraging the Relationship between BIM and Asset ... Retrieved August 31, 2015, from https://www.ice.org.uk/getattachment/disciplines-and-resources/best-practice/relationship-between-bim-and-asset-management/BIM_Modelling-and-Asset-Management_Position-Paper.pdf.aspx.

"Asset management is defined by ISO 55000 as the 'coordinated activity of an organisation to realise value from assets'. Asset management translates business objectives into asset-related decisions, plans and actions within a strategic framework using a set of processes, techniques and tools. It seeks to optimise the cost, risk and performance of assets over their life cycle at an individual asset, asset system and asset portfolio level."

2.1 BIM, ORIGINS & ELEMENTS

"BIM is not CAD. BIM was never meant to be CAD. CAD is a replacement for pen and paper, a documentation tool. By comparison, BIM programs are design applications in which the documentation flows from and is a derivative of the process, from schematic design to construction to facility management." - Pete Zyskowski, Cadalyst[8]

The industry demand of an efficient design process and sustainability is favored by new working methods and tools that enable all stakeholders to integrate the knowledge and objectives (Rezgui et al., 2010). The main purpose of Building Information Modeling (BIM) is the development of such a context offering the capacity to manage the corresponding information. As mentioned before, BIM is mainly a methodology based on the use of computable information (Arayici & Aouad, 2010) about the physical and functional characteristics of a building or infrastructure to facilitate interoperability and collaboration between different actors involved in the construction process, providing reliable support and shared decision-making platform (Rezgui et al., 2011). There is currently a high demand for professionals capable of organizing workflows platform (Clevenger et al., 2010) in the sector with a broad view of all the processes that occur in the life cycle of construction.

In recent years, the BIM trend has been changing the industry methodical traditions and developing the communicational attitude between the various project-based contributors and stakeholders although there are currently no documental regulative approach in Sweden (Juntikka, 2015). Beside the BIM three dimensional representation models, by definition, it contains 4D and 5D models (Jongeling, 2008) in integration with the so-called 3D model in order to provide the project with the traceable production planning and time and cost visualization (Figure. 2.1).

From architects to developers, actually all the stakeholders, enjoy the benefits of the collaborative method of BIM which uses starts from 3D models and matures into interactive deployment through databases in a dynamic modeling sense and far further than intelligent 3D digital models which integrate all types of construction-related data. Nowadays, "BIM

[8] (2009). The World According to BIM, Part 1 | Cadalyst. Retrieved September 7, 2015, from http://www.cadalyst.com/cad/building-design/the-world-according-bim-part-1-3780.

manager"[9] has been started to be defined as a new interdisciplinary branch as a person in charge of the implementation and coordination of BIM Plan[10]. BIM could also be considered as a communication tool (Cerovesk, 2011) in the form of visualization in simulated construction processes (Kamat & Martinez, 2005).

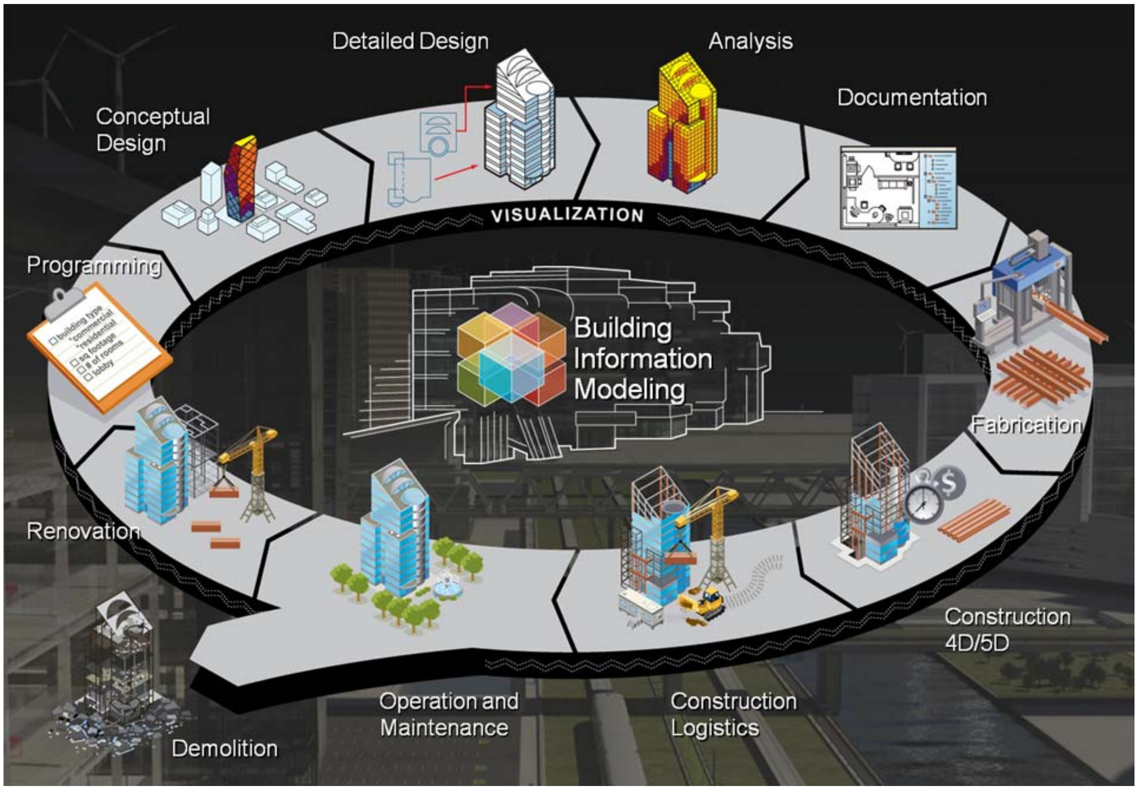

Figure 2.1: An information cycle[11] is followable by applying the BIM concept during the building lifecycle.

The following chapters give a review of a comparative matrix[12] that has been developed in order to analyze the flow of associated information for the exchanges between different BIM software focused on the construction design process.

[9] (2010). 10 Things Every BIM Manager Should Know - Vico Software. Retrieved September 4, 2015, from http://www.vicosoftware.com/vico-blogs/guest-blogger/tabid/88454/bid/22833/10-Things-Every-BIM-Manager-Should-Know.aspx.
[10] (2012). Facilities BIM Execution Plan - MIT. Retrieved September 4, 2015, from http://web.mit.edu/facilities/maps/MIT_BIM_execution_plan.pdf.
[11] (2013). Why Project Managers are perfect for the role of Information ... Retrieved September 1, 2015, from http://evolution5.co.uk/bim-why-project-managers-are-perfect-for-the-role-of-information-manager/.
[12] (2012). BIM Tools Matrix - BIMForum. Retrieved September 5, 2015, from http://bimforum.org/wp-content/uploads/2011/02/BIM_Tools_Matrix.pdf.

2.1.1 BIM SOFTWARE

Currently, the set of tools, techniques and concepts that allow realizing the BIM approach toward general construction design is known internationally as BIM software (Guan-pei, 2010).

2.1.1.1 REVIT BUILDING APPLICATION

Revit[13] (Revise Instantly) as an eighteen year old software and more than thirteen releases (2 to 3 releases per year) is mainly developed as an architectural tool by PTC[14] (Parametric Technology Corporation and Charles River Software, patented by Leonid Raiz and Irwin Jungreis) and since then has become the only[15] "completely parametric Building Information Modeling tool available". In 2002, Autodesk[16] purchased a Revit and developed a family of tools and applications based on the main concept.

Autodesk Revit[17] is capable of 4D level (building's lifecycle traceability) which means that it is completely suitable for structural design (the thesis scope) in 3D and interoperability using "building model's database". Autodesk Revit® Structure software integrates a physical model consisting of multiple materials with an independent analytical model that can be edited and used for efficient structural analysis, design and construction description (Figure 2.2). As the design changes made during the analysis automatically update the physical model and the construction documents automatically which is a direct presentation of information from the same underlying database. This key feature of Revit Structure is the reason why it is so easy and flexible to use, while virtually eliminating coordination errors and improve overall quality of descriptions and documentation.

[13] (2012). Revit Structure and BIM - i-Theses. Retrieved August 30, 2015, from https://i-theses.com/nl/images/stories/pdf/revit_structure_bim_mar07.pdf.
[14] PTC: Technology Solutions for Ongoing Product & Service ... Retrieved September 5, 2015, from http://www.ptc.com/.
[15] (2014). Building Design Software | Revit Family | Autodesk. Retrieved September 5, 2015, from http://www.autodesk.com/products/revit-family/overview.
[16] (2008). Autodesk to Acquire Revit Technology Corporation. Retrieved September 5, 2015, from http://investors.autodesk.com/phoenix.zhtml?c=117861&p=irol-newsArticle&ID=261618.
[17] (2015). Building Design & Construction | Revit Family | Autodesk. Retrieved September 5, 2015, from http://www.autodesk.com/products/revit-family/features/all/gallery-view.

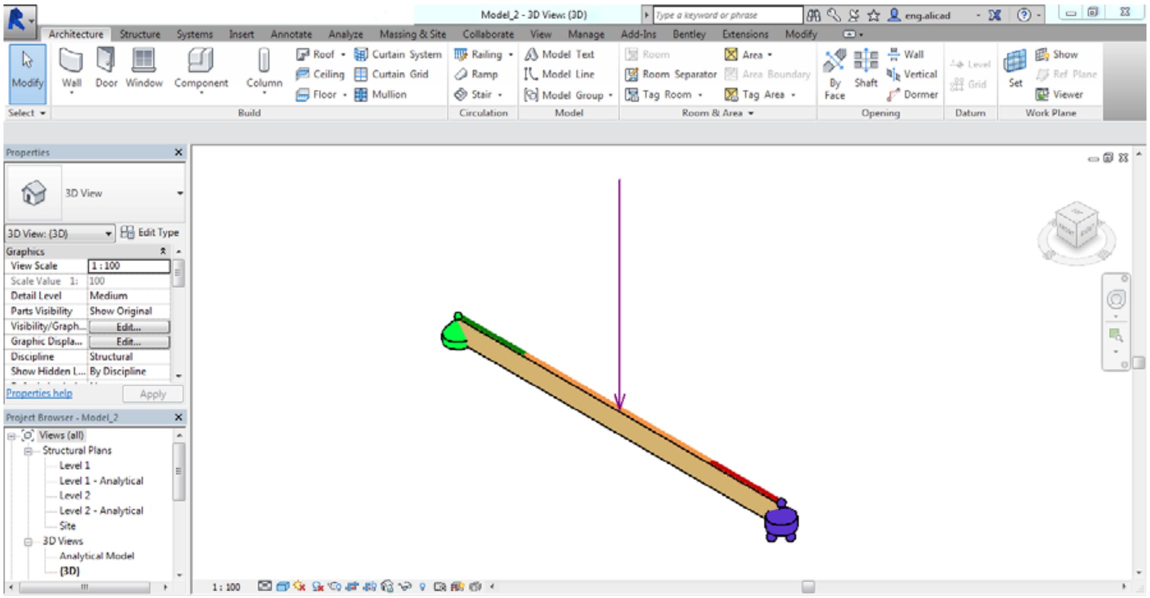

Figure 2.2: The integration of a physical model with an analytical model that can be edited for structural analysis.

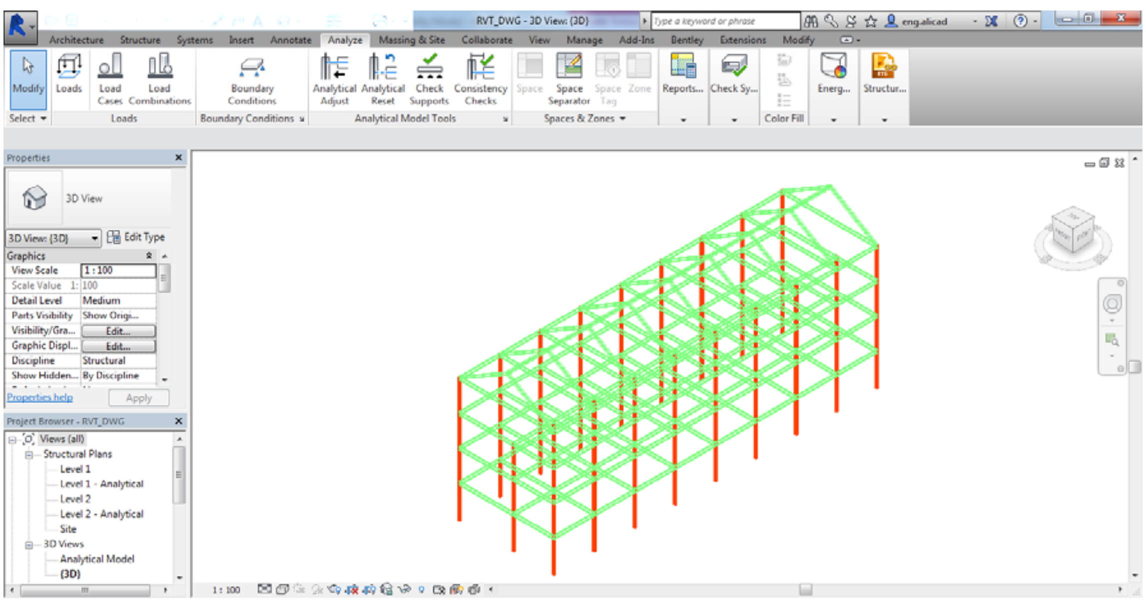

Figure 2.3: Revit Structure offers all the tools for structural design as walls, columns, beams, trusses, concrete, rebar, steel connections, and more.

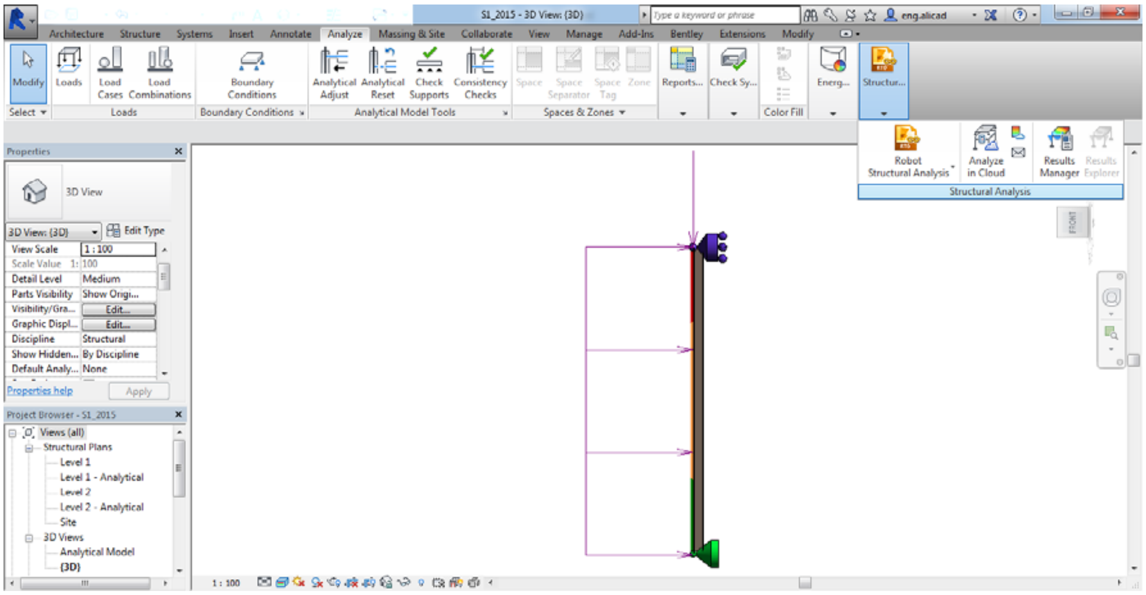

Figure 2.4: The analysis process through Revit based on provided specific analysis tools.

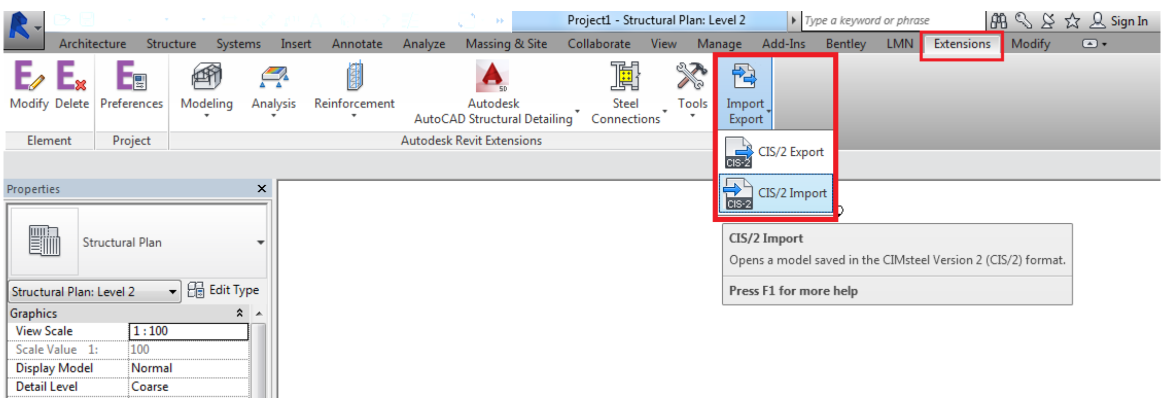

Figure 2.5: The Revit *extension* CIS/2 wizard add on S-BIM tool.

2.1.1.2 RHINOCEROS & RHINOBIM

The Rhino Software (Rhinoceros[18]) is a 3D surface modeler with an engine of NURBS (Non-Uniform Rational Basis Splines[19]) as a curve generator (Farin, 1999) by defined control points on a coordinated basis which are compatible with the majority of visual projections. Rhino opens with four windows XY, XZ (front view), YZ (to the right) and prospective and can enlarge one of its windows by clicking the left button of the window in a single large window and reduce by the same method; there is a simultaneous visualization of the movement of the pointer in the 4 windows in (Figure 2.6).

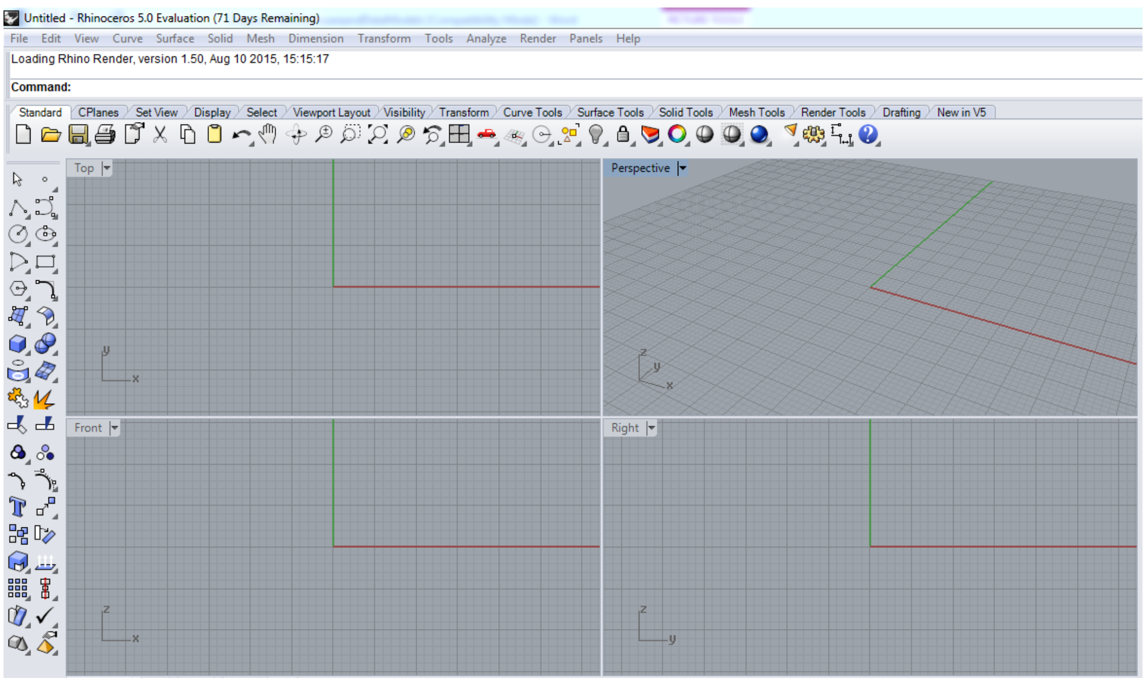

Figure 2.6: RhinocerosBIM software main interface.

[18] (2013). Rhinoceros. Retrieved September 9, 2015, from https://www.rhino3d.com/.
[19] (2015). Rhinoceros - NURBS. Retrieved September 9, 2015, from https://www.rhino3d.com/nurbs.

As an additional expansion of Rhino, RhinoBIM is developed by “Virtual Build Technologies[20]” and “Robert McNeel & Associates[21]” to adapt Rhino more to the concept of BIM. As it has been mentioned in the developer’s website RhinoBIM[22] is a “plug-ins that enhances Rhino”; the “first module” includes:

- Structural Design & Editor.
- Clash & Clear Analysis.
- Quantity take offs in BIM Reporter.
- IFC & CIS2 Translators.
- User Definable database.

2.1.1.3 DYNAMO REVIT + GRASSHOPPER RHINO, NEW TECHNIQUES

Dynamo[23] is an open-source plugin for Revit (and now Robot Structural Analysis[24]), described as visual programming to which adds an icon to the “complements” as "Dynamo 0.X". Dynamo, the visual integration of data modification, is mostly helpful in

- Complex and Parametric Modelling,
- Additional features to the software,
- Automating tedious tasks,
- Exporting data and results to Excel.

In this thesis, the main purpose of application is “transforming computational design in functional structures in Revit”[25]. Dynamo is also considered as the Grasshopper for Revit.

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[20] (2010). Virtual Build Technologies. Retrieved September 12, 2015, from http://www.vbtllc.com/.
[21] Robert McNeel & Associates - North America. Retrieved September 12, 2015, from http://www.mcneel.com/.
[22] (2015). RhinoBIM - Tools for Design through Construction. Retrieved September 12, 2015, from http://rhinobim.com/page/download-3.
[23] (2014). Learn | Dynamo BIM. Retrieved September 17, 2015, from http://dynamobim.com/learn/.
[24] (2014). Structural Software | Robot Structural Analysis | Autodesk. Retrieved September 17, 2015, from http://www.autodesk.com/products/robot-structural-analysis/features/all/list-view.
[25] (2013). Transforming computational design in functional structures ... Retrieved September 17, 2015, from http://bimerworld.blogspot.com/2013/08/transforming-computational-design-in.html.

The Grasshopper[26] plugin for Rhino is also working with a possibility of "visual scripting interface"[27] (Fig. 2.6) although there are some operational differences.

If we consider the Rhino's ability in developing "complex geometries" and consistently the Grasshopper becomes a form-generating plugin which could not be considered as the Dynamo's main concern as Revit is not mainly developed as a "freeform geometry" software.

Eventually in accordance with the basic concept of BIM of "the management of building information", the Dynamo and Revit are more fitted to the procedure.

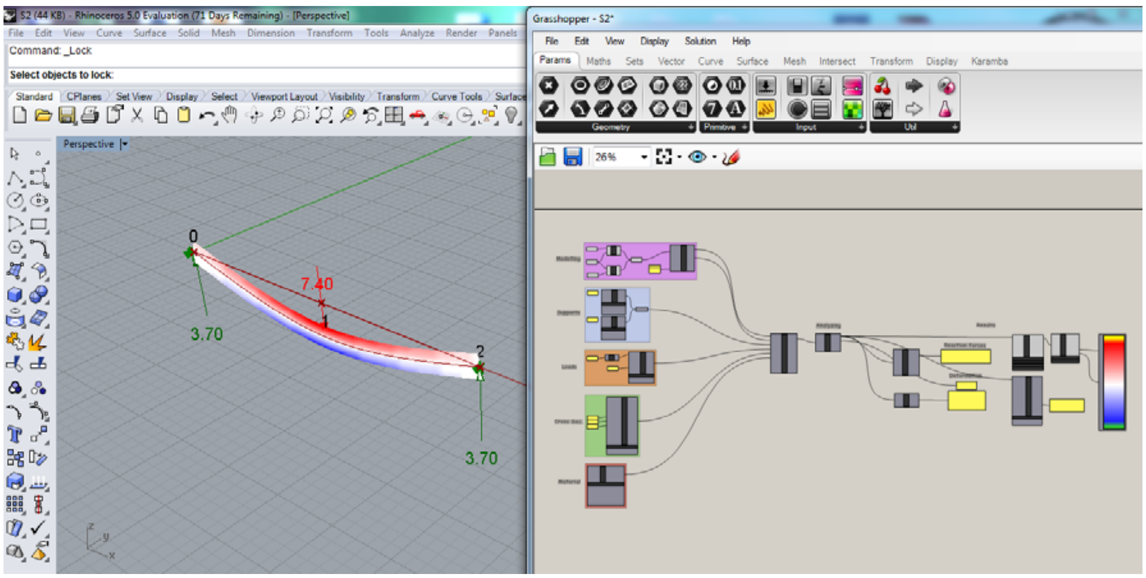

Figure 2.7: The visual scripting interface in Grasshopper.

[26] (2010). Geometry Gym BIM - Grasshopper. Retrieved September 17, 2015, from http://www.grasshopper3d.com/group/geometrygym.
[27] (2015). Dynamo: More Than Grasshopper Lite | CASE. Retrieved September 17, 2015, from http://www.case-inc.com/blog/revit-dynamo-more-than-grasshopper.

2.1.2 STRUCTURAL BIM (S-BIM) TOOLS

As mentioned before, BIM could be considered as a design methodology for the information of a building through its lifecycle. Structural BIM (S-BIM) literally collects the information of the structural[28] part of the design based on the concept of collaborative approach and develops the related digital representation. Consequently, S-BIM (Carrasco & Navarro, 2013) increases the efficiency and the overall quality of the building and the corresponding software.

Basically, the referred information includes all the structural[29] elements and the related analysis and detailing. The workflow effectiveness in BIM is based on the information sharing and exchange, which efficiently influence the collaboration and, by applying the S-BIM technology (Zhang & Hu, 2011), it would even be possible to analyze the structural behavior during construction and safety during the construction process through simulation.

2.2 BIM & DATA EXCHANGE STANDARDS & MODELS

"Drawing is Dead – Long Live Modelling" - CPIC[30]

There is no doubt that the contemporary construction industry is the result of a complex process involving multiple actors; the collaborative value is difficult to achieve since the coordination of the produced information must be unified and integrated with a sense of control of the processes that generate the deliverables enabling the design development and contributing to the procedure as a whole (Grilo & Jardim-Goncalves, 2010).

Basically, BIM is a digital file format (not only a virtual one) which integrates all of the technical information of a building. This file contains every building component object and its characteristics and the relationships between objects that mostly are described as the junctions; the provided information is far beyond the simple geometric shapes.

[28] (2012). BIM Integrity in Structural Engineering - i-Theses. Retrieved August 30, 2015, from https://i-theses.com/nl/images/stories/pdf/bim_integrity_in_structural_engineering_feb07%5B1%5D.pdf.
[29] (2013). The Power of BIM for Structural Engineering. Retrieved August 30, 2015, from http://www.cadac.com/nl/brochures/Documents/autodesk-revit-2013-structural-engineering-brochure-en.pdf.
[30] (2013). CPIC » Drawing Is Dead – Long Live Modelling. Retrieved September 7, 2015, from http://www.cpic.org.uk/publications/drawing-is-dead/.

The construction digital information must be enhanced in accordance with the collaboration among stakeholders through the design process and lifecycle; it must be shared, reliable and durable. On the traditional process of design beside the issue of information documentation, the similar data has been being applied for several time using non-compatible agents which the BIM and unified data models would completely avoid these kind of problems; the new approach toward databases such as “cloud” (Jiao, et. al, 2013) would facilitate the process even more.

BIM is not a file format or a data pattern[31]; the standards listed here, such as IFC and CIS/2 standard, are mechanisms to transfer data from one software application to another, but are not themselves BIM project models[32].

2.2.1 THE INDUSTRY FOUNDATION CLASSES (IFC)

The Industry Foundation Classes (IFC) format is the data model (Isikdag et al., 2007) developed by the buildingSMART[33] and is a part of the international standard STEP (Standard for Exchange of Product data, ISO 10303[34]) (Pratt, 2001). Since 2013, IFC is certified as ISO 1673935 in accordance with the interoperability of BIM software data exchange. Most software has adopted this standard to some extent but the inter-software data exchange is not yet flawless. The importance of sharing information[36] in BIM context emphasizes the significance of IFC standards (or the other models) facilitating the procedure of interoperability and enabling project members to participate, regardless of the software they use.

[31] (2011). Data Exchange Standards in the AEC Industry - Autodesk. Retrieved September 14, 2015, from http://images.autodesk.com/adsk/files/data_exchange_standards_in_the_aec_industry_final.pdf.
[32] (2014). AEC (UK) BIM Protocol. Retrieved September 14, 2015, from https://aecuk.files.wordpress.com/2012/09/aecukbimprotocol-v2-0.pdf.
[33] (2005). Home | buildingSMART | buildingSMART |. Retrieved August 26, 2015, from http://www.buildingsmart.org/.
[34] (2002). ISO 10303 STEP Standards - STEP Tools, Inc. Retrieved August 26, 2015, from http://www.steptools.com/library/standard/.
[35] (2011). ISO 16739:2013 - Industry Foundation Classes (IFC) for ... Retrieved August 26, 2015, from http://www.iso.org/iso/catalogue_detail.htm?csnumber=51622.
[36] (2014). Solibri | About BIM and IFC. Retrieved August 26, 2015, from http://www.solibri.com/support/bim-ifc/.

The IFC is the information that describes the designed objects throughout its lifecycle[37] (design, construction, and operation) and from different points of view (architecture, structure, thermal, Management, etc.) providing the form, characteristics, relationships with other objects regardless the software based file format[38]. The international standard STEP (ISO 10303-21[39]) does guarantee the stability, universality, and independence of the IFC data model format. Eventually, the IFC standard would prepare the needed communication and operation platform for all BIM applications based on a unified database.

The IFC could be considered as a standard, neutral, and independent language which has been being developed under the vision of "the development and adoption of interoperable standards for openBIM" by buildingSMART[40] with the main goal to evolve the IFC standard and promote the concept of BIM in the construction sector. Within BuildingSMART, each country contributes as volunteers to advance the concept and the results have been reflected in the "Standards Library, Tools and Services"[41]. It is interesting that the Swedish division of buildingSMART has not been activated.

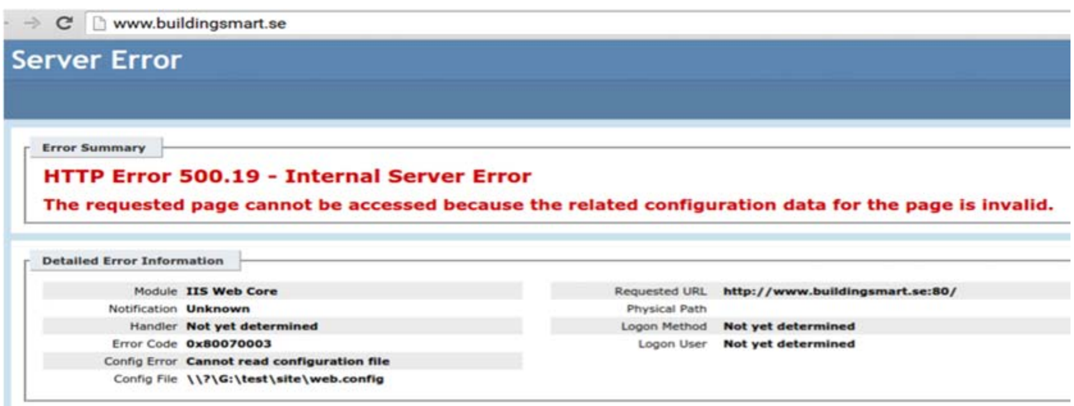

Figure 2.8: buildingSMART.se website internal server error message.

[37] (2014). Exporting to Industry Foundation Classes (IFC) | Revit ... Retrieved August 26, 2015, from http://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2015/ENU/Revit-DocumentPresent/files/GUID-6EB68CEC-6C17-4B16-A509-30537F666C1F-htm.html.
[38] (2012). Industry Foundation Classes Whitepaper - Bentley. Retrieved August 26, 2015, from http://ftp2.bentley.com/dist/collateral/docs/bentley_institute/White_paper_IFC.pdf.
[39] (2010). Reading and Writing STEP Data Sets - STEP Tools, Inc. Retrieved August 26, 2015, from http://www.steptools.com/support/stdev_docs/roselib/read_write.html.
[40] (2005). Home | buildingSMART | buildingSMART |. Retrieved August 30, 2015, from http://www.buildingsmart.org/.
[41] (2005). Home | buildingSMART | buildingSMART |. Retrieved August 30, 2015, from http://www.buildingsmart.org/standards/standards-library-tools-services/.

2.2.2 THE CIMSTEEL INTEGRATION STANDARDS (CIS/2)

The plug-in of CIS/2 (CIMsteel Integration Standards version 2[42]), available for Autodesk® Revit® Structure, is a good example of the promotion of standard formats by Autodesk. CIS/2 is an open standard for the exchange of engineering data structure (Crowley & Watson, 2000), dedicated to steel structures (Lipman, 2006). The management of import and export operations in Autodesk Revit Structure in CIS/2 format is provided by the related extension in Revit® and offered to customers who bought Revit Structure. As Reed (2003) emphasizes:

> *"Successful integration of an automated process into a project delivery system depends on the ability to describe the desired result of the process in a manner understandable to its automation technology. Similarly, it depends on the ability of the automation technology to describe the actual result of the process in a manner understandable to subsequent processes."*

2.2.3 INTEGRATED STRUCTURAL MODELING (ISM)

Some cooperation between different software solution developers and data standard companies have an ongoing cooperation in order to enhance the interoperability. As an example Bentley Systems[43], Autodesk Company, and Tekla Corporation[44], the digital information model provider has developed a "collaboration to advance the interoperability of software within Building Information Modeling"[45]. The Bentley's workflows Integrated Structural Modeling (ISM)[46] provides the "structural practitioner" with the following:

[42] (2003). CIS/2 -- CIMsteel Integration Standard - STEP Tools, Inc. Retrieved September 14, 2015, from http://www.steptools.com/support/stdev_docs/express/cis/.
[43] Bentley: Architecture, Engineering, Construction Design ... Retrieved September 15, 2015, from http://www.bentley.com/.
[44] (2008). Tekla | Model-based software for construction, infrastructure ... Retrieved September 15, 2015, from http://www.tekla.com/us.
[45] (2012). Bentley Systems and Tekla Advance Interoperability of ... Retrieved September 15, 2015, from http://www.bentley.com/en-US/Corporate/News/News+Archive/2011/Quarter+2/tekla+advance+ilnteroperability.htm.
[46] (2010). Integrated Structural Modeling - Bentley. Retrieved September 15, 2015, from http://www.bentley.com/en-US/Products/Structural+Analysis+and+Design/ISM/.

- Interoperability among all ISM-compatible software;
- Common structural data model;
- Trackable and comparable results;
- Visually and textuality during the changes of the model;
- Publishing collaborative features;
- Extra integrative visualization tools, facilities, and open source capability.

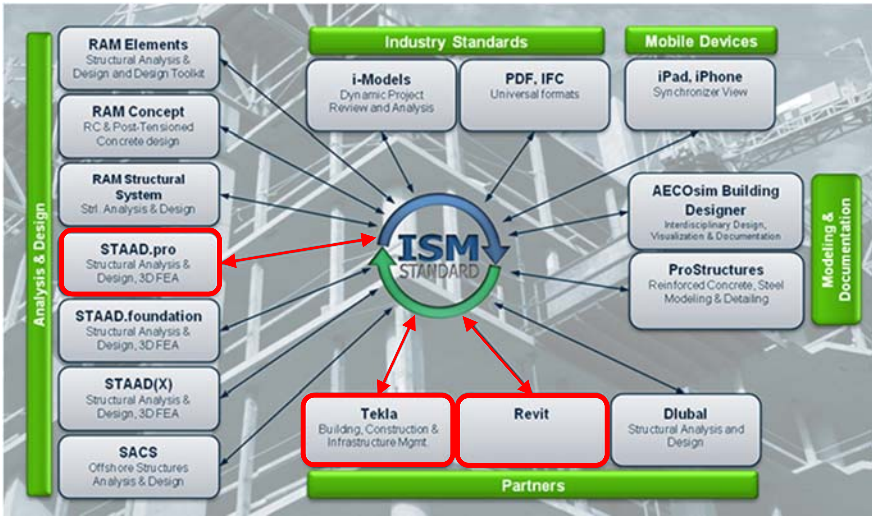

Figure 2.9: ISM enabled products (Revit, STAAD Pro, IFC…etc.) [47]

[47] Integrated Structural Modeling from http://www.bentley.com/.

CHAPTER 3

ANALYSIS OF S-BIM FOR AUTODESK AND RHINOCERS PRODUCTS FOR SIMPLE 2D STRUCTURES

In this chapter, several BIM commercial software and their structural BIM tools have been studied through the modeling of two simple structures in steel and timber materials as well as beam and column physical structures.

3.1 ANALYSIS METHODS

In this thesis, the applicability of structural BIM is investigated by testing it on two, relatively simple, 2D structures. Firstly, a simply supported steel column that is a widely used element of building construction is investigated. Secondly, a simply supported timber is of interest in order to clarify whether S-BIM tools would be enabled to handle an anisotropic timber construction material as simple supported.

Furthermore, the capabilities of transferring the analytical model from and to S-BIM and commercial BIM software have been studied. The implemented workflow used in the tests has been illustrated in Figure 3.1-3.2 respectively.

In the first case, different software applications for Revit and Dynamo have been applied:

- Using indirect link ***Structural Analysis for Dynamo*** between DYN and RSA.
- Using indirect link (***CIS/2 Import/Export 2015***) from Revit to RSA via CIS/2.
- Using indirect link (***ISM Revit plug-in***) from Revit to SPro via ISM.

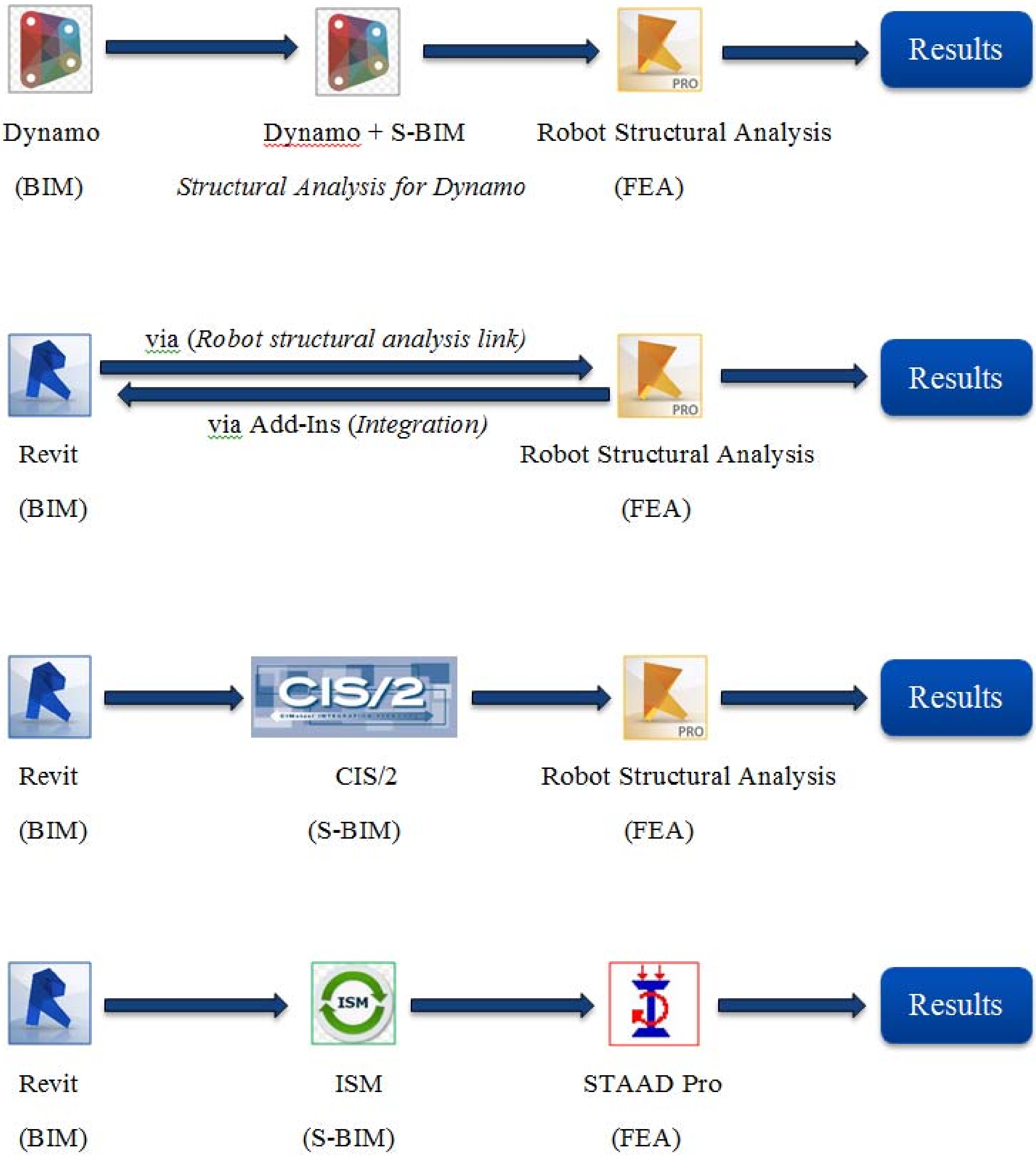

Figure 3.1: The workflow information from BIM process to FEM results for Structure 1

The second structure is also modelled by Revit and Rhinoceros BIM commercial software. The new S-BIM (Karamba) is used as FEM software beside SPro and RSA for analysis processes, which applied via S-BIM tools:

- Using indirect link ***Karamba*** between DYN and RSA.
- Using Autodesk direct link (***Robot Structural Analysis link***) from Revit to RSA.

- Using indirect link (***ISM Revit plug-in***) from Revit to SPro via ISM.

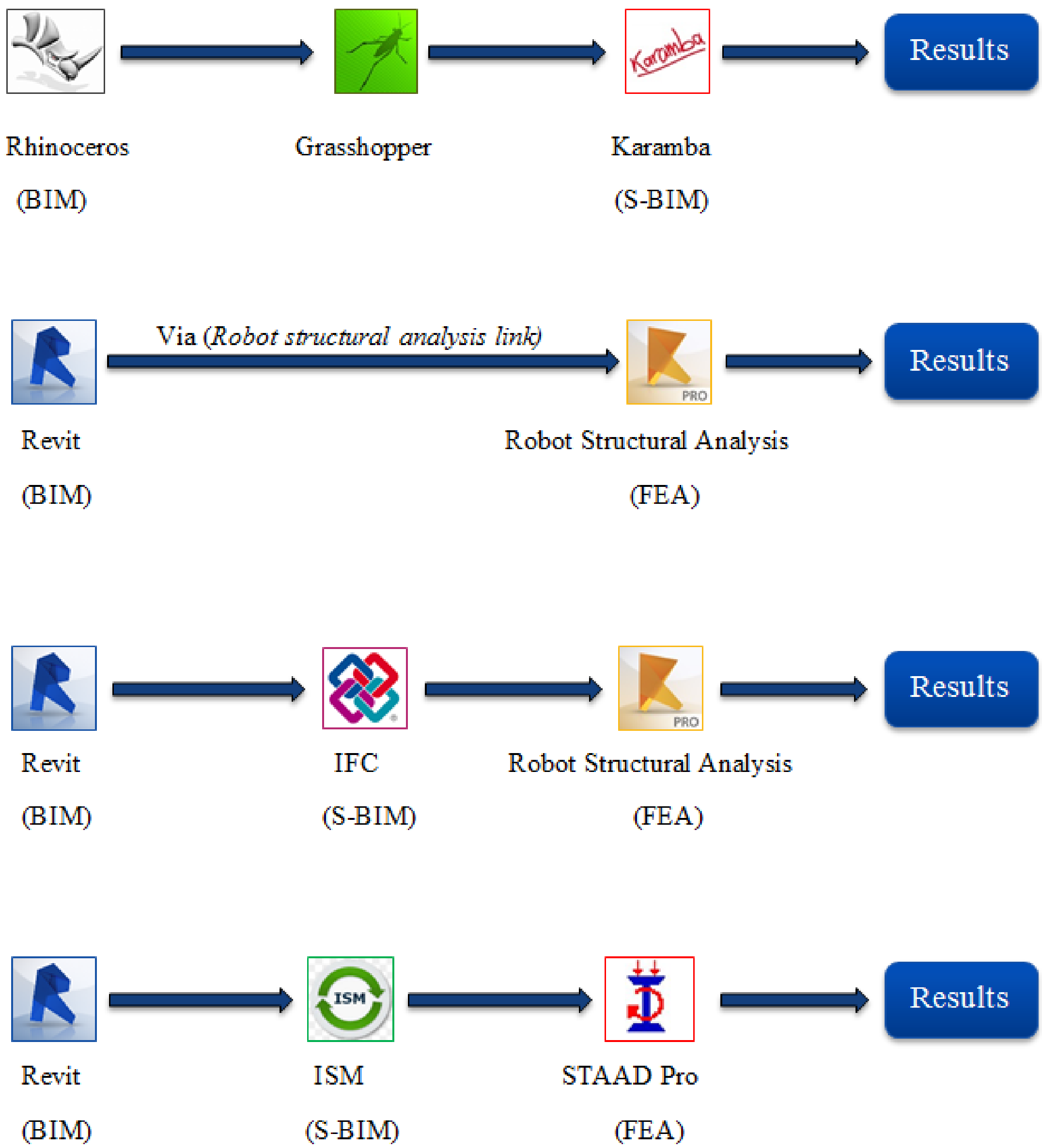

Figure 3.2: The workflow information from BIM process to FEM results for Structure 2

In order to analyze different structures modelled with BIM software, S-BIM tools should be able to handle a number of specific parameters.

The input parameters in order of workflow are as follows:

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

The final results from FEM software are compared with correct hand calculations which performed according to Eurocode.

3.2 STRUCTURE-1 SIMPLY SUPPORTED STEEL COLUMN (LATERAL TORSIONAL BUCKLING TEST)

The first structure in this chapter is extracted from course handouts from the course *AF2213, Steel and Timber Structures* given at KTH 2015. A pure flexural column buckling test is performed, is 2.85 m simply supported steel column (pinned – roller ends). The structure is free to deflect in the stiff direction and the column is subjected to an axial load P_{Ed} = 371 kN in combination with transverse uniformly distributed load W_{Ed} = 3.32 kN/m. The column is made a H-section, HEB100 of steel type S235. The static system of the steel beam and the cross section are shown in figure 3.3.

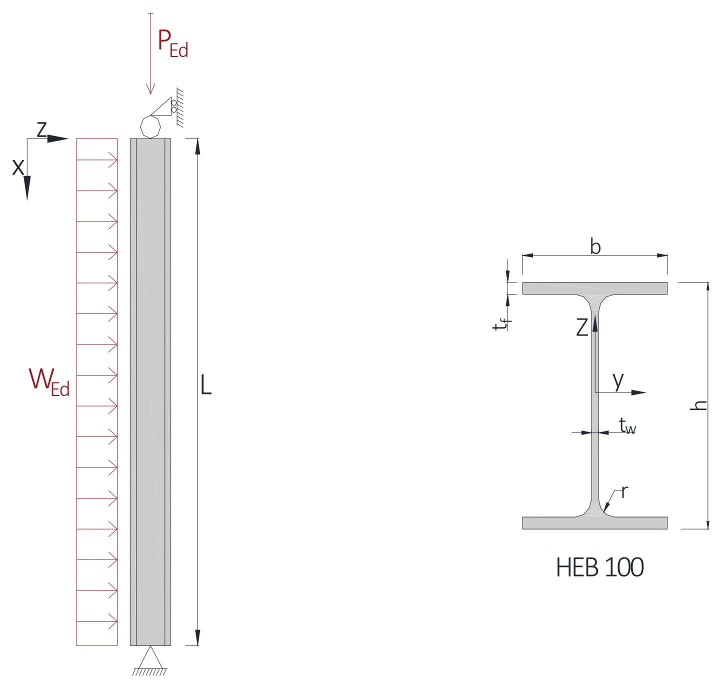

Figure 3.3: Left: Simply supported column. Right: Cross section (HEB-profile)

Both applied loads (arbitrary load and distributed uniformly load) and the chosen HEB100 cross section provide sufficient bending and shear strength but insufficient lateral column buckling resistance. This model is used in order to ensure that the structural BIM software and its tools meet the design requirements [not according Eurocode 3 through different software environment]. Relevant design criteria for Eurocode (EC3) of the steel column are found by:

Table 3.1: Design criterion for analysis Structure 1

Design Criteria		**Hand calculations**	**Robot Structural Analysis**	**STAAD Pro**
Bending moment	*EC3: 6.2.5*	EN 1993-1-1:2003	EN 1993-1:2005/AC:2009	EN-1-1:2005
Shear resistance	*EC3: 6.2.6*	EN 1993-1-1:2003	EN 1993-1:2005/AC:2009	EN-1-1:2005
Buckling resistance	*EC3: 6.2.6*	EN 1993-1-1:2003	EN 1993-1:2005/AC:2009	EN-1-1:2005

All the parameters that need to be evaluated and the lateral column buckling design criteria are presented in Appendix A.

3.2.1 RESULTS OF TEST (1)

The applicability of modelling and structural BIM (S-BIM) tools are tested by applying simply supported steel column through different BIM software based on design criteria and the design parameters in Appendix A and the results are shown in Table 3.2. The calculation procedures are shown in Appendix A (**A.2 Procedures of Test 1**). The procedures demand different choices according to the modelling and analyzing process.

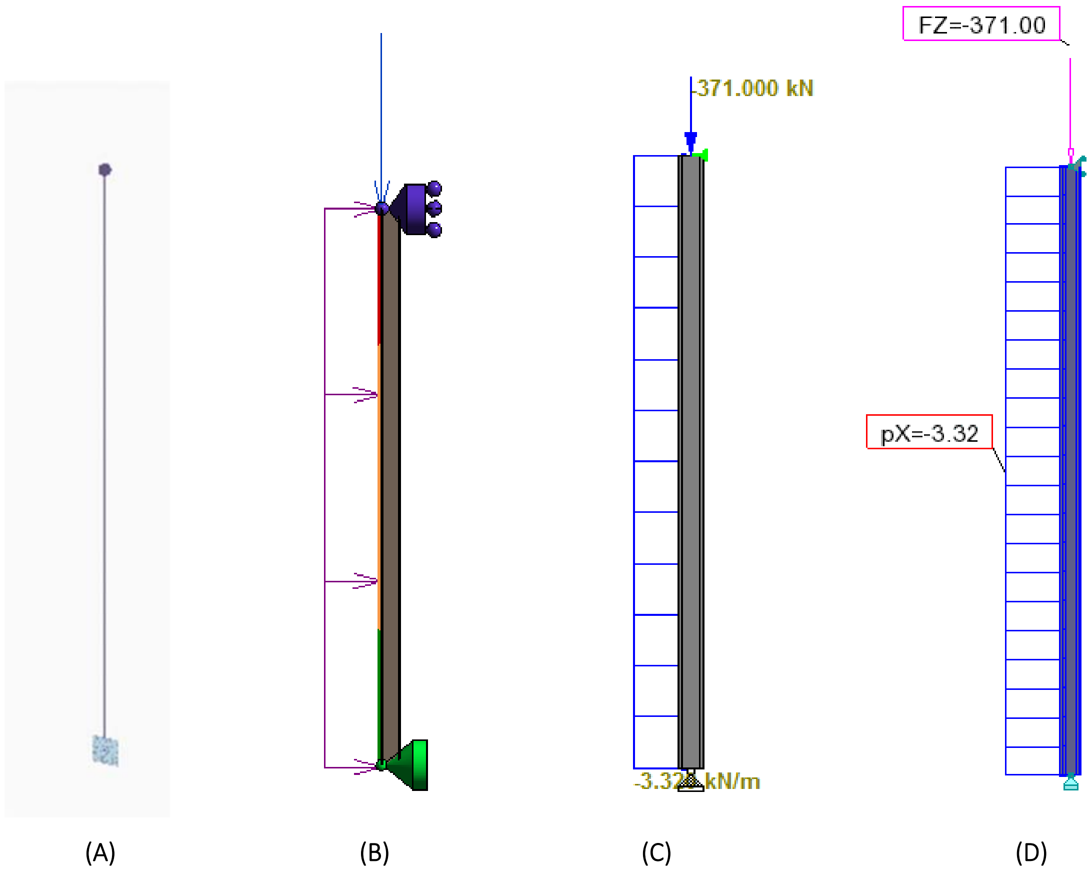

Figure 3.4: Screen dump of Structure 1 representations in different BIM software
(A) Dynamo (B) Revit (C) Robot structural analysis (D) STAAD Pro

Table 3.2: Lateral buckling test results for simply supported steel column.
● *refers to no problem or error occurs while* ○ *refers to feature does not work or parameter is not available*

Description	Dyn	Dyn (Plug-In)	RVT	RVT ↓ RSA	RSA ↓ RVT	RVT ↓ CIS/2 RSA	SPro	RVT ↓ ISM SPro
1. Section properties								
Class classification (1,2,3,4)	○	○	○[2]	●	○[2]	○	●	○
Height *(h)*	●[1]	●	●[3]	●	●	●	●	●
Width *(b)*	●[1]	●	●[3]	●	●	●	●	●
Web thickness *(t_w)*	●[1]	●	●[3]	●	●	●	●	●
Flange thickness *(t_f)*	●[1]	●	●[3]	●	●	●	●	●
Radius *(r)*	●[1]	●	●[3]	●	●	●	○	○
Area *(A)*	○	●	●[3]	●	●	●	●	●
Shear area *(A_y, A_z)*	○	●	○	●	○[2]	●	●	●
Moment of inertia *(I_y, I_z)*	○	●	●	●	●	●	●	●
Elastic section modulus *($W_{el,y}$)*	○	●	○	●	○[2]	○	●	●
Plastic section modulus *($W_{pl,y}$)*	○	●	○	●	○[2]	○	●	●
Radius of gyration *(i)*	○	●	○	●	○[2]	○	●	○
2. Geometry								
Length *(L)*	●	●	●	●	●	●	●	●
Effective length *(L_{eff})*	○	○	○[2]	●	○[2]	○	○	○
3. Material properties								
Yield stress *(fy)*	○	●	●	●	●	●	●	●
Modulus of elasticity *(E)*	○	●	●	●	●	●	●	●
Shear modulus *(G)*	○	●	●	●	●	●	●	●
Weight *(W)*	○	●	●	●	●	●	●	●
4. Loads								
Magnitude *(P, q)*	○	●	●	●	●	○	●	○
Position	○	●	●	●	●	○	●	○
5. Boundary conditions								
Pinned	○	●	●	●	●	○	●	○
Roller	○	○[5]	●	●	●	○	●	○
6. Design data								
Critical bending moment *(M_{cr})*	○	○	○[2]	●	○[2]	○	●	○
Resistance moment *($M_{b.Rd}$)*	○	○	○[2]	●	○[2]	○	●	○
Slenderness parameter (λ_{LT})	○	○	○[2]	●[4]	○[2]	○	○	○
Imperfection parameter (α_{LT})	○	○	○[2]	●[4]	○[2]	○	○	○
Reduction factor *(χ_{LT})*	○	○	○[2]	●[4]	○[2]	○	○	○
7. Results								
Deflection	○	●	○[2]	●	○[2]	○	●	○
Section forces	○	●	○[2]	●	○[2]	○	●	○
Code check *(EC3)*	○	○	○[2]	●	○[2]	○	●	○

Notes for table 3.2:

1) Sections properties standards in Dynamo are not available for any type of material; however, the user can create any cross section dimensions and extrude the length (L) in depth.
2) This parameter is not available in Revit.
3) Revit does not provide European steel sections as its defaults. The user must either (a) add a UK library to *Revit Library Content*, where UK library has European steel sections such as IPE, HEA, HEB, etc.; or (b) install *Revit Extensions* database tool to Revit for more standard sections.
4) Slenderness parameter (λ_{LT}) in Robot is 0.65, but it is 0.73 from the hand calculations. Thus, the imperfection parameter (α_{LT}) and reduction factor (χ_{LT}) and thereby the final member stability check (0.76) is deferent with no influence with compared to hand calculations (0.97).
5) Dynamo package *Structural Analysis for Dynamo* contains limited supports function, only fixed, pinned, free options are given. Roller and other supports types are not available.

Notes for figure 3.4:

1) The coordinate system differs for different software.
2) In Revit, the analytical line is in placed in the top surface of the column, but the analytical representation of the column is convergent to the centerline of the section, i.e. there is no influence to the final performed results for test steel column simply supported. However, the coordinate system should be taking into considerations with complex structures especially where connections located.
3) Coordinate system in both Revit and Robot is different compared to STAAD Pro, thus, it should take into consideration variation degree of freedom (DOF) *xxxfff* [1] i.e. Revit coordinates DOF is defined as *fxxfff* corresponding to *xxffff* in STAAD Pro.

1) (x) refers to a fixed degree of freedom while (f) refers to free degree of freedom. First three marks are related to translations in (X, Y, Z) and rest are related to rotations around (X, Y, Z).

3.2.3 EVALUATION OF TEST (1)

The first evaluation of simply supported steel column performed tests with BIM model is given depending on Table 3.11 tests results:

Dynamo	Result 1/5

In the first test, the Dynamo obtains one credit (1/5 rating) because many parameters are missing, since sections properties standards in Dynamo are not available for any type of material, however the user can create any cross section dimensions and extrude the length (L) in depth. Analytical performed properties area (A), section moment ($W_{el,y}$, $W_{pl,y}$) and moment of inertia (Iy, Ix) can only be performed by adding operation functions individually to calculate the specific parameter. No section forces and deflections can be obtained through Dynamo, consequently neither design parameters nor design calculations can be determined.

Dynamo Plug-In *(structural analysis for dynamo)*	Result 3/5

Dynamo plug-ins tool *structural analysis for dynamo* drives Dynamo through Robot directly, thus it allows using any common sections i.e. material properties are given, nodes may be support, section forces can be evaluated and deflections can be calculated. On other hand, there is no availability to assess the design criteria, where no design parameters could be found, and it is not possible to evaluate cross section resistance according to Eurocode.

RVT	Result 2.5/5

In Revit the cross section dimensions, specifications, boundary conditions and load can be defined, while the structural stability cannot be analyzed.

RVT ↔ RSA (Direct link and backwards)	Result 4/5

The direct link from Revit to Robot makes it possible to transfer the whole relevant data (BIM model, boundary conditions and loads) from Revit to Robot. It enables the determination of buckling length coefficient, consequently code check (buckling check) in RSA consists of the ability to perform both flexural-torsional buckling and whole lateral buckling parameters according to the general method [6.3.2.2] as well as a simplified method [6.3.2.4] related to EN 1993-1:2005/AC:2009.

All the relevant parameters can be transferred from Robot to Revit except design data and results, since structurally design criteria are not available in Revit.

RVT $\xrightarrow{CIS/2}$ RSA	Result 1/5

The CIS/2 Import/Export Revit extension gives the ability to transfer a steel BIM model from Revit to CIS/2 file format with limited analytical, drawing, detailing model without any transformation of boundary conditions or loading. Thereby CIS/2 is obtained low rating.

SPro	Result 4.5/5

In test of lateral buckling with STAAD Pro, steel section HEA100 does not fulfill check code requirement (EC-6.3.3-662) because of a warning notice is found related with roller support due to weak stability. Thereby another steel section (HEA160) has been chosen automatically where produces ratio (0.83).

RVT $\xrightarrow{ISM}$ SPro	Result 1/5

The last test with column buckling is performed with ISM indirect link between Revit and STAAD Pro. It lacks to export loads and boundary conditions and thereby it obtains only one star in ranking.

3.3 STRUCTURE-2 SIMPLY SUPPORTED TIMBER BEAM

The second structure, a timber simply supported is extracted from the course *AF2213, Steel and Timber Structures* given at KTH 2015. A 3.6 m beam length subjected to concentrated load of P_{Ed} = 7.40 kN and its line of action coincides with the symmetry plane of the cross-section as shown in figure 3.5 The beam is made of timber softwood C30 with a cross section 25x220 mm.

The maximum shear stress in the beam is also calculated. The beam is under service class 2 and medium-term load duration. The static system of the timber beam and the cross section are shown in figure 3.5.

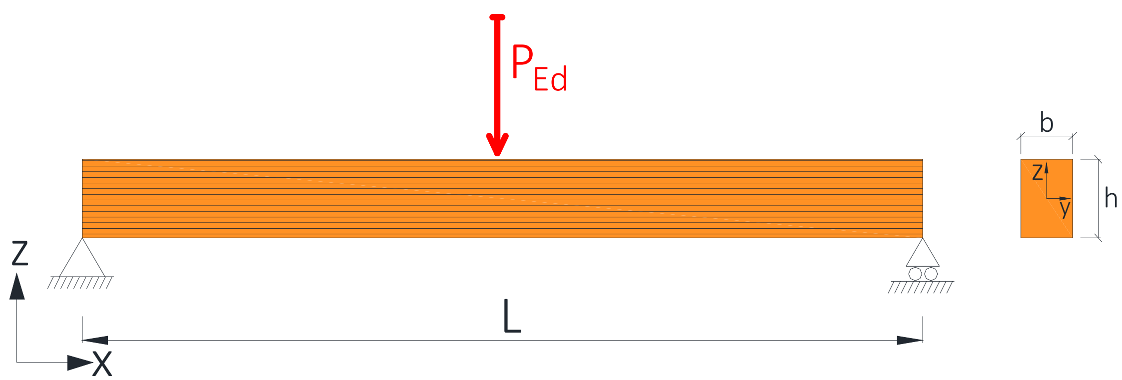

Figure 3.5: Left: Simply supported beam; Right: Cross section

A relevant design criterion for Structure 2 is determined according to EC5 (EN 1995-1-1), whereas the design criterion are[1]:

Table 3.3 Design criterion for analysis Structure 2

Design Criteria		Hand calculations	Robot Structural Analysis	STAAD Pro
Compression resistance	*EC5: 6.3.3*	EN 1995-1-1:2004	EN 1995-1:2004/A1:2008	EC5
Shear resistance	*EC5: 6.60*	EN 1993-1-1:2004	EN 1995-1:2004/A1:2008	EC5

In order to test the applicability of BIM and S-BIM software, the following changes are made:

- The used material (timber) in Karamba is VH1 instead of softwood C30, because of limited timber types.
- Coordination system (XYZ) is changed with different software.
- Glued laminated timber (GLT_D.Fir-L-20f-E) is used instead of softwood C30 in SPro.

(1) All the parameters needed to evaluate design criteria above are presented in Appendix B

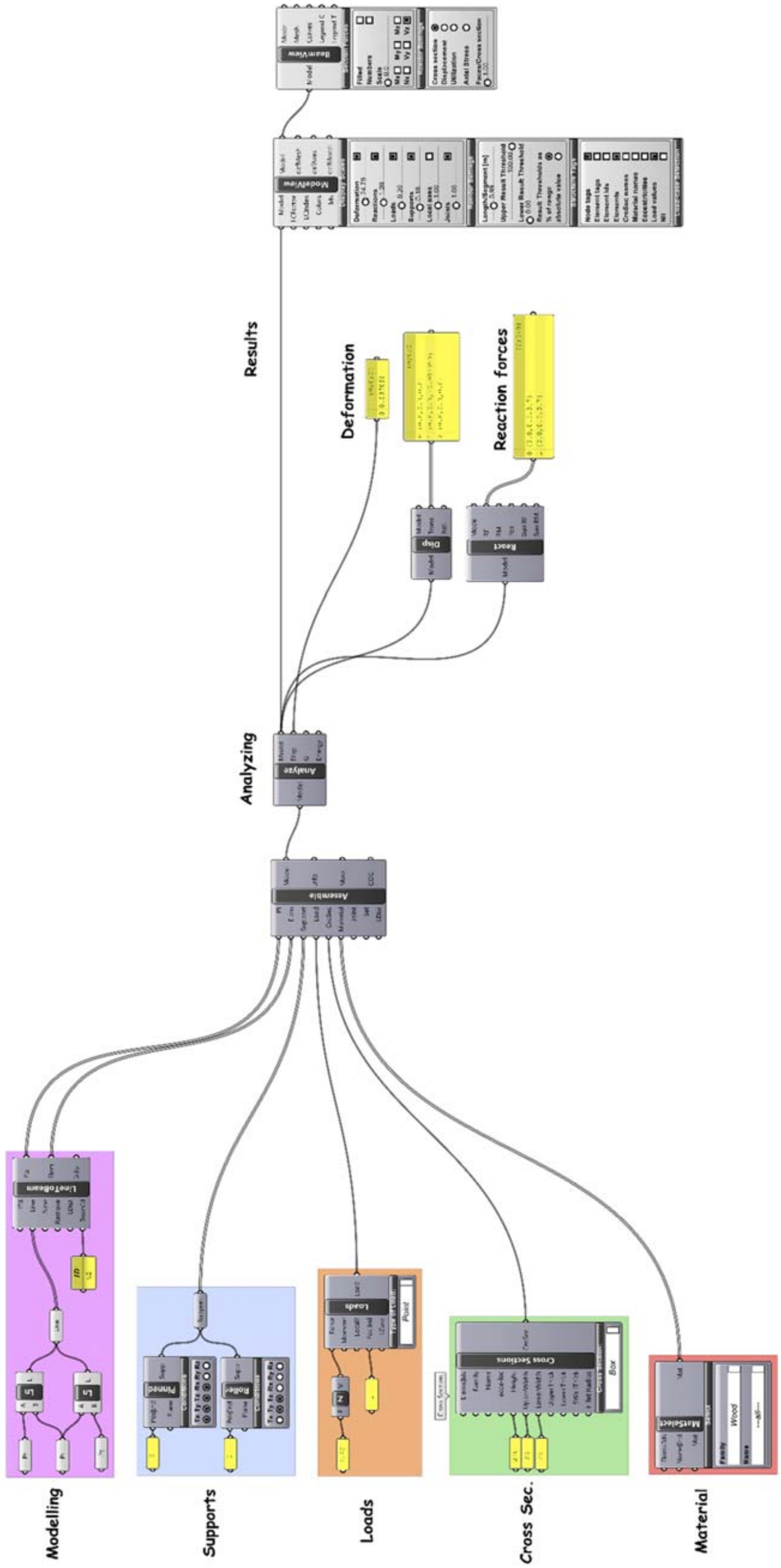

Figure 3.6: Algorithm modelling shapes used through Rhinoceros and Karamba in Structure 2

3.3.1 RESULTS OF TEST (2)

For simply supported timber beam, the applicability of modelling and structural BIM (S-BIM) tools is tested based on design criterion which already described in Table 3.3 and the design parameters described in Appendix B.1

The procedures leading to the results in Table 3.4 request different choices. The two test procedures related with visual logic (Grasshopper) and S-BIM tools are described in detail in Appendix B.2 Test two procedures screen dumps of the timber beam modelled are shown in Figures 3.7-3.10 respectively.

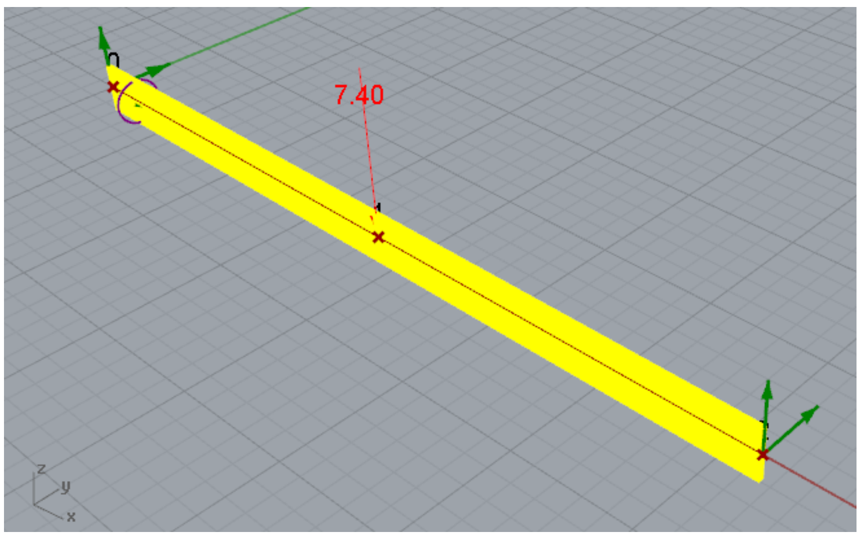

Figure 3.7: Timber beam model with mid-span load in Rhino (GH+K plug-Ins)

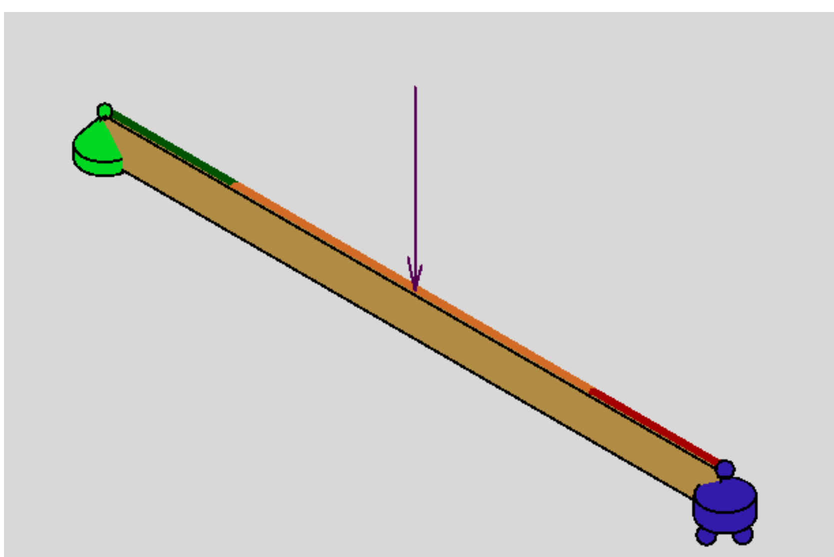

Figure 3.8: Timber beam model with mid-span load in Revit

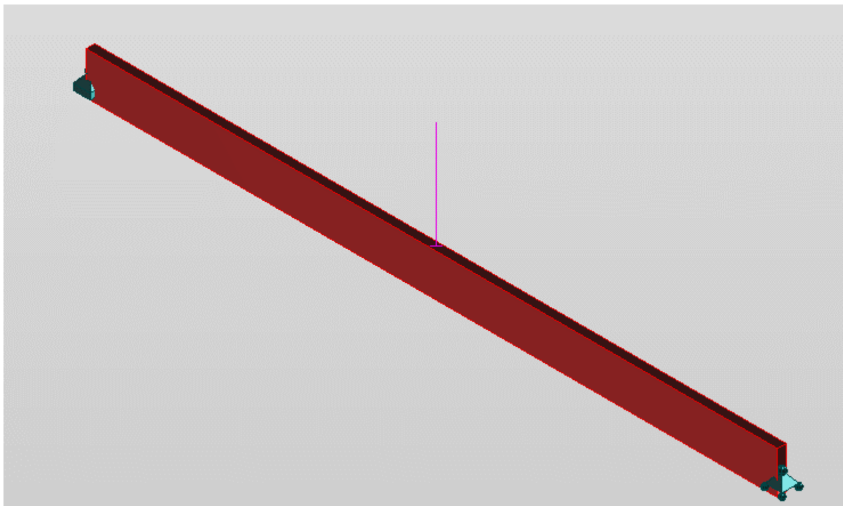

Figure 3.9: Timber beam model with mid-span load in Robot structural analysis

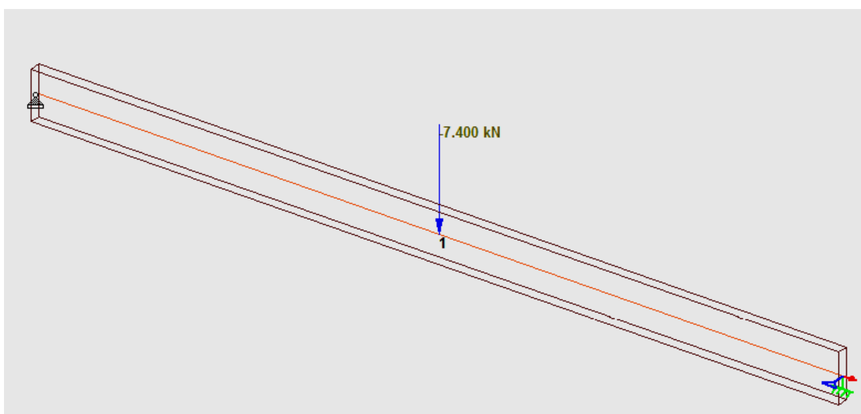

Figure 3.10: Timber beam model with mid-span load in STAAD Pro.

Table 3.4: Moment resistance test results for simply supported timber beam
● *refers to no problem or error occurs while* ○ *refers to feature does not work or parameter is not available*

Description	Rhino	Rhino ↑↓ *K* GH	RVT	RVT ↓ RSA	RSA ↓ RVT	RVT ↓ IFC RSA	SPro	RVT ↓ ISM SPro
1. Section properties								
Height *(h)*	●[1]	●[1]	●[1]	●	●	●	●	○
Width *(b)*	●[1]	●[1]	●[1]	●	●	●	●	○
Area *(A)*	○	○	●[1]	●	●	●	●	○
2. Geometry								
Length *(L)*	●	●	●	●	●	●	●	●
3. Material properties								
Bending strength $(f_{m,k})$	○[2]	○	●[3]	●	●	○	○	○[6]
Compressive strength $(f_{c,0,k})$	○[2]	○	●[3]	●	●	○	○	○[6]
Modulus of elasticity *(E)*	○[2]	○	●[3]	●	●	○	●[5]	○[6]
Shear modulus *(G)*	○[2]	○	●[3]	●	●	○	●[5]	○[6]
Weight *(W)*	○[2]	○	●[3]	●	●	○	●[5]	○[6]
4. Loads								
Magnitude *(q)*	○	●	●	●	●	○	●	○
Position	○	●	●	●	●	○	●	○
Duration class	○	○	○	●	○	○	●	○
5. Boundary conditions								
Pinned	○	●	●	●	●	○	●	○
Roller	○	●	●	●	●	○	●	○
6. Design data								
Bending strength $(f_{m,d})$	○	○[4]	●[3]	●	●	○[4]	○	○
Shear strength $(f_{v,d})$	○	○[4]	●[3]	●	●	○[4]	○	○
Service class	○	○[4]	○	●	○[4]	○[4]	●	○
Modification factor (k_{mod})	○	○[4]	○	●	○[4]	○[4]	○	○
Volume factor (k_h)	○	○[4]	○	●	○[4]	○[4]	○	○
System effect factor (k_{sys})	○	○[4]	○	●	○[4]	○[4]	○	○
Reduction parameter (k_{cr})	○	○[4]	○	●	○[4]	○[4]	○	○
7. Results								
Section forces	○	●	○	●	○[4]	○	●	○
Deflections	○	●	○	●	○[4]	○	●	○
Code check *(EC5)*	○	○	○	●	○[4]	○	●	○

Notes for Table 3.4:

1) For the given cross section (25x220 mm), a user define is used to define height, width and area.
2) Karamba S-BIM tool for Rhino has a limited timber material type VH-I, VH-II, VH-III.
3) For softwood timber type C30, S-BIM tool Revit Extensions are used to recall Europe timber standards with its mechanical and strength properties, since Revit 2015 libraries do not provide all types of timber.
4) Parameters are not available in Revit.
5) Section database timber in STAAD Pro only provides AITC timber tables for American and Canadian timber.
6) Parameters transferred with wrong values.

Notes for Figures 3.7 - 3.10:

1) The coordinate system differs for different software.
2) Due to different coordinate system (XYZ), degree of freedom (DOF) *xxxfff* [1] i.e. Revit coordinates DOF is defined as *fxxfff* corresponding to *xxxxff* in Karamba for pinned support, roller is defined *fxxfff* respectively.
3) In both Rhino and STAAD Pro the analytical line in placed in in the mid surface of the beam. In Revit, the analytical line in placed in the top surface of the beam, while the analytical representation of the beam is convergent to the centerline of the section (i.e. there is no influence to the final performed results for test timber beam simply supported). However, the coordinate system should be taking into consideration with complex structures especially where connections located.

1) (*x*) refers to a fixed degree of freedom while (*f*) refers to free degree of freedom. First three marks are related to translations in (X, Y, Z) and rest are related to rotations around (X, Y, Z).

3.3.3 EVALUATION OF TEST (2)

The second evaluation of timber simply supported beam performed tests with BIM model is given depending on Table 3.4 tests results:

Rhino	**Result 0/5**

In Rhino, it is not possible to run any analysis process, and design criteria cannot be assessed. Rhino is an excellent software to model a complex structures and it is easy to modifications through NURBS.

Rhino $\xrightarrow{K}$ GH	**Result 2.5/5**

With S-BIM, plug-in Karamba can handle loading, boundary conditions and enable to compute deflections and section forces. It does however lack the possibility to import specific characterizations i.e. material (wood) types. It cannot be used to make checks according to EC3 and cannot be used to compute design parameters and factors.

Revit	**Result 2.5/5**

In Revit, the cross section dimensions, specifications, boundary conditions, and load are defined but the design criteria cannot be assessed, since no design parameters and factors can be determined.

Revit ↔ RSA (Direct link and backwards)	**Result 4/5**

With the direct link from Revit to Robot, it is possible to transfer the whole relevant data (BIM model, boundary conditions and loads) from Revit to RSA.

All the relevant parameters can be transferred from RSA to Revit except design data and results, since structurally design criteria are not available in Revit.

CHAPTER 4

ANALYSIS OF S-BIM TOOLS (IFC, CIS/2) FOR 3D STEEL STRUCTURE

In this chapter, three of the S-BIM tools which presented in chapter two are analyzed through a three-dimensional steel structure. An evaluation has been presented after the analysis and obtaining results is followed at the end of this chapter.

4.1 INTRODUCTION

In this chapter, the applicability of S-BIM tools is tested with a three dimensional steel structure from *Steel Building Design: Worked examples for students*. A non-typical of building design is choosing because the structural solutions demonstrate a range of design solutions. The building area is 672 m^2 with five stories (including roof). The project design is shown in figures 4.1-4.2. The building consists of precast floor units and steel members. The three dimensional steel structure considered in this study is a steel end plate connection. An overview of the steel structure is shown in figure 4.4. The structure is chosen to see if the S-BIM tools (IFC,CIS/2) are capable to handle a structure which is more advance than a simple structures in chapter three. The structure is more advanced in the sense that several members are joint together in three dimensions and the total form of the structure does not follow any traditional geometric shape.

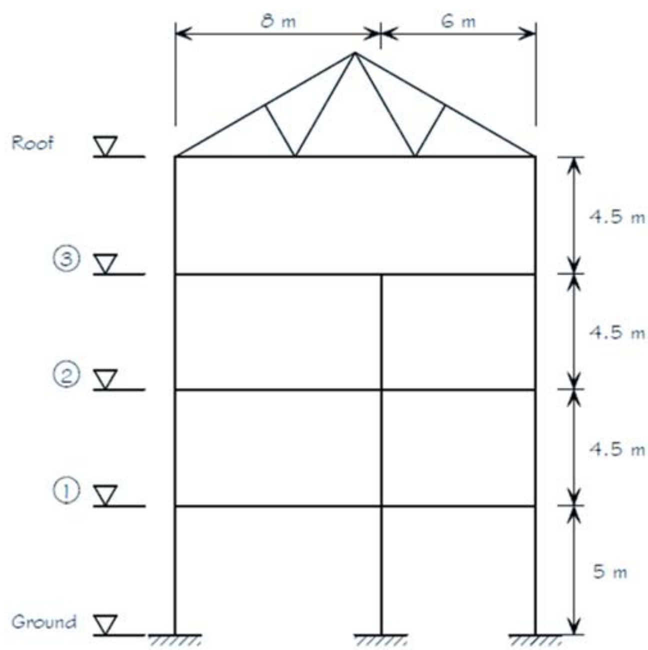

Figure 4.1: Cross section of the building

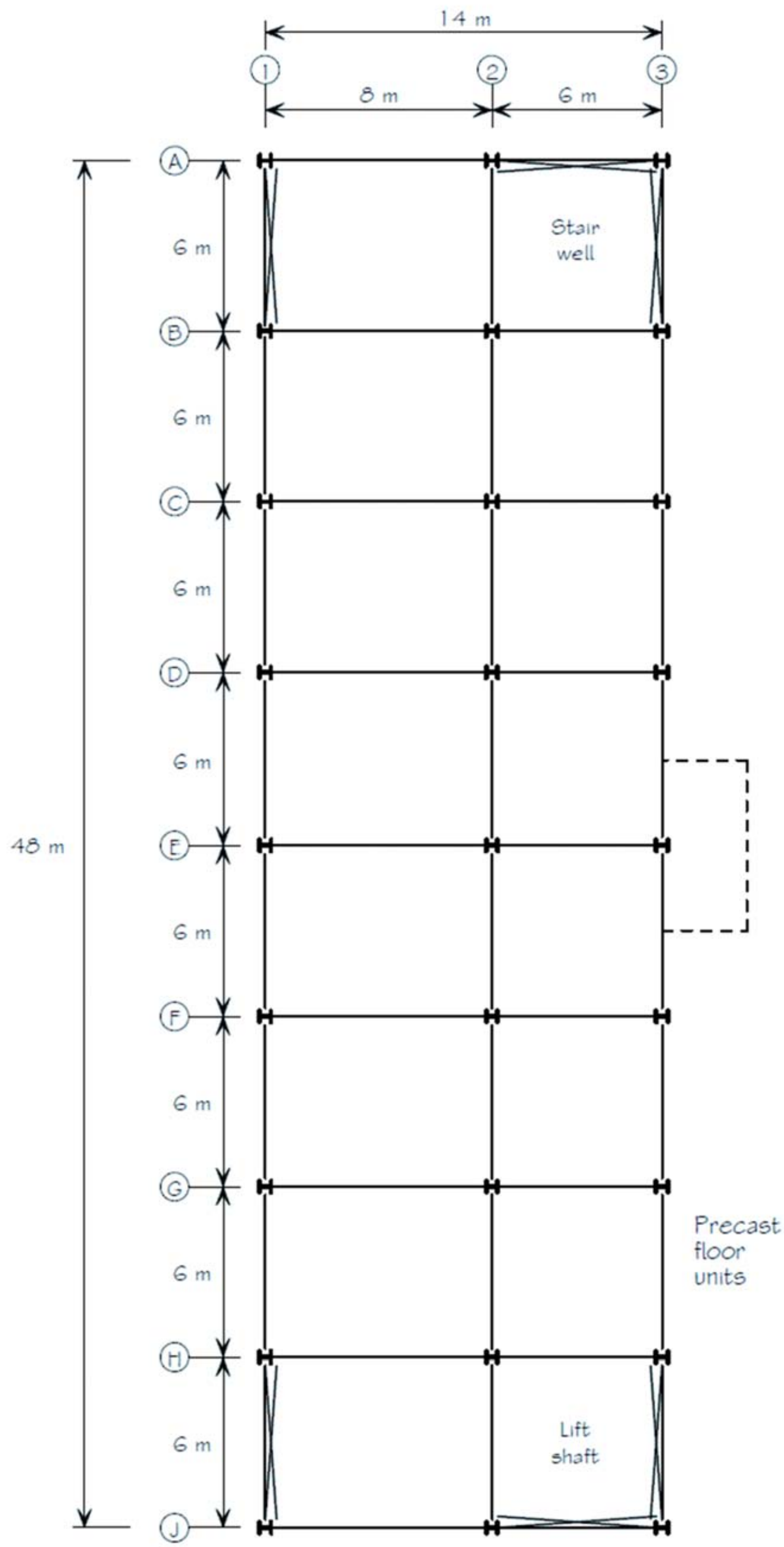

Figure 4.2: floor plan of the building

4.2 ANALYSIS METHODS

The particular method used in this chapter corresponds with the method in Chapter 2. However, an additional aspect of data exchange is considered, since the three dimensional steel structure (BIM model) has been modelled in Tekla Structures. In order to able to perform the S-BIM tests, the steel structure is exported to Revit. The information flow treated in this chapter is shown in figure 4.3.

Figure 4.3: The workflow information from BIM process to FEM results for Structure 3

The following methods are used for export to Revit and STAAD Pro:

- Export from Tekla to Revit via a DWG file (Tekla $\xrightarrow{dwg}$ RVT)
- Export from Tekla to Revit via a IFC file (Tekla $\xrightarrow{ifc}$ RVT)
- Export from Tekla to Revit via a CIS/2 file (Tekla $\xrightarrow{cis/2}$ RVT)
- Export from Robot to Revit via a CIS/2 file (RSA $\xrightarrow{cis/2}$ RVT)
- Export from Tekla to Revit via a direct link from Autodesk (RSA $\xrightarrow{Add-Ins}$ RVT)
- Export to STAAD Pro via a CIS/2 file (Tekla $\xrightarrow{cis/2}$ SPro)

The following S-BIM tools have been tested:

- Indirect link IFC between TEK and RVT.
- Indirect link CIS/2 between TEK and RVT.
- Indirect link CIS/2 between RSA and RVT.

The S-BIM tools must contain the ability to handle the parameters described in Chapter 3. These parameters are:

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

In addition to the described design parameters, the S-BIM tools must be able to deal with the issue related with the three dimensional analytical model. The structural members are jointed via steel connections with bolts, welds and plates. It is significant that the analytical model corresponds to the physical model. It can probably be an issue since by default the analytical line of a beam is located at the top surface of the element in Revit whereas it is at center of cross section in both RSA and SPro.

In this chapter, the calculations are made by hand as well as with RSA and SPro software and the parameters necessary for analysis are listed. The applicability of the S-BIM tools is compared to the design criteria of Eurocode 3.

4.3 TESTS BASIS

The steel structure of study has been obtained from "Steel Building Design: Worked examples for students[1] " is built of traditional steel members (beams and columns) with British special profiles 254 × 254 × 73 UKC for columns and 457 × 191 × 82 UKB for beams. The perspective structure has 48 m long, 14 m wide and approximately 23.5 m height (Figure 4.4).

The steel structure is subject to its own weight and imposed loads (ULS) 57.4 kN/m. All elements are modelled as steel type S275. The relevant design criteria for Eurocode (EC3) of the steel column are as listed in table 4.1.

Table 4.1: Design criterion for analysis Structure 3

Design Criteria		Hand calculations	Robot Structural Analysis	STAAD Pro
Bending moment	*EC3: 6.2.5*	EN 1993-1-1:2003	EN 1993-1:2005/AC:2009	EN-1-1:2005
Shear resistance	*EC3: 6.2.6*	EN 1993-1-1:2003	EN 1993-1:2005/AC:2009	EN-1-1:2005
Torsion resistance	*EC3: 6.2.6-7*	EN 1993-1-1:2003	EN 1993-1:2005/AC:2009	EN-1-1:2005

The members and connection to which the design criteria are relevant are shown in Table 4.2, the parameters needed to evaluate design criteria are presented in Appendix C.1

Table 4.2: Design criterion for analysis Structure 3

Design Criteria		Member	
• Bending moment	*EC3: 6.2.5*	18	
• Shear resistance	*EC3: 6.3.1-6.3.2*	18	
• Flexural Buckling resistance	*EC3: 6.2.6-7*	14	G2
• Lateral Torsional resistance	*EC3: 6.3.2*	14	
• Deflection	*BS EN 1993-1-1*	18	
• Design of Joints	*EC3: 1.8*		G2

For ultimate limit state in 3D steel structure modeling, partial factors are applied to the loads, since the amount of loads is irrelevant in order to evaluate the S-BIM tools and results.

[1] (2009). Steel Building Design: Worked examples for students In accordance with Eurocodes and the UK National Annexes, from http://www.tatasteelconstruction.com/file_source/StaticFiles/Construction/p387.pdf

In order to investigate the applicability among software, some modifications are made in material properties in modeling with Tekla. Profile sections of structure are changed from UK types to Eurocode library types because of wide use in Sweden. The new modified profiles are:

- Column profiles are changed to HEB260
- Beams profiles are changed to IPE450
- Steel type is changed to S275J0

The changes are chosen to show how 3D BIM model and S-BIM tools will handle the parameters groups presented in Chapter 2.

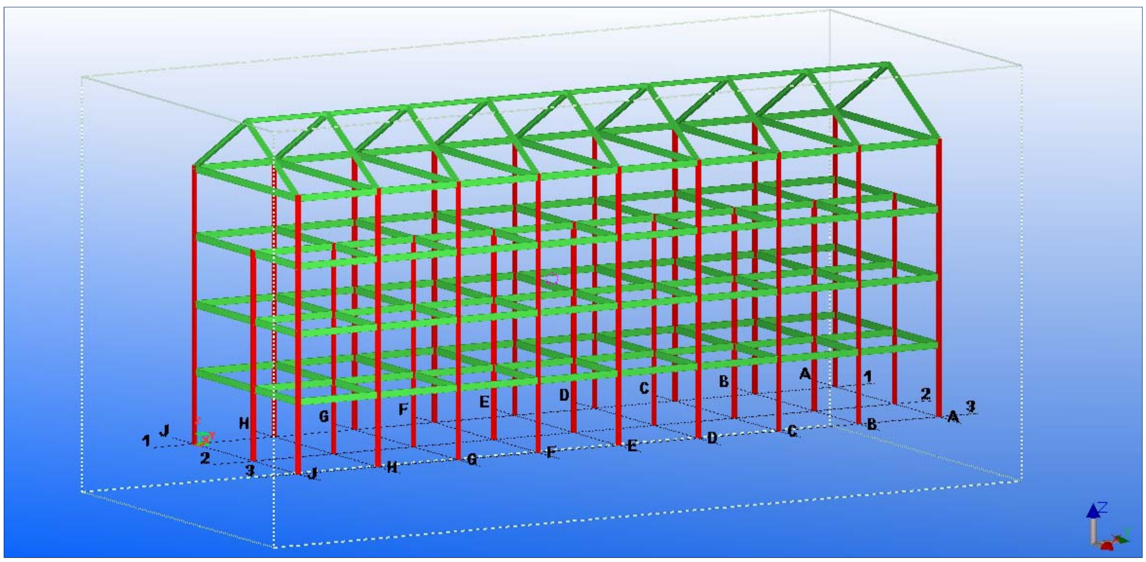

Figure 4.4: 3D building BIM modelled in Tekla

4.4 DATA EXCHANGE FROM TEKLA STRUCTURES (BIM) TO REVIT

The research to date has tended to focus on the exchange of data between the S-BIM software and the FEM software. However, there has been little discussion about the exchange of data from the BIM (model) to the S-BIM software, which is needed to accomplish the investigation. The three-dimensional (3D) steel structure has been modelled in Tekla Structures.

The three-dimensional steel structure is available as a DWG file (*.dwg), IFC file (*.ifc) and CIS/2 file (*.stp) to test S-BIM modelling in Revit.

An analytical representation of the three-dimensional steel structure is needed to exchange data between the S-BIM software and the FEM software. Therefore, importing the structure from the three file formats (*.dwg), (*.ifc) and (*.stp) to Revit was done to determine which file format of the three provides the best representation of the structure in Revit.

The procedure leading to the results obtained in Revit, after importing from Tekla Structures by use of the different file formats, are described in Appendix C. After importing from Tekla Structures using the three file formats, the procedure leading to the results obtained in Revit are presented in Appendix C.2. The results revised in the following text:

4.4.1 EXPORT TO REVIT VIA IFC (TEK $\xrightarrow{.ifc}$ RVT)

The 3D steel structure from the IFC file does not appear as a block similar to DWG, however the BIM model is missing structural data such as loads and boundary conditions. The entire members profiles (IPE450, HEB260) are transferred correctly via IFC. It enables to add missing data manually into Revit.

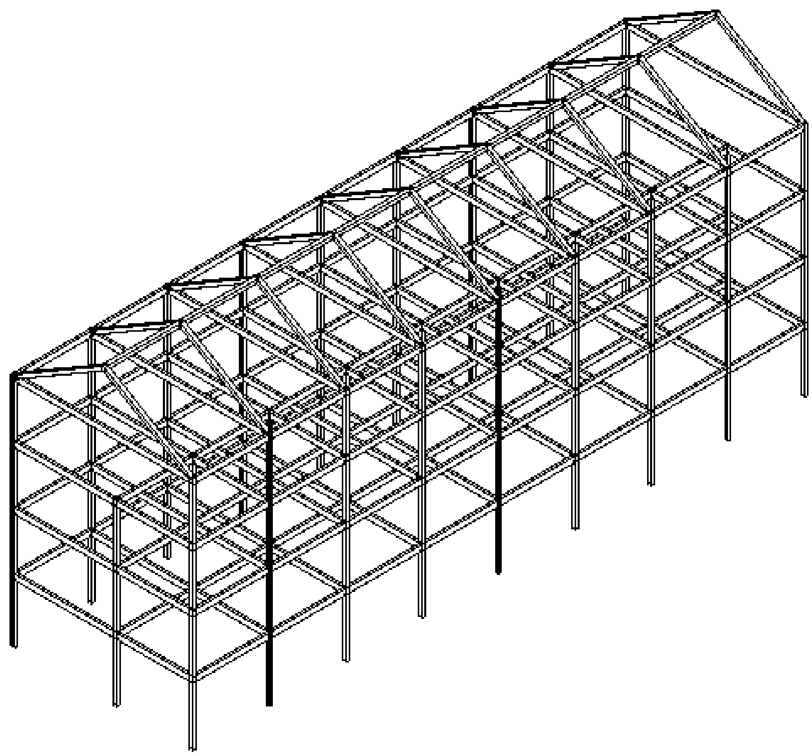

Figure 4.5: The 3D steel structure after export to Revit via IFC format.

4.4.2 EXPORT TO REVIT VIA CIS/2 (TEK $\xrightarrow{.stp}$ RVT)

Similar to IFC format file, the transferred model through using *Extensions* ribbon into Revit *CIS/2 import/export* results in the physical representation for each member of the 3D steel structure in Revit showing lengths and material properties. However, neither loads nor boundary conditions could be transferred via CIS/2. However, it is possible to add the missing data manually.

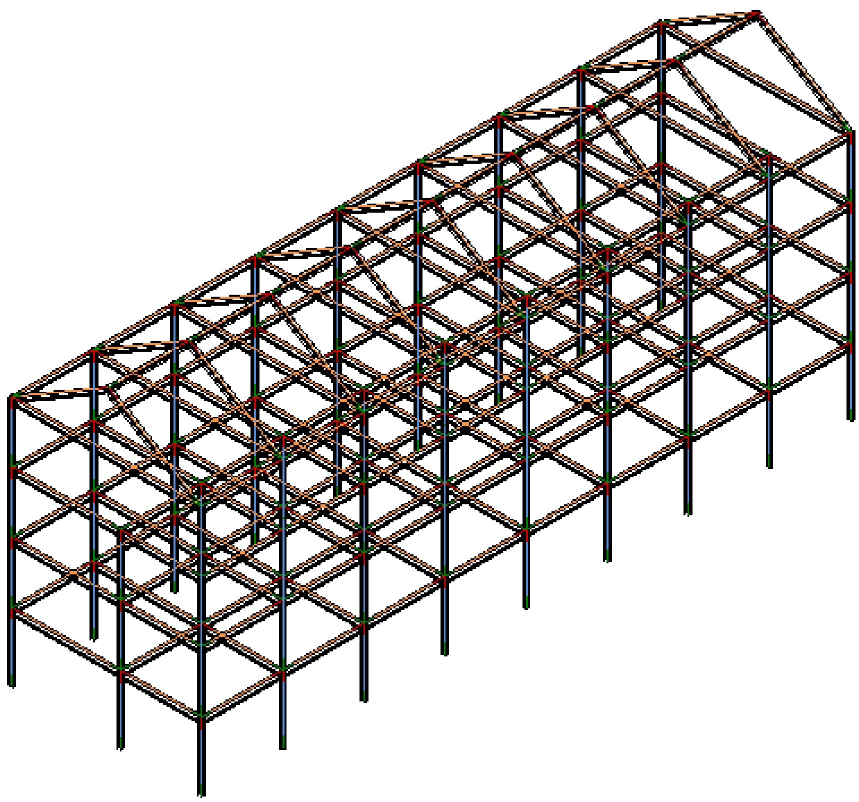

Figure 4.6: The 3D steel structure after export to Revit via CIS/2 format.

4.4.3 EXPORT TO REVIT VIA DWG (TEK $\xrightarrow{.dwg}$ RVT)

The 3D steel structure from the DWG file appears as a block in Revit and the elements are only represented by lines. It is a rather inadequate representation of the structure as the member can neither be shown as geometric objects nor applied in an analytical model.

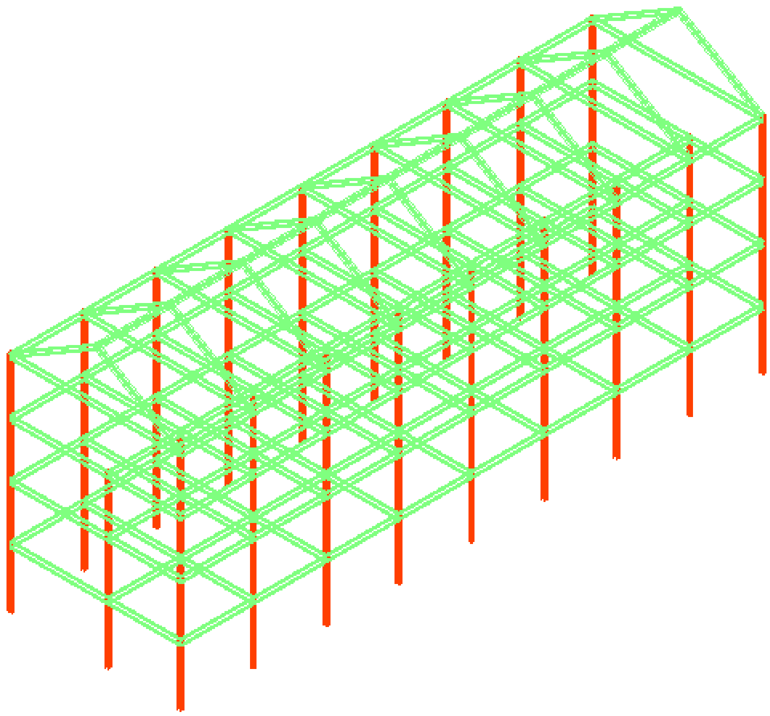

Figure 4.7: The 3D steel structure after export to Revit via DWG format.

The exchange of data from the BIM model to the S-BIM software represents just a part of the information flow in the structural design process. The exchange of data between the S-BIM software and the FEM software will be discussed in the next sections of this chapter. The exchange of data should work well in the two parts of the process to obtain an efficient information flow.

The tests results showed that the three file formats did not give a satisfactory representation of the 3D steel structure after exporting to Revit. This could be due to the file formats or due to the Revit. However, in both cases, there was a lack of the information flow in the first part of the process.

4.5 BIM MODELLING AND ANALYSIS HANDLING ISSUES

As mentioned before, the three exported files formats IFC (*.ifc), CIS/2 (*.stp), CAD (*.dwg) did not give a satisfying representation of the 3D steel structure. Therefore, modeling the structure from the bottom should be implemented to achieve a proper representation. However, since the structure was modelled in Robot, the steel structure is available in the RSA file format (*.rtd). Thus, to obtain a complete model of the 3D steel structure, the (*.rtd) file was used.

In Robot, the model is saved as a (*.stp) file format which afterwards can be exported to Revit to investigate the implement of BIM environment for 3D model.

4.5.1 EXPORT TO REVIT VIA CIS/2 (RSA $\xrightarrow{.stp}$ RVT)

The workflow of the exporting BIM from Robot to Revit through CIS/2 format is shown in figure 4.8. **Analytical model** is selected instead of **Drawing model** in *Extensions* S-BIM tool panel in exporting process to investigate the ability to transport loading and boundary conditions as a structural analysis design. All the 276 elements of 3D frame structure could be imported into Revit without any error or warning.

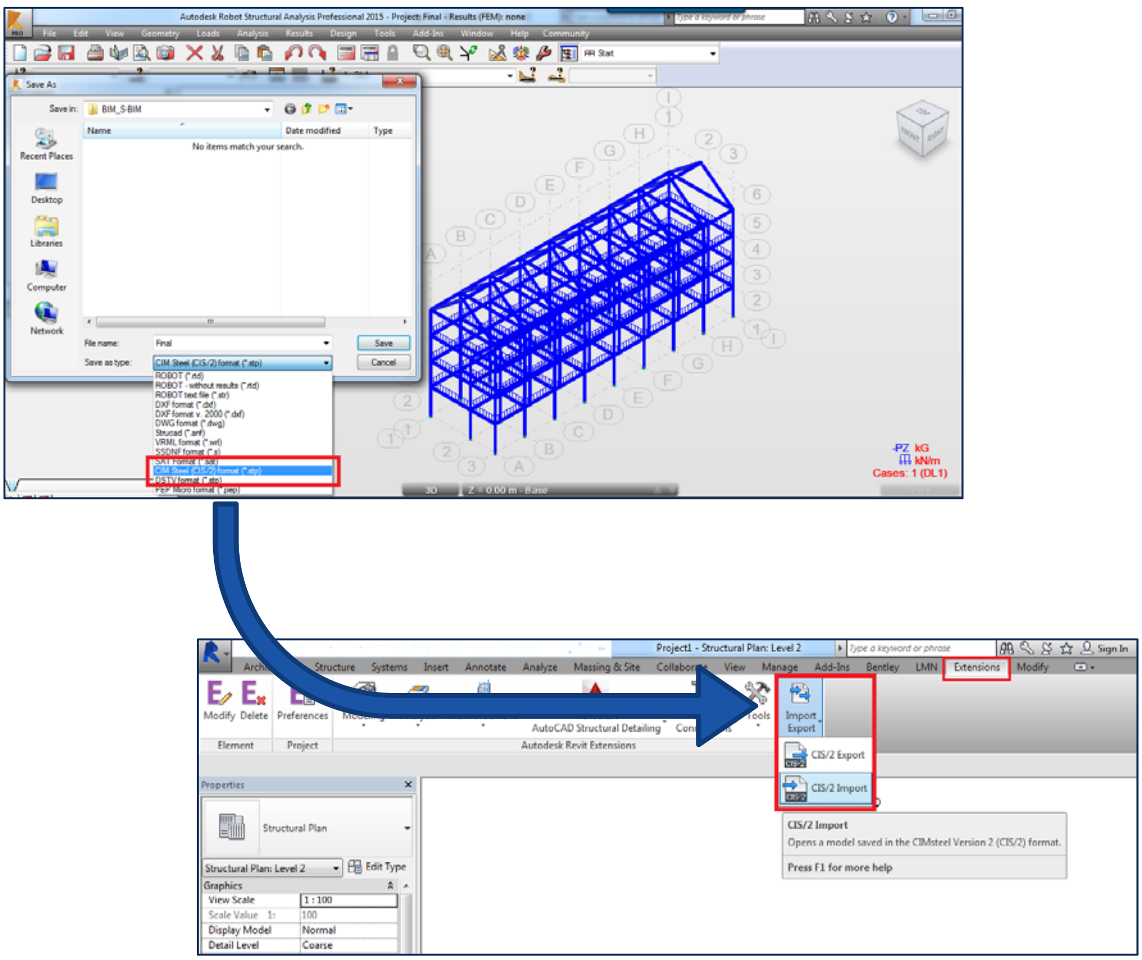

Figure 4.8: Using Revit Extensions CIS/2 in exporting 3D BIM model

4.5.2 ADD-INS (INTEGRATION) LINK BETWEEN ROBOT AND REVIT (RSA $\xrightarrow{Add-Ins}$ RVT)

As a second method of investigating the relationship between Autodesk software (Revit and Robot), an own link provided from Autodesk which including under Add-Ins wizard is used. No warnings or error messages appear during the linking and the loads and boundary conditions were correctly transferred to Revit with all 276 elements with their material properties and profiles.

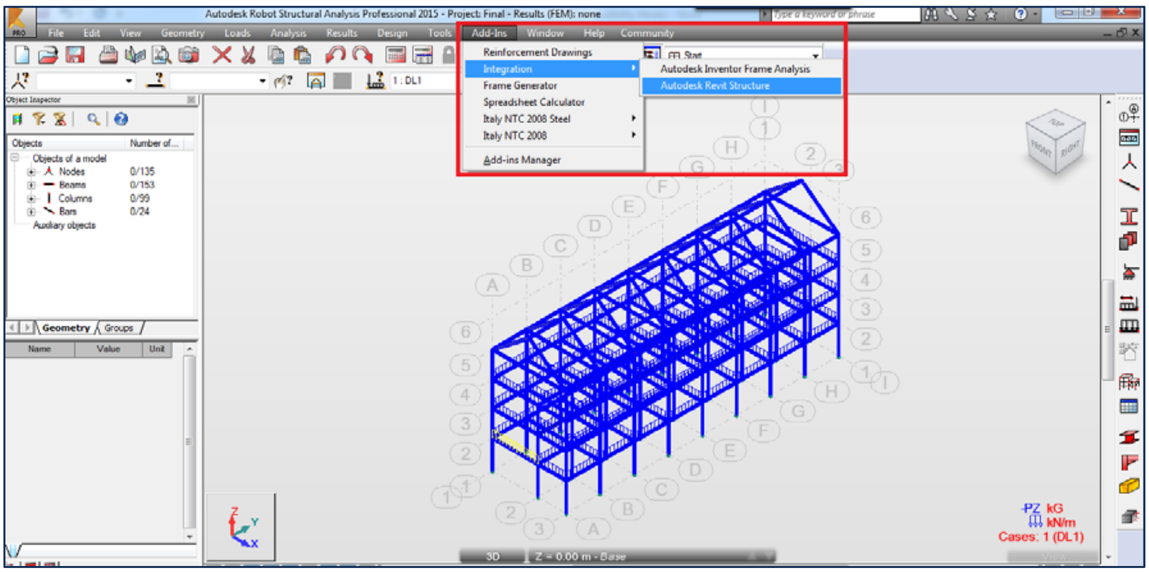

Figure 4.9: Using Autodesk Add-Ins tool in exporting 3D BIM model to Revit

The 3D frame structure using Add-Ins (Integration) and CIS/2 Revit *Extensions* are shown in figures 4.10-4.11 respectively. The 3D steel structure of some S-BIM tools lack the loads and boundary conditions while it is sometimes possible to add missing data manually. The analytical model influences the tests results.

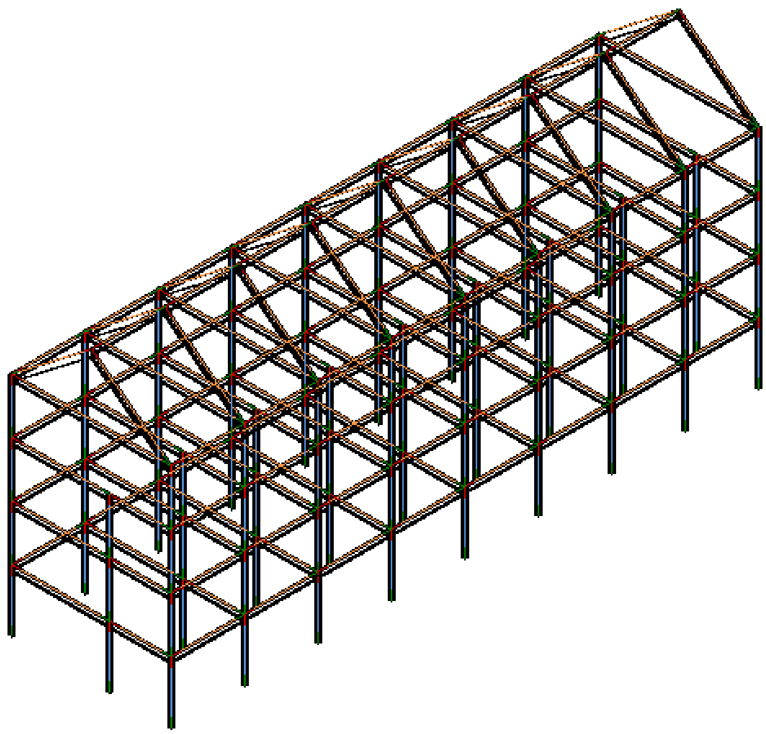

Figure 4.10: Structure perspective after exporting to Revit via CIS

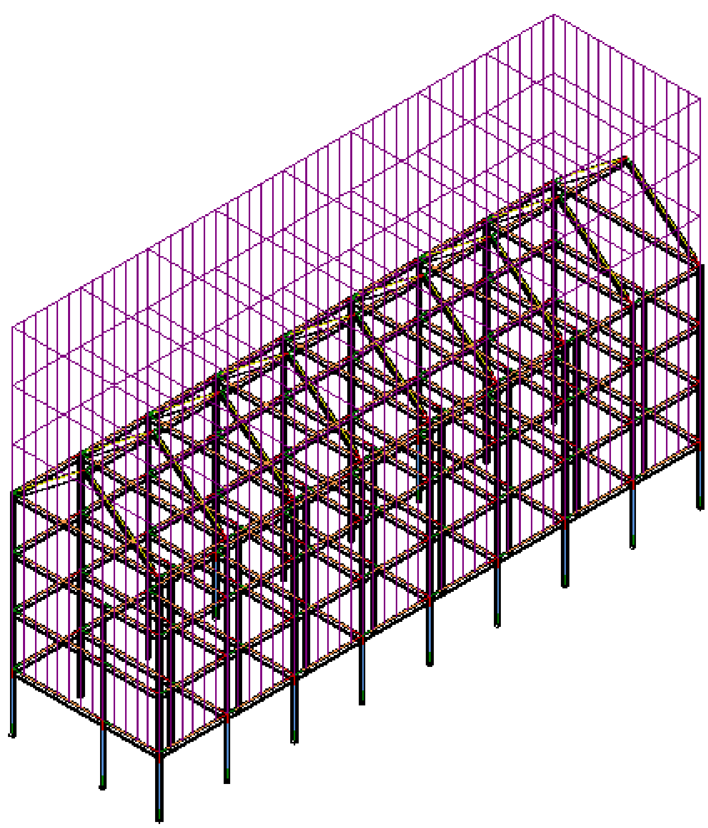

Figure 4.11: Structure perspective after exporting to Revit via Integration

4.6 RESULTS OF TESTS

The applicability of S-BIM for 3D steel structure is tested in terms of the following:

- Design criteria which described in section 4.3.
- Described procedures in Appendix C.3
- Design parameters and hand calculations in Appendix C.3

The 3D tests results are shown in table 4.3 on page 63.

Beam 18, column 14, and end plate connection G2 (beam to column flexible end plate connection at level 1 between gridline G and 2) are selected as elements and connection to be analyzed through S-BIM tools.

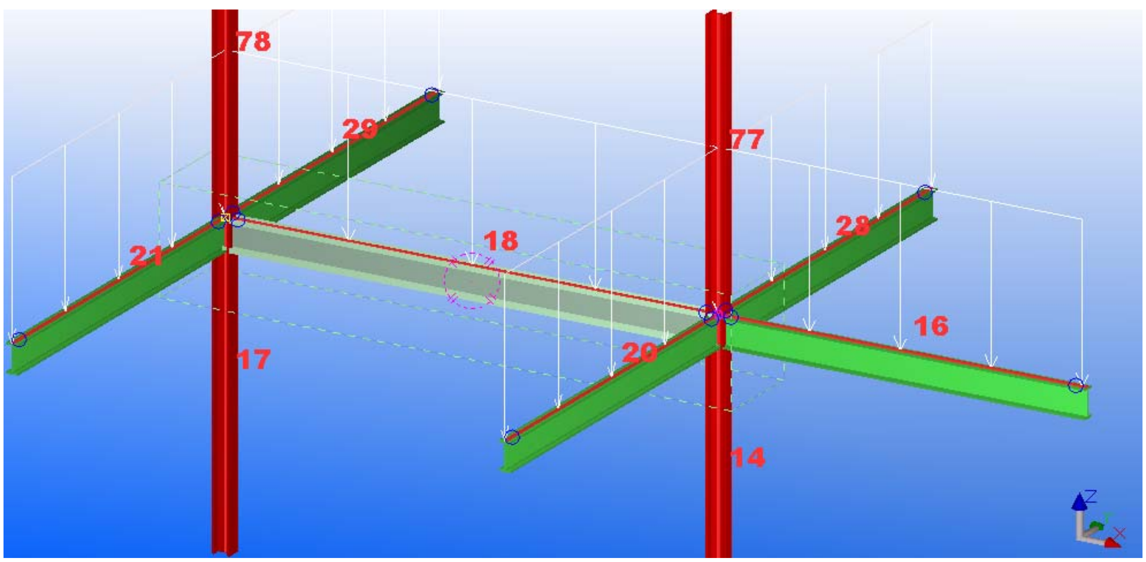

Figure 4.12: Selected study beam in 3D building BIM

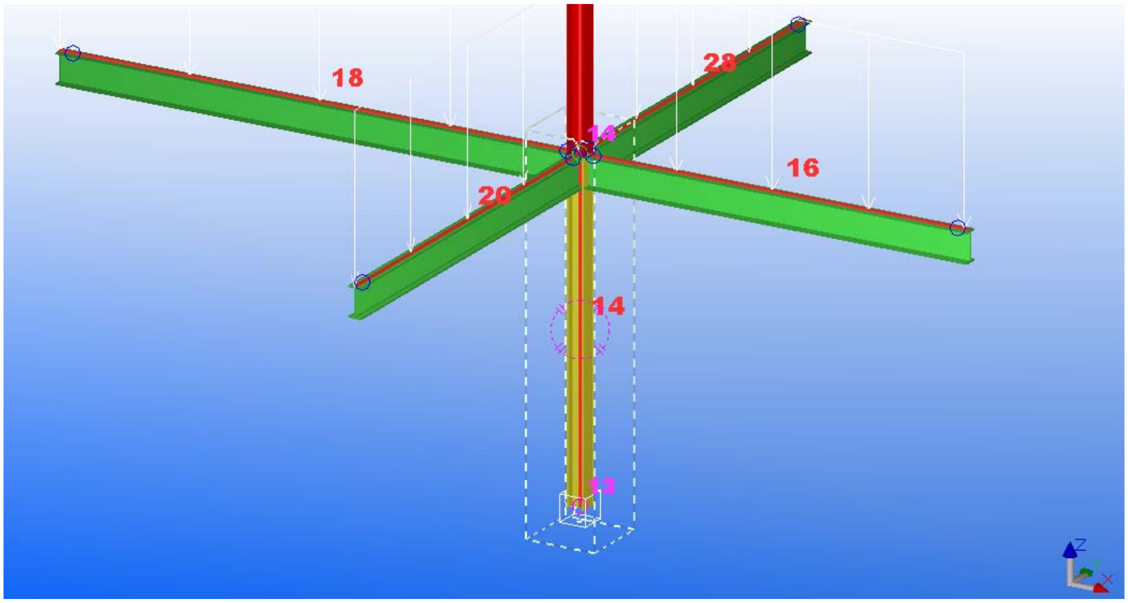

Figure 4.13: Selected study Column in 3D building BIM

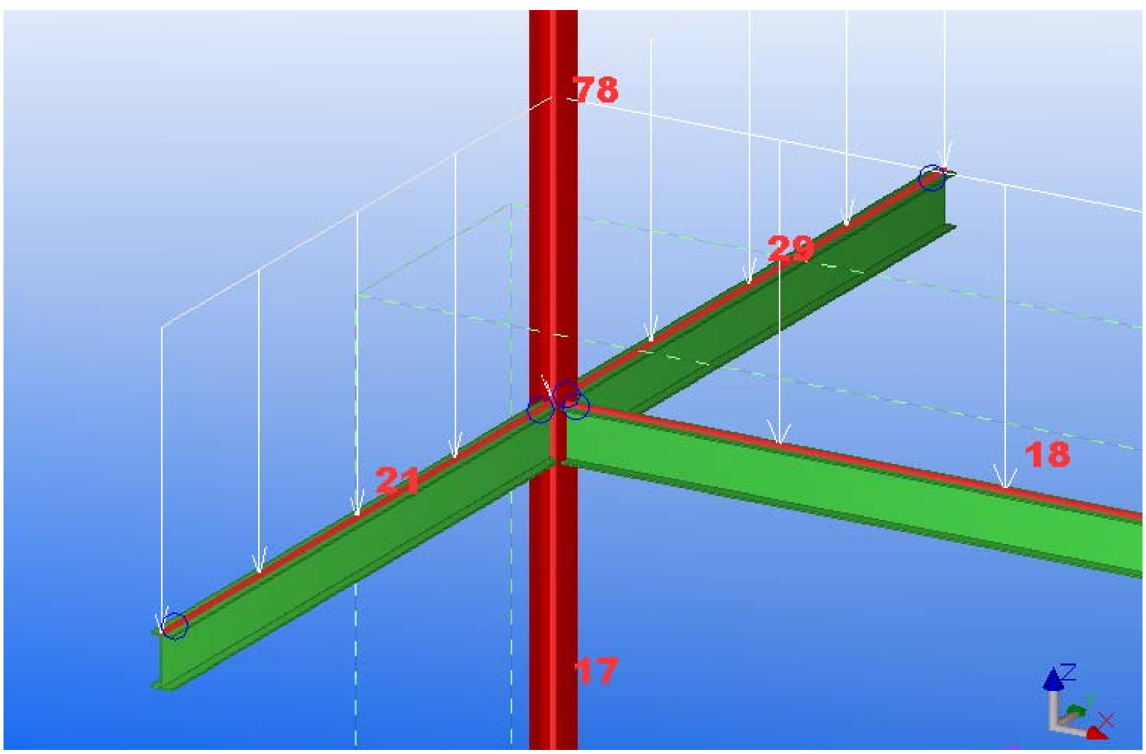

Figure 4.14: Selected study beam to column connection in 3D building BIM

Table 4.3: Moment resistance test results for 3D steel structure

● *refers to no problem or error occurs while* ○ *refers to feature does not work or parameter is not available*

Description	TEK	TEK ↓ IFC RVT	TEK ↓ CIS/2 RVT	RSA	RSA ↓ Add – Ins RVT	RSA ↓ CIS/2 RVT	RSA ↓ CIS/2 SPro
Section properties							
Height *(h)*	●	●	●	●	●	●	● [5,6,7]
Width *(b)*	●	●	●	●	●	●	● [5,6,7]
Web thickness (t_w)	●	●	●	●	●	●	● [5,6,7]
Flange thickness (t_f)	●	●	●	●	●	●	● [5,6,7]
Radius *(r)*	●	●	●	●	●	●	● [5,6,7]
Area *(A)*	●	●	●	●	●	●	● [5,6,7]
Shear area *(Ay, Az)*	●	●	●	●	●	●	● [5,6,7]
Moment of inertia *(Iy, Iz)*	●	●	●	●	●	●	● [5,6,7]
Section modulus *(Wy)*	●	●	●	●	●	●	● [5,6,7]
Geometry							
Length *(L)*	●	○ [2]	●	●	●	●	●
Material properties							
Yield stress *(fy)*	●	●	●	●	●	○	● [7]
Modulus of elasticity *(E)*	●	○	●	●	●	○	● [7]
Shear modulus *(G)*	○	○	●	●	●	○	● [7]
Density (ρ)	●	○	●	●	●	○	● [7]
Loads							
Magnitude *(q)*	●	○ [2]	○	●	●	○	○
Position	●	○ [2]	○	●	●	○	○
Boundary conditions							
Fixed	●	○ [2]	●	●	○	○	●
Design data							
Normal capacity *(Ncr), (Npl,R)*	○ [3]	○ [2,3]	○ [3]	●	○ [4]	○ [4]	●
Shear capacity *(Vc,R)*	○ [3]	○ [2,3]	○ [3]	●	○ [4]	○ [4]	●
Resistance bending moment *(Mpl.Rd)*	○ [3]	○ [2,3]	○ [3]	●	○ [4]	○ [4]	●
Results							
Section forces	○ [3]	○ [2,3]	○ [3]	●	○ [4]	○ [4]	○
Deflections	○ [3]	○ [2,3]	○ [3]	●	○ [4]	○ [4]	○
Design Code check *(EC3)*	● [1]	○ [2,3]	○ [3]	●	○ [4]	○ [4]	○

Notes for table 3.2:

1) Tekla for non-commercial uses only provides design check code for steel structures and thereby no results could be determined because there is no ability to link Tekla model with FEM analysis software such as SAP2000, RSA, etc. Furthermore, no ability to use S-BIM tools such as IFC and CIS/2.
2) Unfortunately, there is no ability to read loading and boundary conditions.
3) Because a non-commercial version of Tekla was used, the, the analysis process handling is disable, thereby S-BIM tools (IFC and CIS/2) into RVT environment are lacking the analysis results.
4) This parameter is not available in Revit.
5) During transfer a 3D analysis model from RSA to SPRO via CIS/2 format, some data was lost:
   A) All columns steel profiles HEB260 are missing, however, a user can assign this type with HE260B (same section properties with HEB260) under European-section profile sections wizard and should consider the difference between axes names for Y, Z. Since moment of inertia I_y, I_z in RSA are equivalent with I_z, I_y in SPro respectively.
   B) A user has the ability to change or modify any steel section profile.
6) Via CIS/2, columns profiles HEB260 do not exported correctly, however, the user enables to assign a missing steel profiles manually from SPro *section database*. Section profile tables provide European steel sections **HE shape**, subsequently it could be chosen HE260B (similar HEB260).
7) Columns profiles (HEB260) are missing through transfer via CIS/2, however, the user can add the missing profiles manually.

4.8 EVALUATION OF TEST (3)

The last evaluation of 3D steel frame structure performed tests with BIM corresponds to the test results of table 4.3.

TEK $\xrightarrow{IFC}$ RVT	**Result 0/5**

The S-BIM tool (*IFC*) obtains no rating; since neither loads nor boundary conditions could be transferred. Subsequently, it is not possible to analyze the structure.

TEK $\xrightarrow{CIS/2}$ RVT	**Result 3/5**

In spite of no block model, all elements have been transferred with their correct section profiles in the second S-BIM test via CIS/2, the test obtained a satisfactory rating, whereas neither loads nor boundary conditions are transferred from Tekla into Revit.

RSA $\xrightarrow{Add-Ins}$ RVT	**Result 3/5**

The third S-BIM tool test via CIS/2 from RVT to SPro to handle analysis process resulted in missing data especially with columns profiles HEB260, furthermore no loads could be imported into SPro and unknown missing physical members through processing.

RSA $\xrightarrow{CIS/2}$ RVT	**Result 3/5**

The results of S-BIM CIS/2 format using export data from RSA have obtained same results related with CIS/2 which exported from Tekla

RVT $\xrightarrow{CIS/2}$ SPro	**Result 3/5**

Via CIS/2 from RVT to SPro to handle analysis process resulted in missing data especially with columns profiles HEB260. Furthermore, no loads could be imported into SPro and unknown missing physical members through processing.

$\text{TEK} \xrightarrow{CIS/2} \text{SPro}$	**Result 0/5**

The last S-BIM tool test via CIS/2 from TEK to SPro obtains no rating no results due to disability to read CIS/2 file format exported from TEK.

4.9 TEST (3) EVALUATION ANALYSIS

In this chapter, a more advanced steel structure has formed the basis of evaluation of the applications of both BIM and S-BIM tools. The 3D structure was chosen to investigate whether S-BIM tools can handle in more advance than simple structures, which analyzed in chapter 3.

Firstly, the 3D is modelled in Tekla as BIM model, imported process achieved via different formats to Revit (*.dwg, *.stp, *.ifc). However, none of these models obtained a full satisfactory representation whereas each model is missing different data, which caused insufficient information for analysis/design processes.

As an alternative solution to handle 3D model, a backward attempt to export model from Robot to Revit to study the ability and capability. To S-BIM CIS/2 is tested, the analytical data (Loads, Boundary conditions) are lost with exporting process via indirect link. It is possible to add missing data manually for each member.

Finally, it is hard to specify which of S-BIM tool is best in this test, since no clear causes and errors found to explain why missing important data between BIM model and its S-BIM data.

Based on all tests with the ability to determine results, the Autodesk products have the best results out due to compatible environment between BIM software (Revit) as well as FEM analyzing software (Robot Structural Analysis) to deal with different S-BIM tools (IFC, CIS/2, DWG, ISM, Add-Ins). Furthermore, many extended tools from third party, which enriches Revit library to worldwide uses material such as European steel and timber and supporting Eurocode design criteria and specific factors and parameters.

CHAPTER 5

CONCLUSION

In this thesis, a differentiation framework was defined in which the BIM and S-BIM and related interoperability data models (such as IFC, CIS/2) in order to: determine different aspects of the BIM as a structural tool, compare different common software to improves their usage in the construction at structural level, and anticipate their strengths and weaknesses. We have examined different structural capabilities of the common BIM software and compared between them as well as different data models and standard in accordance with the interoperability. We have also evaluated the S-BIM tools as a plug-in of commercial software modeling which ended up to the result of the lack of proper communication between different BIM software and the open source file format of standards.

Current BIM commercial software in simple and advanced structures have been investigated through case studies; the S-BIM applications have been tested through common FEA to achieve a analysis processes.

The studies included the investigation of the reliability of different BIM software and data standards including the S-BIM, BIM, and related data models (Table 5.1). The proposition could be considered as a guideline for the structural usage of BIM software and interoperability with S-BIM tools in this thesis (Table 5.2).

Table 5.1: BIM and FEA software interoperability with S-BIM tools

		Structural BIM Tools (S-BIM)				
		Structural analysis for dynamo	K	IFC	CIS/2	ISM
BIM (Modelling)	RVT	No	No	Yes	Yes	Yes
	DYN	Yes	No	No	No	No
	Rhino	No	No	No	No	No
	GH	No	Yes	No	No	No
	TEK	No	No	Yes	Yes	No
FEA	RSA	No	No	Yes	Yes	No
	SPro	No	No	No	Yes	Yes

All the results are based on case studies, which based on the comparing processes of different components in BIM software and the related data standards and the performance evaluation system. The mismatch of correspondence of interoperability between different software has been investigated for different models. Considering that the BIM file contains every building component object and its characteristics and the relationships between objects, the structural information must be reliable and durable which by the current research. The final conclusion has been visualized through figure 5.1

In the rest of this chapter, the conclusion of different parts of the examinations has been summarized.

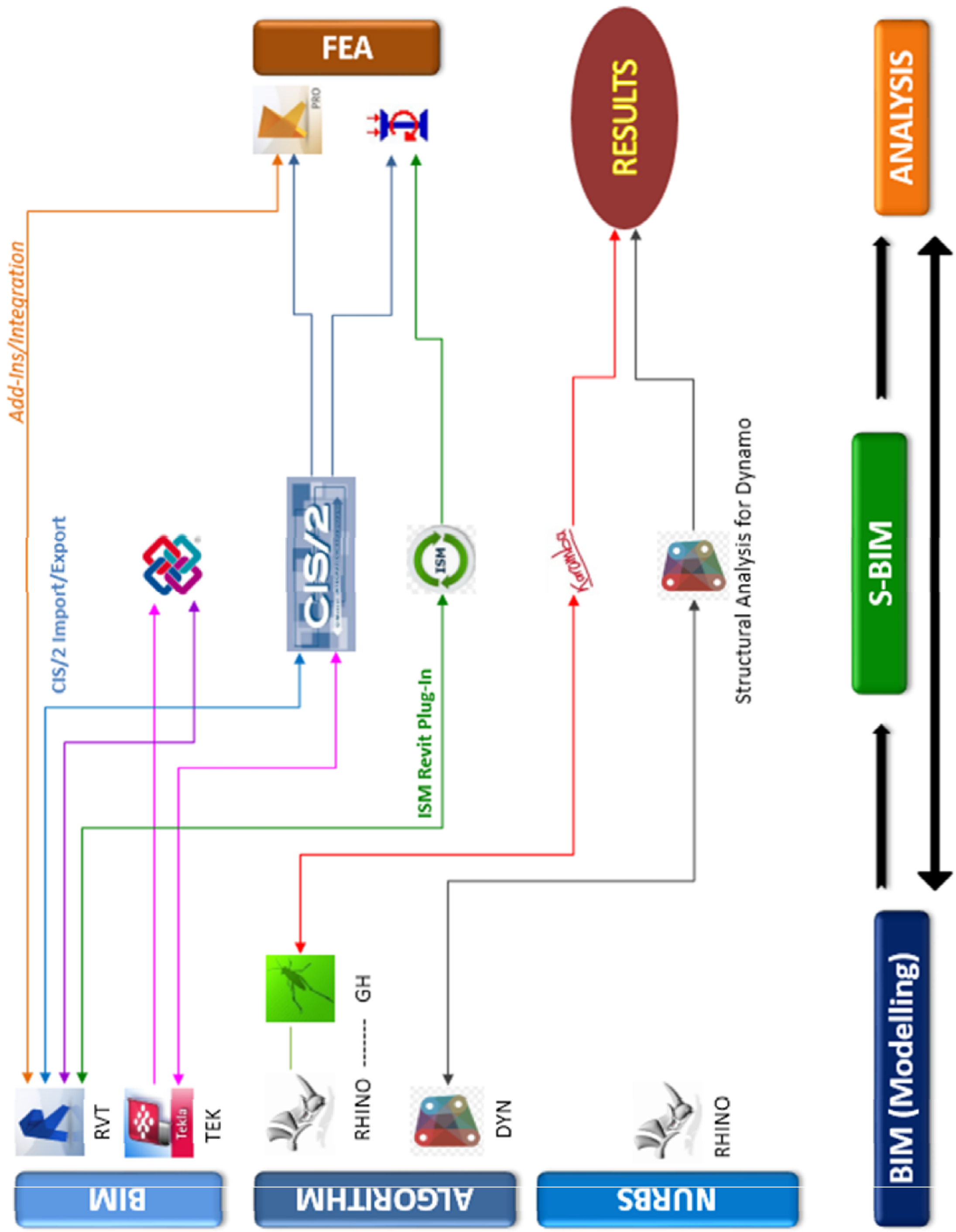

Figure 5.1: Overview of the interoperability between BIM software and FEA.

APPLICABILLITY OF S-BIM TOOLS

An overview of the tests results is presented in table 5.2 based on previous tests evaluations in chapters three and four. The data exchange between BIM software and its S-BIM tools have been investigated via different file formats (IFC, CIS/2, ISM, etc.) and different methods (direct and indirect link). Hence, the table contents will be discussed in detail separately.

Table 5.2: Overview of the performed tests results. The maximum rating is 5 points.

	2D Structure		3D Structure
	Steel	Timber	Steel
	Column	Beam	Frame
Dynamo	**1**	-	-
Dynamo Plug-In *(structural analysis for dynamo)*	**3**	-	-
Revit	**2.5**	**2.5**	-
Revit ↔ Robot (Direct link and backwards)	**4**	**4**	-
Revit $\xrightarrow{CIS/2}$ Robot	**1**	-	-
SPro	**4.5**	-	-
RVT $\xrightarrow{ISM}$ SPro	**1**	-	-
Rhino	-	No Rating	-
Rhino $\xrightarrow{K}$ GH	**2.5**	-	-
TEK $\xrightarrow{IFC}$ RVT	-	-	No Rating
TEK $\xrightarrow{CIS/2}$ RVT	-	-	**3**
RSA $\xrightarrow{Add-Ins}$ RVT	-	-	**3**
RVT $\xrightarrow{CIS/2}$ SPro	-	-	**3**
TEK $\xrightarrow{CIS/2}$ SPro	-	-	No Rating

NURBS GEOMETRY BIM SOFTWARE DIRECT LINK FROM BIM SOFTWARE VIA S-BIM TOOL

Currently, a new technique of modeling most complex structures via using non uniform rational B-Splines (NURBS) as mathematical representations in order to model line, arc, or curve from 2 dimensional to 3 dimensional surface or solid. In this thesis, a couple of Rhinoceros Grasshopper and Autodesk Dynamo are applied to model two different simple structures to investigate the power, capability, and ability to handle analysis structures within NURBS environments. Both of them are compatible in ability to edit and modify structure in an easy way to change the dimensions and elevations of each perspective of structure. However, none of them are ready sufficient to deal with analytical model, since they lack to create and apply physical properties e.g. loads, boundary conditions and so on.

DIRECT LINK FROM BIM SOFTWARE VIA S-BIM TOOL

To support and strengthen the ability of Dynamo and Rhinoceros and Grasshopper to handle with analytically models, a couple of *Karamba* and *Structural Analysis for Dynamo* are used for regarding tests. A description of each S-BIM is presented in following paragraphs.

A- USING KARAMBA IN GRASSHOPPER AND STRUCTURAL ANALYSIS FOR DYNAMO IN DYNAMO

To enhance NURBS BIM software, some of specific S-BIM is provided from third party side e.g. *Karamba* and Structural *Analysis for Dynamo* as an attempt to link physically model with analytically one. Through two studies with two different structures in sections properties, material, serviceability and so on, both of them used S-BIM resulted in a somewhat evaluations. Loads, boundary conditions, sections dimensions could be added to original physical model. Subsequently an ability to perform section forces and deflections. It should be mentioned about some issues in analysis handle processing, such as disability to check Eurocode for any type of material, timber sections profile library is too poor in *Karamba*, while it could be used RVT material properties into *Structural Analysis for Dynamo.* Boundary conditions status (Fixed, pinned, and roller) did not work correctly especially in *Structural Analysis for Dynamo* since some warning appeared in RSA while exporting due to displacements related with roller.

B- ADD-INS WIZARD (INTEGRATION-AUTODESK REVIT STRUCTURE) DIRECT LINK BETWEEN RVT AND RSA

The already provided link from Autodesk is totally compatible in exchange data interoperability between Revit and Robot Structural Analysis, since analytical model could be transferred right including loadings, boundary conditions, materials and sections dimensions. Hence, it is possible to perform various analysis/design processes through FEM in RSA regarding with Eurocode. RSA enables to perform all related design parameters to Eurocode for both steel and timber structures materials, which are congruently with hand calculations. This makes analyses results more compatible and trustable. However, in other side not all FEM enables to perform design parameters and factors.

INDIRECT LINK (IFC, CIS/2, ISM)

The indirect linking has been between BIM (modelling) software and FEM analyses software via IFC, CIS/2, and ISM. In spite of availability of IFC format in most of BIM and FEM software, the data exchange via IFC was rather incomplete since only shape (perspective) of the model could be transferred. The weak implementation of IFC makes the evaluation of the applicability unsatisfactory since this type of S-BIM needs to be developed more in according to be sufficient to engineers to exchange data.

- For CIS/2 tool is totally compatible with steel structures, all members could be transferred individually. The profile section dimensions were transferred correctly regarding with European steel types, subsequently steel material properties such as yielding, bending resistance, etc. could be transferred in further.

- The provided S-BIM from Bentley Co. (ISM) was rather complex, incompatible due to the differences between Autodesk products to Bentley environments. However, the transformation process was passed into many steps, this might be caused warnings/errors through them. Further, the test 1 (Column buckling) showed weakness of ISM, since no analytical data could be transferred such as loads and boundary conditions.

5.2 FUTURE RESEARCH

The author presents some suggestions for improving the BIM (modelling) software as well as S-BIM (FEA) software in accordance to compatibility and interpolation between them to achieve analysis/design structures through implementation BIM:

- **Material Library**

A global material library consists of all types (at least for European), for all types of constructions material (e.g. steel, concrete, and timber) along with their manufacture (European, American, British, Canadian). Furthermore, it makes this unified library as standards in the future for industrial cost management in order to improve 5D (Costing) by updating entire related prices.

- **IFC**

In spite of IFC common used in most BIM software, some companies/corporations needs to develop lacks of transferring analytical data in some software such as (loads and boundary conditions). IFC has been developed staring from version 2 to IFC version 4 and still continues to provide enhancements to users, this means concern of wide used of it in industrial engineering.

- **CIS/2**

CIS/2 works in efficient procedure for steel structures, it provides and deals with most steel sections types. Only analytical missing data through transfer from BIM (model) to FEA are needed to fix such as (boundary conditions and loads).

- **ISM**

The S-BIM tool ISM is not common in different analyses FEM software, since it belongs Bentley Corporation consists of complex procedure to transfer BIM model. It is not eligible to deal with Autodesk compatible material libraries.

- **TEK**

Tekla lacks to provide indirect S-BIM link ISM. Tekla offers flexible links for only companies/corporations to connect with Autodesk products and CSI software products to perform FEA.

- **RVT AND RSA**

In order to better Analytical exchange data RVT needs as backwards from RSA and so on to be compatible to be able to read analysis/design exchange data especially design factors ad parameters.

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APPENDICES

APPENDIX A

SIMPLY SUPPORTED STEEL COLUMN

In this appendix design parameters and test procedures are described from the basis of checking column buckling stability in Section 3.2

A.1 DESIGN PARAMETERS

The relevant parameters in related with the design criteria of the 2850 mm simply supported steel column are presented in this appendix. The column is a HEB100 profile of steel type S235. The statically system of the steel column and the cross section illustrates in figure B.1, whereas the parameter data related to cross section (Table B.1) should be defined at the beginning of the buckling test and the remaining parameters can be calculated depending on the already defined parameters.

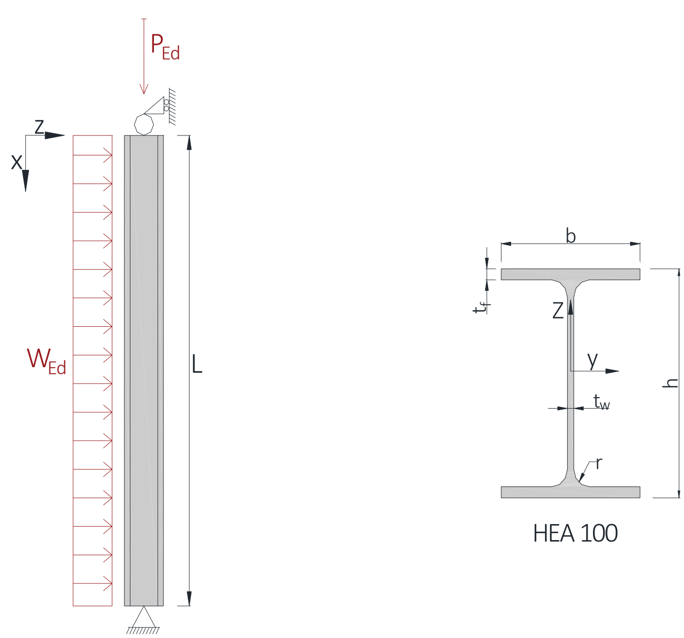

Figure A.1: Left: Simply supported column. Right: Cross section (HEB-profile)

Section properties			
Height	h	100	mm
Width	b	100	mm
Web thickness	t_w	6	mm
Flange thickness	t_f	10	mm
Radius	r	12	mm
Area	A	2604	mm^2
Shear area	A_y	2268	mm^2
Shear area	A_z	904	mm^2
Moment of inertia	I_y	4495450	mm^4
Moment of inertia	I_z	1672720	mm^4
Elastic section modulus	$W_{el,y}$	899000	mm^3
Plastic section modulus	$W_{pl,y}$	104000	mm^3
Radius of gyration	i_y	41.6	mm
Radius of gyration	i_z	25.3	mm

Table A.1: Cross Section Parameters Data

The relevant geometric parameters are shown in Table B.2

Geometry			
Length	L	2850	mm
Effective Length	L_{eff}	2850	mm

Table A.2: Geometry Parameters

Steel S235 material parameters are shown in Table B.3

Material Properties			
Yield stress	f_y	235	MPa
Modulus of elasticity	E	210000	MPa
Shear modulus	G	81000	MPa
Weight	W	20.4	Kg/m

Table A.3: Material Parameters

Loading is divided between uniformly line load 3.32 kN/m and concentrated force 371 kN applied at roller end support which can be shown in Table B.4.

Loads			
Uniform load	q	3.32	kN/m
concentrated force	P	371	kN

Table A.4: Loads Parameters

The boundary conditions for simply supported column are defined in Table B.5 since (x) refers to a fixed degree of freedom while (*f*) refers to free degree of freedom. First three marks are related to translations in (X, Y, Z) and rest are related to rotations around (X, Y, Z).

Boundary Conditions		
Roller	*S1*	*fxxfff*
Pinned	*S2*	*xxxfff*

Table A.5: Boundary Conditions Parameters

The applied BIM and S-BIM applications have to able to determine the required parameters to assess the design criteria, Parameters in relation to design due to hand calculations are shown in Table B.6 and Table B.7

Design Parameters			
Section classification		1	-
Bending moment	$M_{y.Ed}$	3.37	kN.m
Resistance moment	$M_{y.Rd}$	24.4	kN.m
Compression resistance	N_{Rd}	611.9	kN
Imperfection parameter	α_{LT}	0.34	-
Buckling curve		b	-
Reduction factor	χ_{LT}	0.766	-

Table A.6: Design Parameters

The interaction checks (6.61) and (6.62) must results in value less than 1.0 to fulfill the EC-3 requirements for column buckling. The final result of hand calculations is shown:

Results			Status
Check code (EC-3)	Eq.(6.61)	0.973	**Passed**
Check code (EC-3)	Eq. (6.62)	0.735	**Passed**

Table A.7: final results of hand calculations for steel column buckling check.

To examine the reliability of implementation structural BIM S-BIM, it must have the ability to handle whole parameters described above. All the described parameters are present for the evaluation of tests performed for simply supported steel column.

A.2 PROCEDURES OF TEST (1)

The procedures used in modelling Structure 1 can be described as:

The relevant parameters in related with the design criteria of the 2850 mm simply supported steel column are presented in this appendix. The column is a HEB100 profile of steel type S235. The statically system of the steel column and the cross section illustrates in figure B.1, whereas the parameter data related to cross section (Table B.1) should be defined at the beginning of the buckling test and the remaining parameters can be calculated depending on the already defined parameters.

Dynamo

The first BIM software used to model Structure 1 is open source Autodesk Dynamo that extends BIM with logic environment of graphical algorithm editor. The procedure used into create model illustrates below:

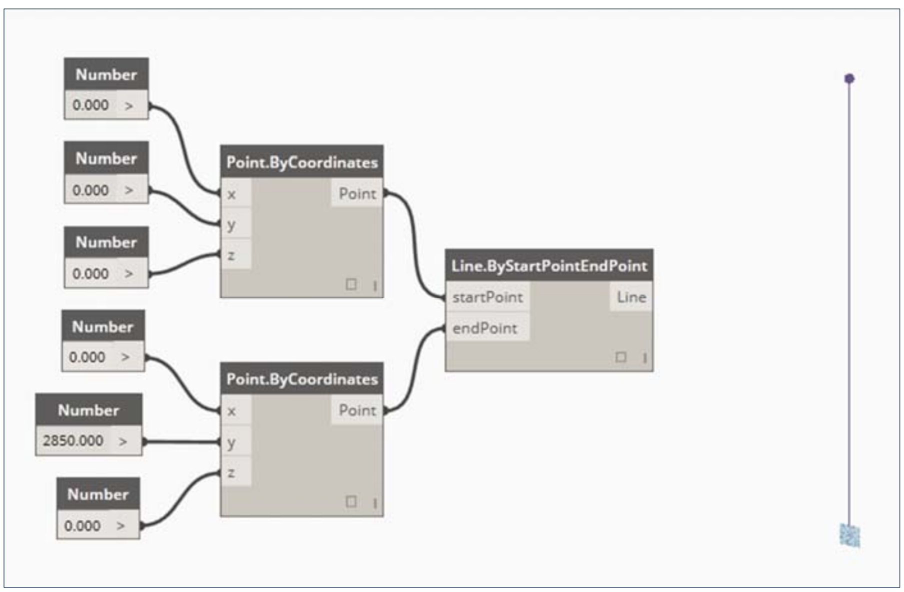

Figure A.2: Algorithm modelling structure 1 through Dynamo

Dynamo Plug-In (*structural analysis for dynamo*)

The analytical results in Dynamo are obtained directly through link with RSA.

1) During using plug-in Structural analysis for dynamo, Dynamo can only open the finite defaults parameters in RSA, Warnings are showing in buff or red colored function to provide the desired missing values. For this reason it is needed always to recall the section properties, boundary condition once each time from Robot firstly before acting Run function in Dynamo.
2) In RSA roller support defined as *fxxfff*.
3) Roller end support obtains a warranty (No error) as instability support (Same in SPro), However no influence to the final results.(figure A.5)
4) Verification → RSA obtains one warning related with end support instability (same warning in STAAD pro), but no influence to the final analytical results.
5) Run → Watch (Only section forces can be performed throughout analysis process).

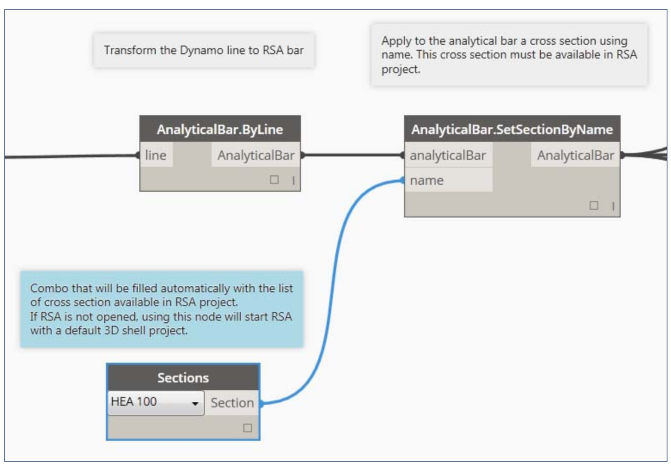

Figure A.3: Define column and section in DYN from RSA directly via *Structural analysis for dynamo*

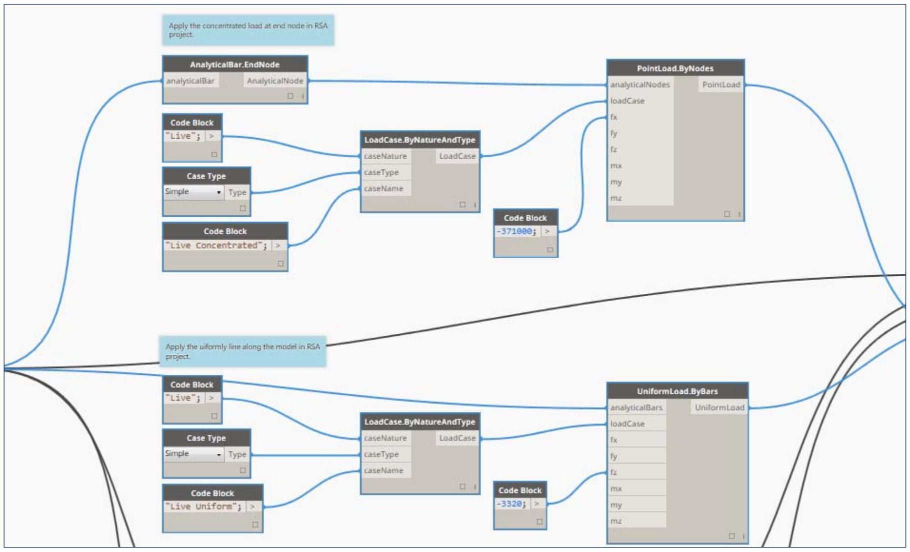

Figure A.4: Define loads (Imposed+ uniform) in DYN via Structural analysis for dynamo

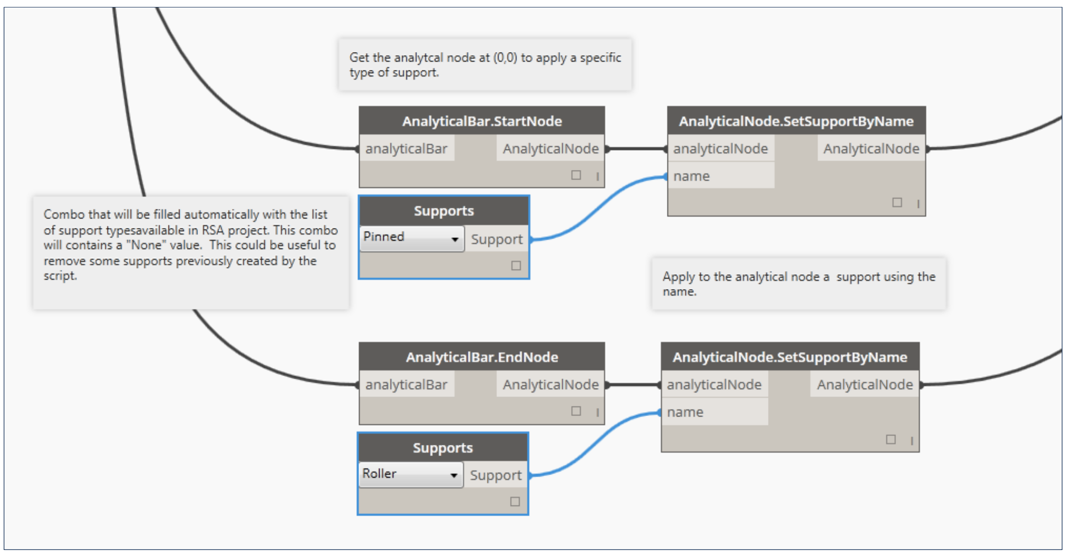

Figure A.5: Define boundary conditions in DYN from RSA directly *via Structural analysis for dynamo*

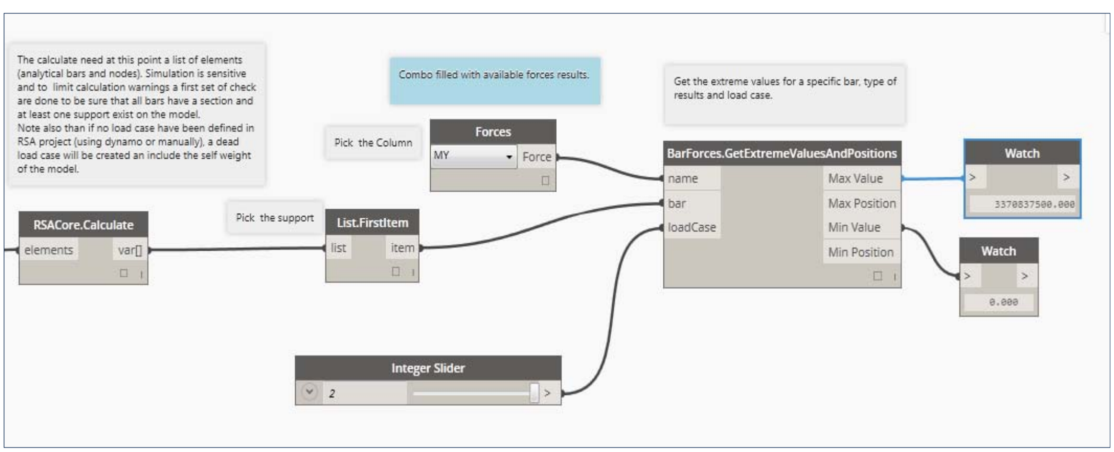

Figure A.6: Section forces results into DYN through Structural analysis for dynamo

Direct link between Revit and Robot (Revit Extension, Integration with Robot Structural Analysis)

The provided extension between Revit and Robot from Autodesk is totally reliable and compatible, since:

- Revit

1) Ability to choice a right cross section from a various Revit libraries.
2) Ability to choice a right cross section from a various Revit libraries.
3) Ability to create model end release as boundary conditions.
4) Ability to define materials with its defaults parameters, as well as ability to customize values.
5) Ability to define different loading types.

- Robot

1) Verification → No warnings, No errors happen.
2) Defines element as column manually.
3) Calculation → No warnings, No errors happen.

Indirect link between Revit and Robot (CIS/2)

During the export process via CIS/2, it is chosen both analytical and drawing model. Only some model properties could be exported, loads and boundary conditions are missing through this process. No errors, no warnings happen.

- Revit

1) Export to CIS/2 file.

- Robot

1) Open CIS/2 file (Only geometry appears (Length, cross section dimensions, material properties)
2) Verification → Warnings: No supports, No load cases.

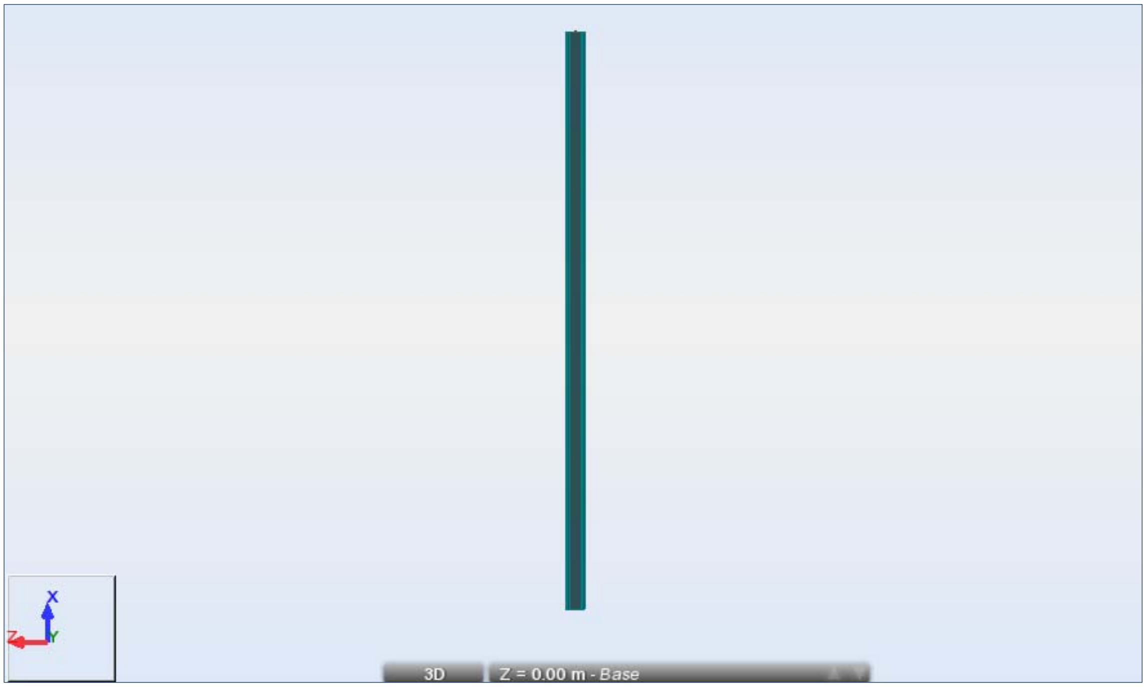

Figure A.7: Structure 1 layout through exporting from RVT to RSA via CIS/2

Indirect link between Revit and STAAD Pro (ISM)

In ISM tool S-BIM test the structural model is missing loads and boundary conditions.

1) Run → Run Analysis → No errors, no warnings happen (Only input data can be showed and no structural analysis S-BIM can be run).

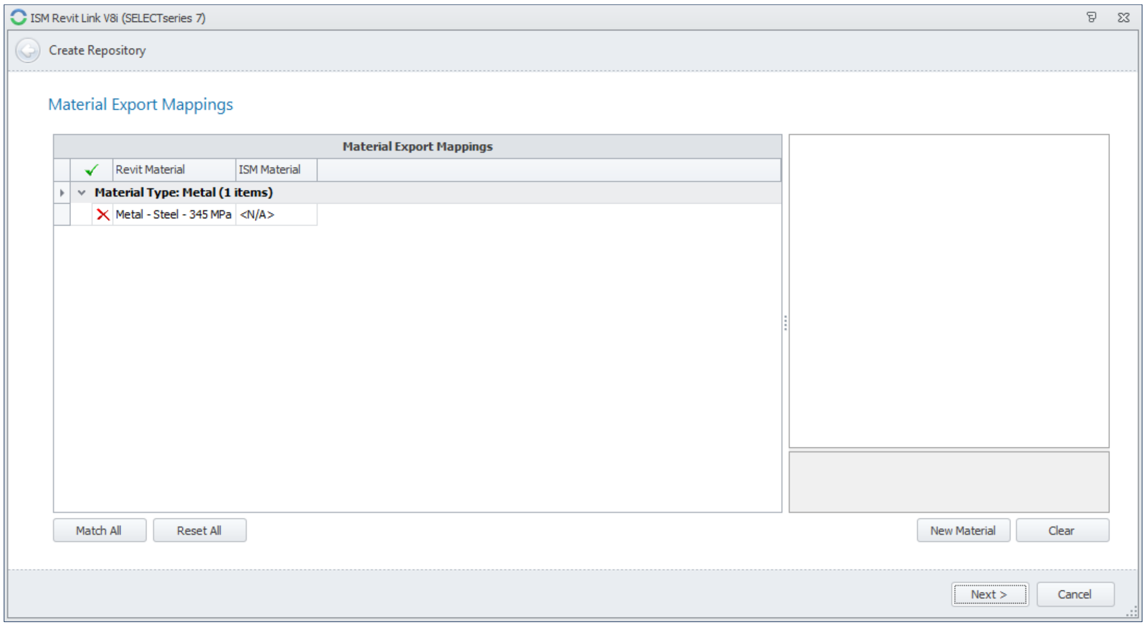

Figure A.8: ISM Revit Link procedure –Step 1

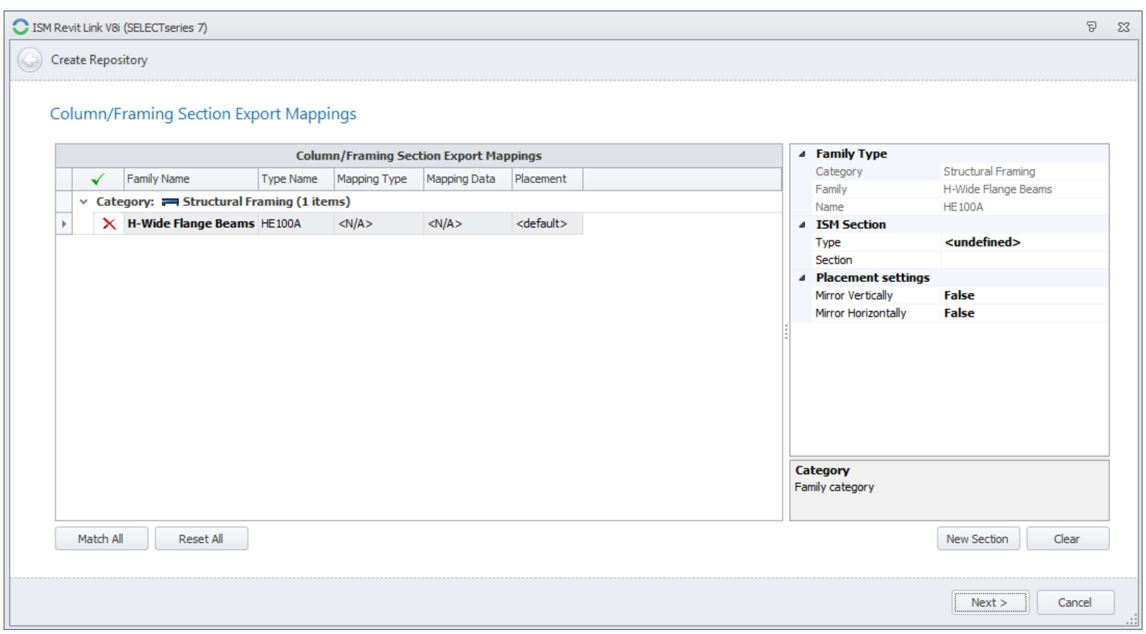

Figure A.9: ISM Revit Link procedure –Step 2

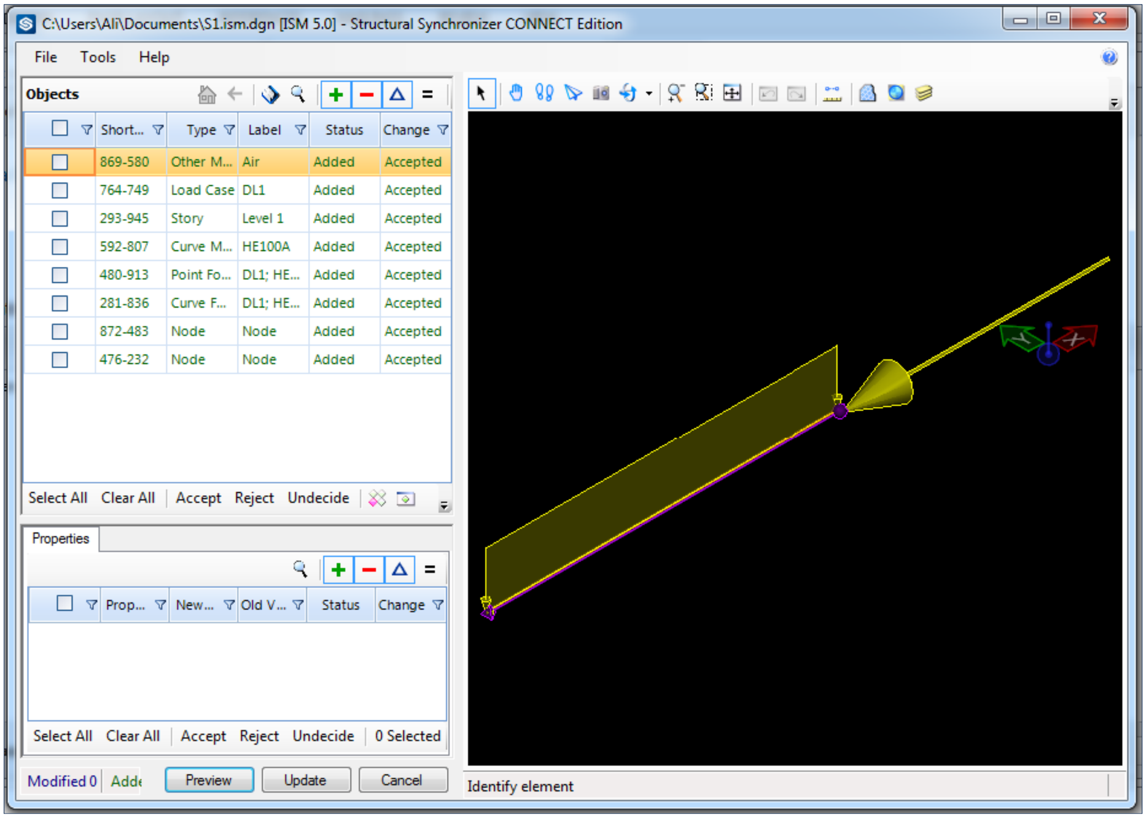

Figure A.10: ISM Revit Link procedure –Step 3

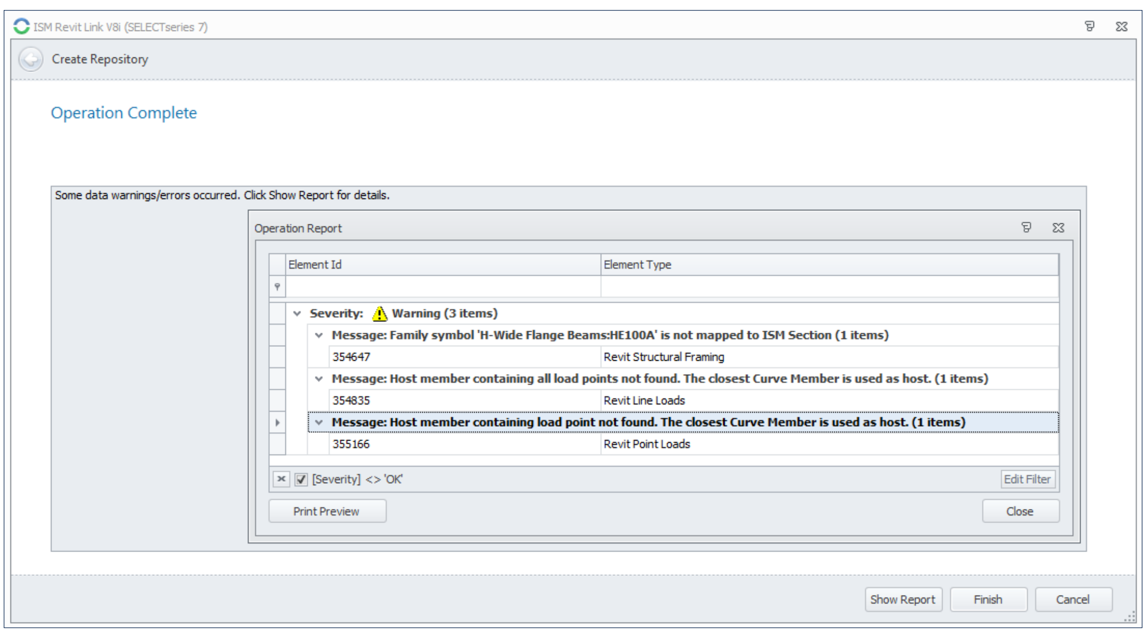

Figure A.11: ISM Revit Link procedure –Step 4

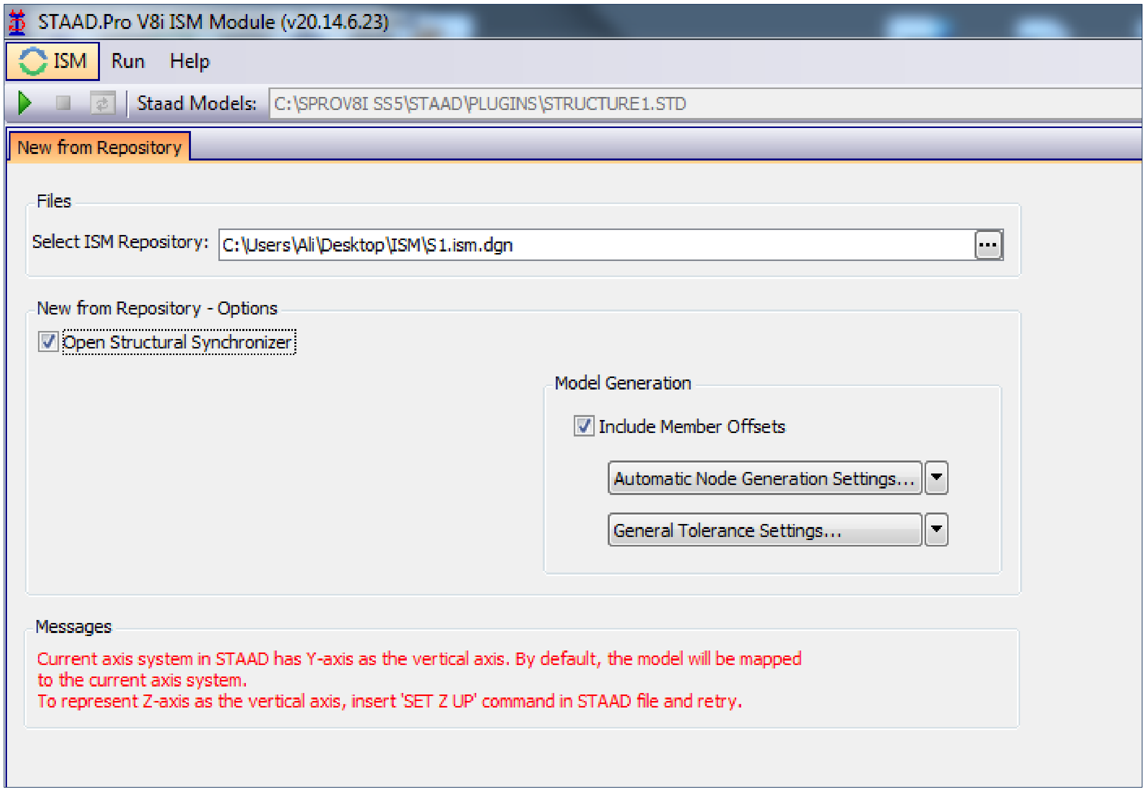

Figure A.12: ISM Revit Link procedure –Step 5

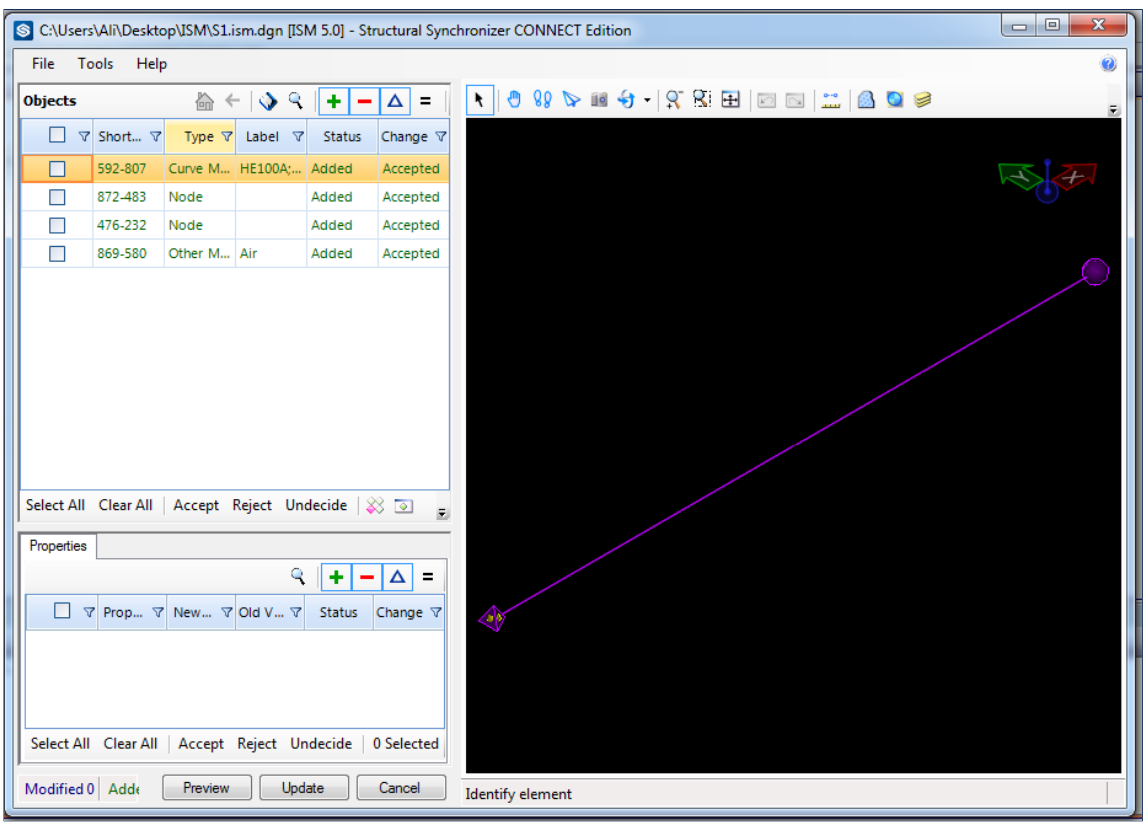

Figure A.13: ISM Revit Link procedure –Step 6

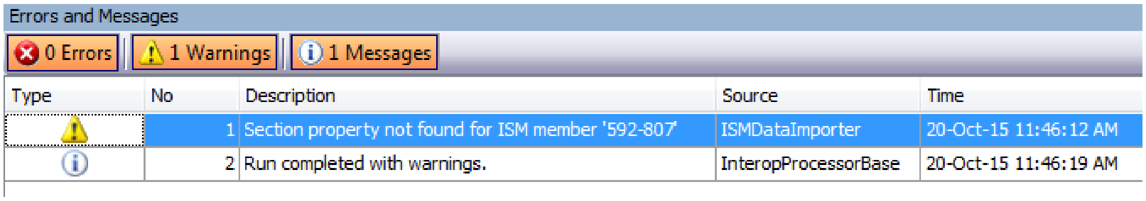

Figure A.14: ISM Revit Link procedure –Step 7

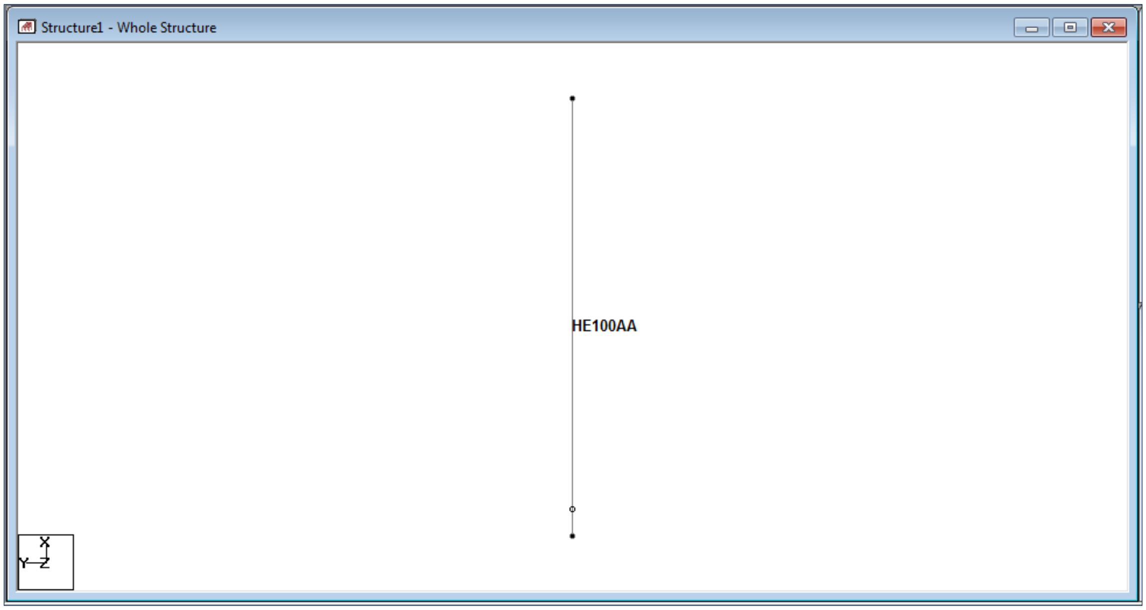

Figure A.15: ISM Revit Link procedure –Step 8

APPENDIX B

SIMPLY SUPPORTED TIMBER BEAM

In this appendix design parameters and test procedure are described from the basis of checking euro code EC5 design criterion for Structure 2 in section 3.3.

B.1 DESIGN PARAMETERS

The relevant parameters in related with the design criteria of the 3600 mm simply supported timber beam are presented in this appendix. The beam is 220x45 mm section of C30 softwood timber. The statically system of the timber beam and the cross section illustrates in figure C.1, whereas the parameter data related to cross section in Tables B.1-B.3.

The static system of the timber beam and the cross section are shown in figure B.1

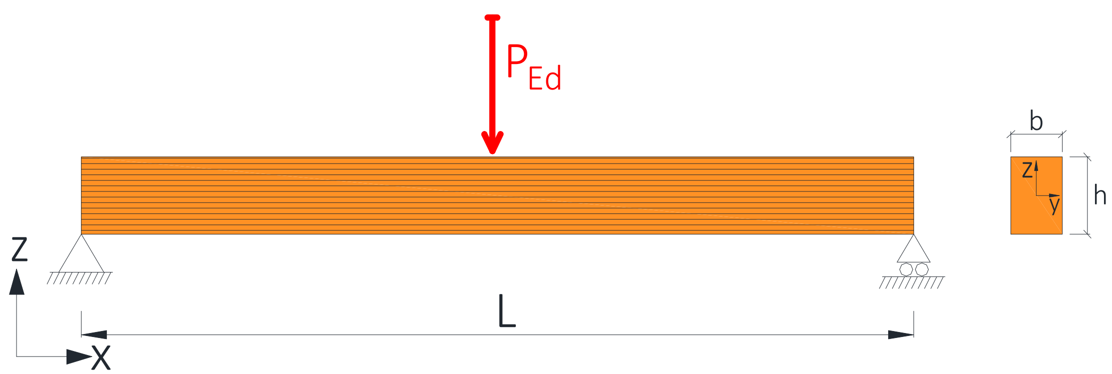

Figure B.1: Left: Simply supported beam. Right: Cross section

Section properties			
Height	h	220	mm
Width	b	45	mm
Area	A	9900	mm^2
Moment of inertia	I_y	39930000	mm^4

Table B.1: Cross Section Parameters Data.

The relevant geometric parameters are shown in Table B.2

Geometry			
Length	L	3600	mm

Table B.2: Geometry Parameters.

Softwood timber type C30 material parameters are shown in Table B.3

Material Properties			
Mean modulus of elasticity	E	12	kN/mm^2
Bending strength	$f_{m,k}$	30	MPa
Shear strength	$f_{v,k}$	4	MPa
Density	ρ	380	Kg/m^3

Table B.3: Material Parameters.

Loading is concentrated force 7.40 kN applied at mid span is shown in Table B.4.

Loads			
concentrated force	P	7.40	kN
Duration	-	Medium-term	-

Table B.4: Loads Parameters.

For simply supported beam the boundary conditions are defined in Table B.5 since (*x*) refers to a fixed degree of freedom while *(f)* refers to free degree of freedom. First three marks are related to translations in (X, Y, Z) and rest is related to rotations around (X, Y, Z).

Boundary Conditions		
Roller	S1	*fxffff*
Pinned	S2	*xxxfff*

Table B.5: Boundary Conditions Parameters.

The applied BIM and S-BIM applications have to able to determine the required parameters to assess the design criteria, Parameters in relation to design due to hand calculations are shown in Table B.6 and Table B.7.

Design Parameters			
Service Class	-	2	-
Design bending strength	*fm,d*	18.5	MPa
Design shear strength	*fv,d*	2.46	MPa
Partial factor	*γmod*	1.3	-
Modification factor	*kmod*	0.8	-
Modification factor	*Ksys*	1	-
Modification factor	*Kcrit*	1	-
Modification factor	*Kh*	1	-
Modification factor	*Kcr*	0.67	-

Table B.6: Design Parameters.

The results of hand calculations are shown in table C.7:

Results			
Section forces	*Mb,Rk*		MPa
Section forces	*Mb,Rd*		MPa
Check code (EC5)	Eq. (6.62)		MPa

Table C.7: The hand calculations results for timber simply supported beam.

To examine the reliability of implementation S-BIM, it must have the ability to handle whole parameters described above. All the described parameters are present for the evaluation of tests performed for simply supported timber beam.

B.2 PROCEDURES OF TEST (2)

Direct link between Rhino and (Grasshopper + Karamba)

The analytical results through generative algorithms in Rhino are obtained directly.

1) During using couple of S-BIM plug-Ins (Grasshopper + Karamba), Grasshopper is developed via Karamba S-BIM tool to perfume section forces and displacements directly for structural analysis.
2) Warnings are showing in buff colored function require to provide missing values.
3) For timber sections types, Karamba only provides VH timber profiles (VH)I, (VH)II, (VH)III.
4) Roller end support defined as *xffxxx* and pinned end *ffffxx*.
5) No errors, No warnings have been occurred during analysis process.
6) Through generative algorithms, Section forces and displacements can be performed directly in Grasshopper layout and deformed shape illustrates in Rhino in 3D.

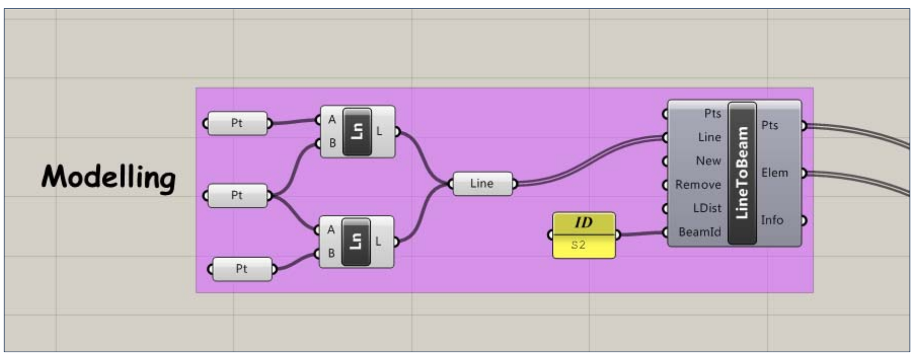

Figure B.2: Algorithm modelling structure 2 through Grasshopper- Part 1/4

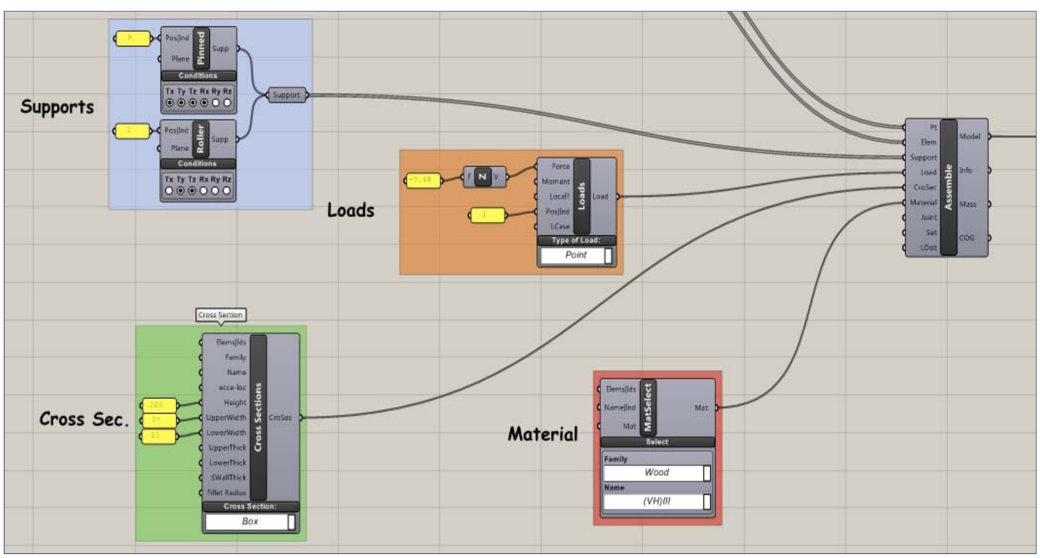

Figure B.3: Algorithm modelling structure 2 through Grasshopper- Part 2/4

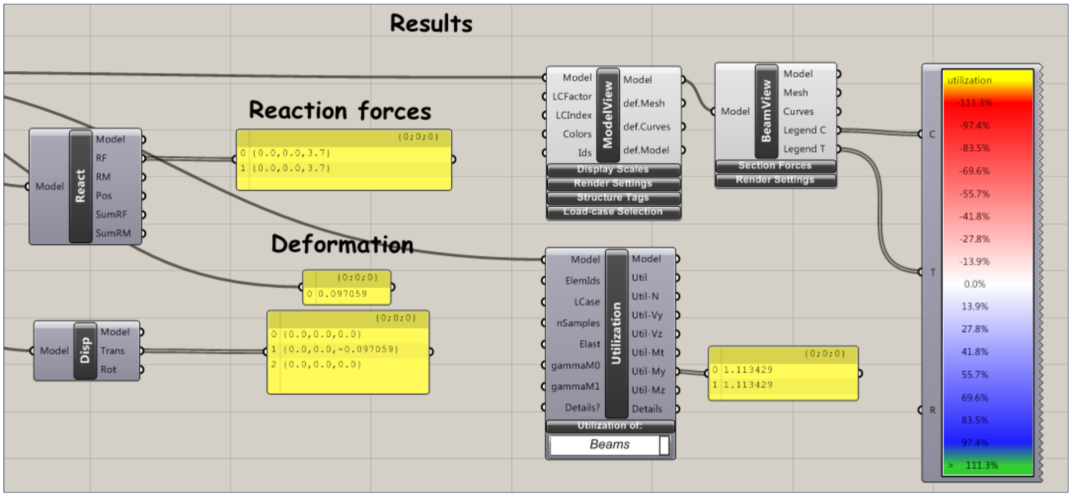

Figure B.4: Algorithm modelling structure 2 through Grasshopper- Part 3/4

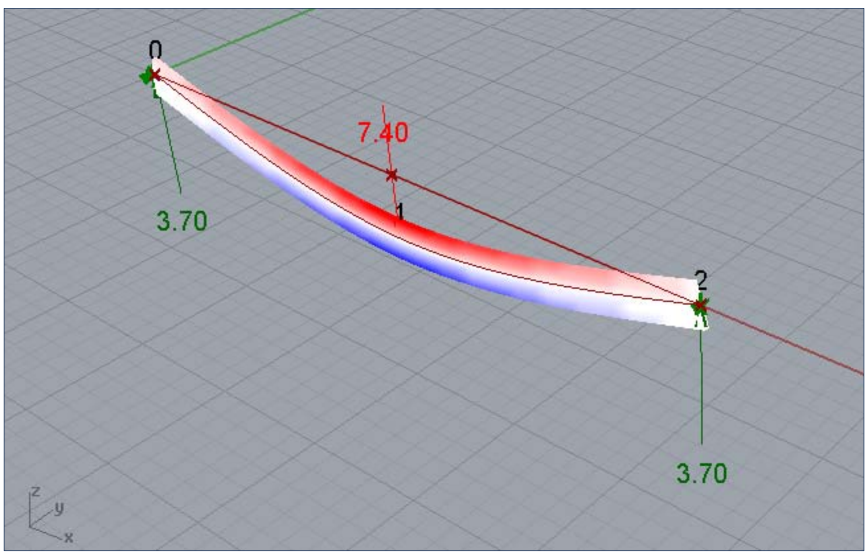

Figure B.5: Algorithm modelling structure 2 through Grasshopper- Part 4/4

Direct link between Revit and Robot (Revit Extension, Integration with Robot Structural Analysis)

The provided extension between Revit and Robot from Autodesk is totally reliable and compatible, since:

- Revit

1) Ability to choice a right cross section from a various Revit libraries.
2) Ability to create model end release as boundary conditions.
3) Ability to define materials with its defaults parameters, as well as ability to customize values.
4) Ability to define different loading types.

- Robot

1) Verification → No warnings, No errors happen.
2) Defines element as beam manually.
3) Calculation → No warnings, No errors happen.

To update model from RSA in Revit, some selections are required.

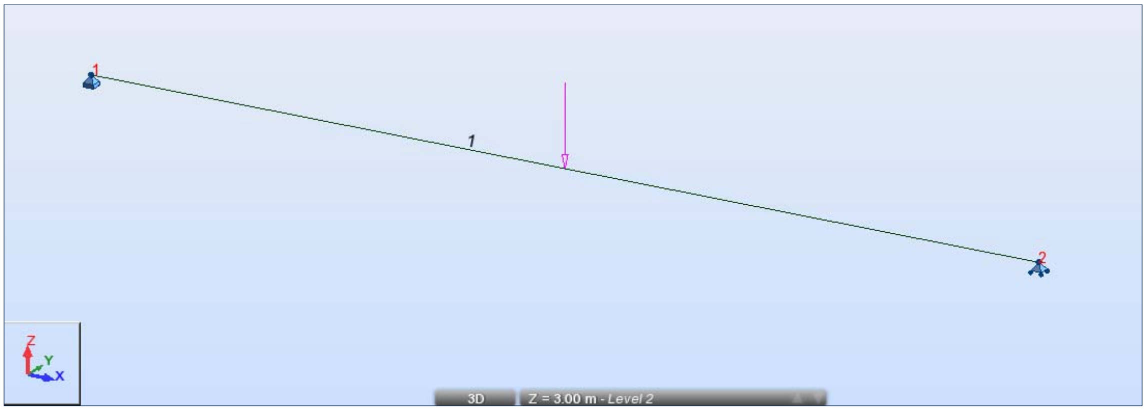

Figure B.6: The updated model of structure 2 through Autodesk *Integration*

Indirect link between Revit and Robot (IFC)

During the export process via IFC, it is chosen both analytical and drawing model. Only some model properties (section properties and length) could be exported, loads and boundary conditions are missing through IFC. No errors, no warnings happen.

- Revit

1) Export to IFC file.

- Robot

1) Open IFC file (Only geometry appears (Length, cross section dimensions)
2) Verification → Many information are missing such as: No supports, No material properties, No load, No right cross section cases could be transferred.

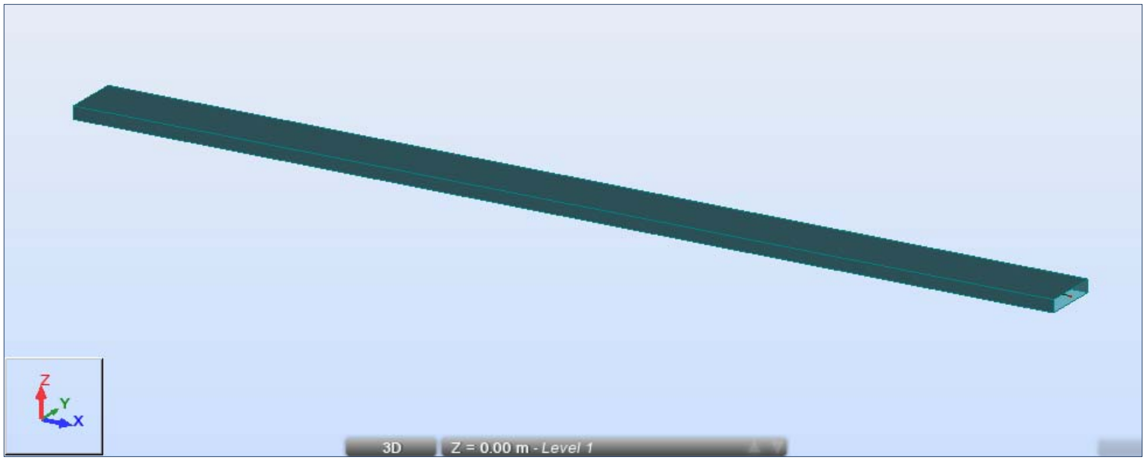

Figure B.7: The updated model of structure 2 through IFC

Indirect link between Revit and STAAD Pro (ISM)

In ISM tool S-BIM test the structural model data are missing except model length.

1) Run → Run Analysis → No errors, no warnings happen (Only input data can be showed and no structural analysis S-BIM can be run)

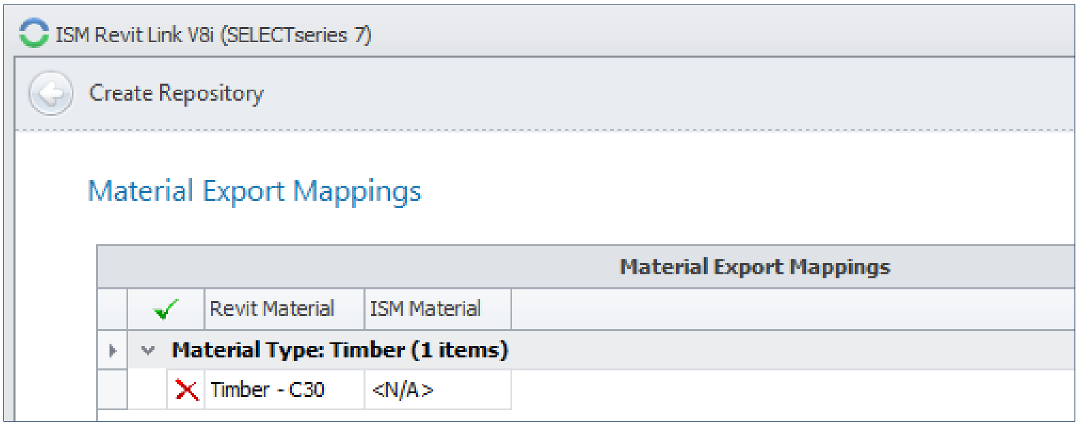

Figure B.8: ISM Revit Link procedure –Step 1

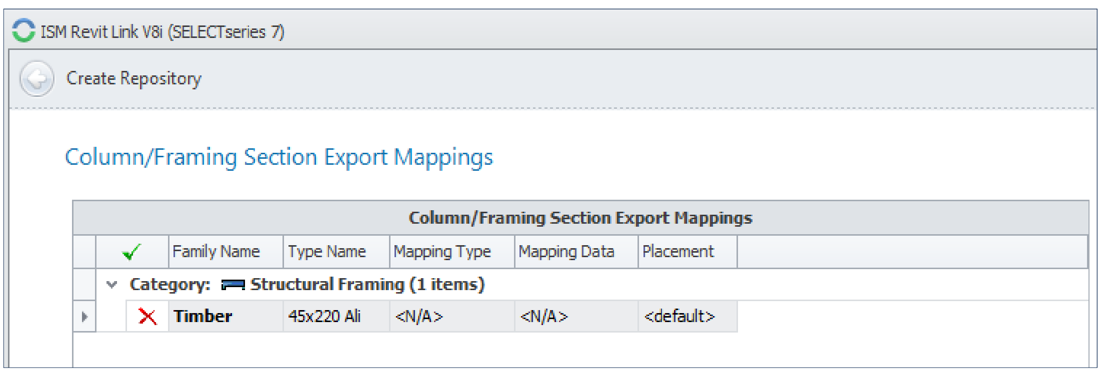

Figure B.9: ISM Revit Link procedure –Step 2

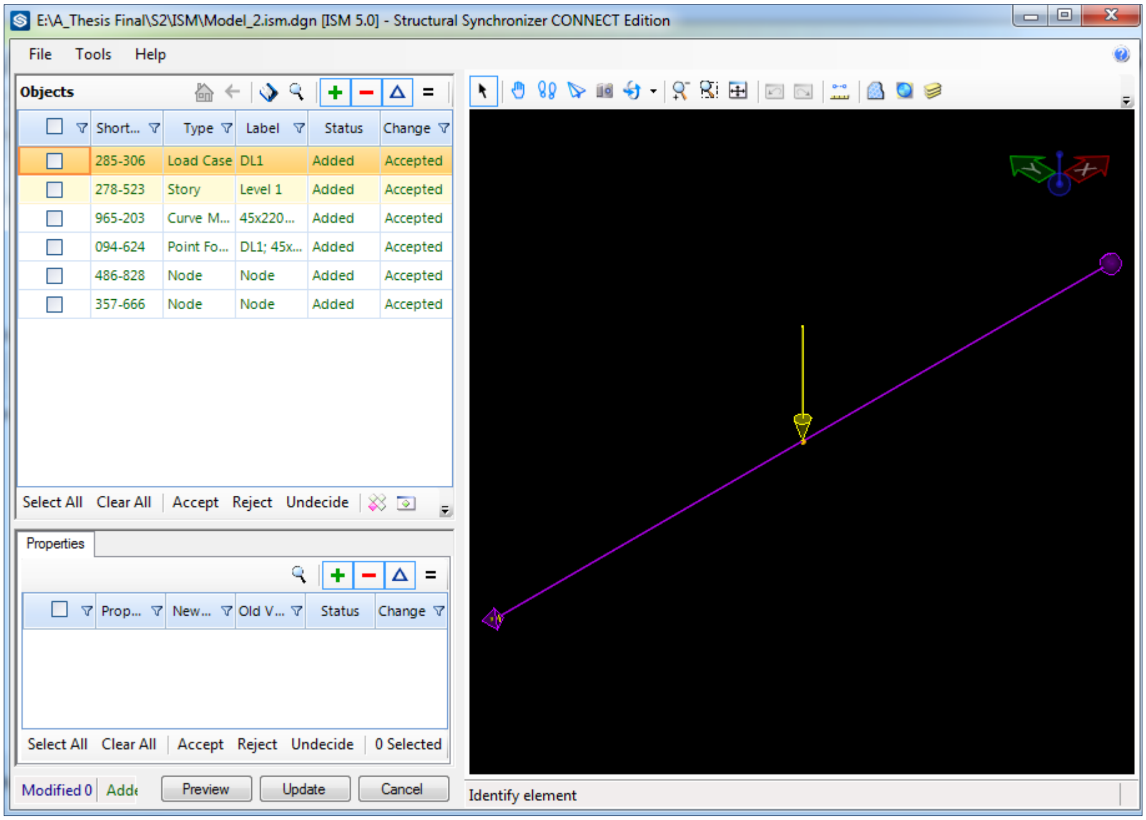

Figure B.10: ISM Revit Link procedure –Step 3

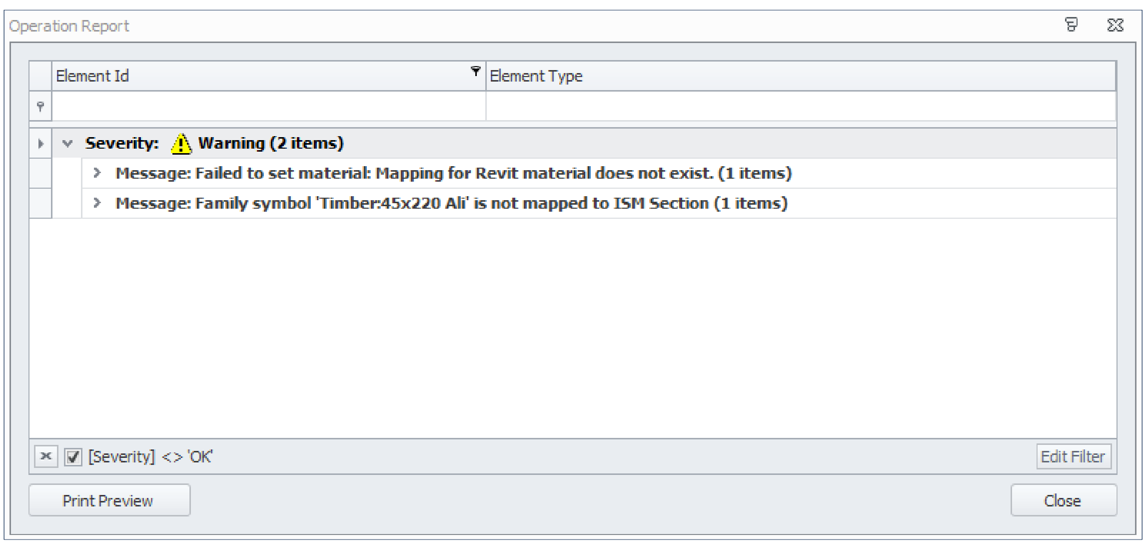

Figure B.11: ISM Revit Link procedure –Step 4

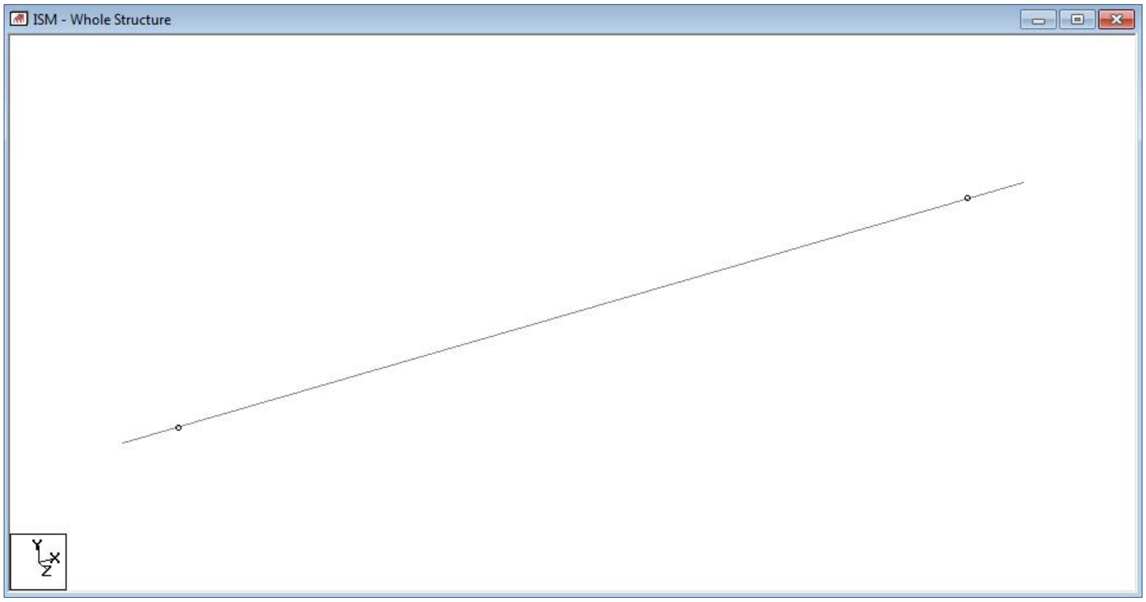

Figure B.12: ISM Revit Link procedure –Step 5

APPENDIX C

THREE DIMENSIONAL STEEL FRAME STRUCTURE

In this appendix design parameters and test various procedures are described from the basis of checking euro code EC3 design criterion for Structure 3 in chapter 4.

C.1 DESIGN PARAMETERS

The relevant parameters in related with the design criteria in section 4.3 for three dimensional steel frame structure in figure C.1.

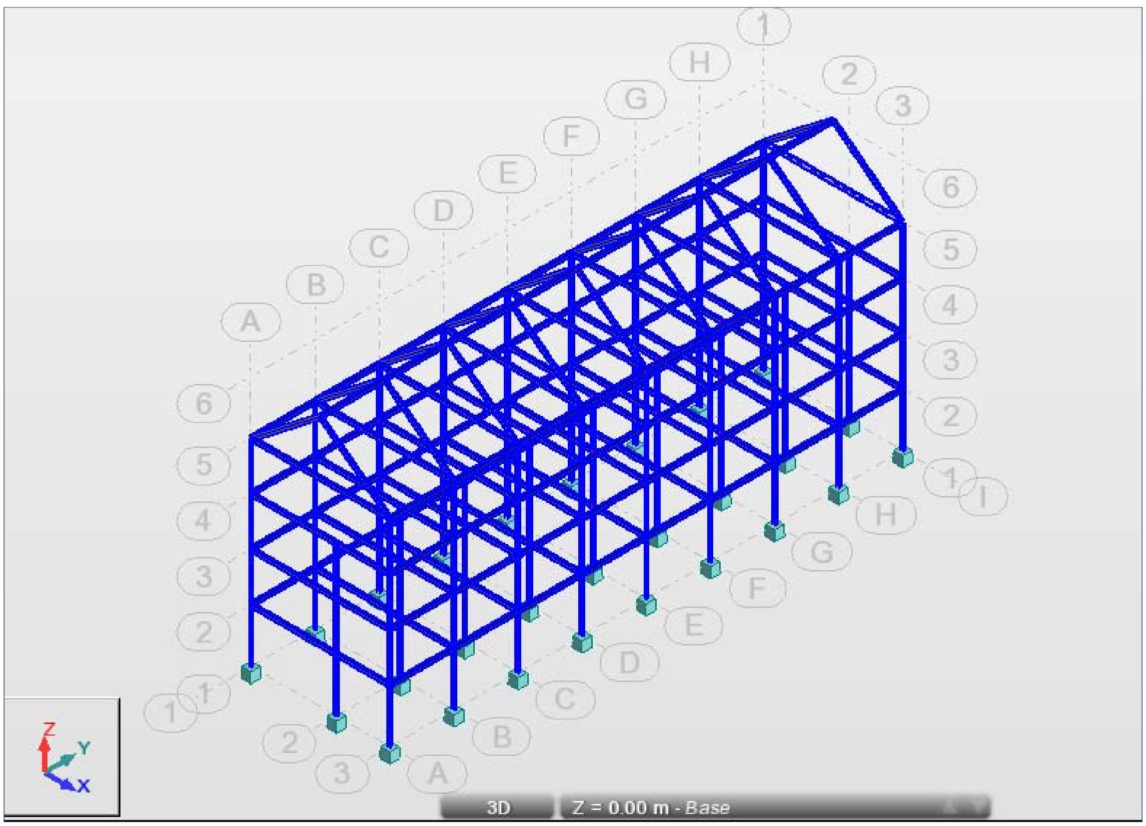

Figure C.1: The 3D steel structure modelled in RSA.

The related parameters for the selected members are shown below:

Section properties				
Member		**Beam 18**	**Column 14**	
Profile		**IPE450**	**HEB260**	
Height	h	450	100	mm
Width	b_f	190	100	mm
Web thickness	t_w	9.4	6	mm
Flange thickness	t_f	14.6	10	mm
Radius	b	21	12	mm
Moment of inertia	I_y	33700000	4495000	mm^4
Moment of inertia	I_z	16760000	1670000	mm^4
Plastic moment	W_x	46000	70900	mm^3
Area	h	9882	2604	mm^2
Weight	b	77.5	20.4	kG/m

Table C.1: Cross section parameters data for the selected members.

The relevant geometric parameters are shown in Table C.2

Geometry				
Member		B-18	C-14	
Length	L	8000	5000	mm
Effective length	L_{eff}	-	5000	mm

Table C.2: Geometry parameters for the selected members.

Steel material S275J0 parameters are shown in Table C.3

Material Properties			
Modulus of elasticity	E	210000	MPa
Yield strength	f_y	275	MPa
Steel grade		1	
Density	ρ	7850	Kg/m^3

Table C.3: Material parameters for the selected members.

Loading is distributed uniform load (ULS) applied at each beam span along with axial force on C-18 = 1206, are shown in table C.4.

Loads			
Uniform load on beams	q	57.400	kN/m
Axial load on column 18	N_{ed}	1206	kN

Table C.4: Loads Parameters.

For simply supported beam the boundary conditions are defined in Table C.5 since (x) refers to a fixed degree of freedom while *(f)* refers to free degree of freedom. First three marks are related to translations in (X, Y, Z) and rest are related to rotations around (X, Y, Z).

Boundary Conditions		
Roller	S1	*fxxfff*
Pinned	S2	*xxxfff*
Fixed (footings)	S3	*xxxxxx*

Table C.5 Boundary conditions parameters.

The applied BIM and S-BIM applications have to able to determine the required parameters to assess the design criteria, Parameters in relation to design due to hand calculations are shown in below tables.

Design Parameters			
Partial factor	γ_G	1.35	-
Partial factor	γ_Q	1.5	-
Partial factor	γ_{M0}	1.0	-
Partial factor	γ_{M1}	1.0	-

Table B.6 Design Parameters.

The result of hand calculations is shown in tables C.7-C.8:

Results				
Element	**B-18**			Section is Adequate
Design moment	$M_{y,Ed}$	459	kN.m	
Design moment resistance	$M_{pl,Rd}$	468	kN.m	
Design shear force	V_{Ed}	230	kN	
Design shear resistance	$V_{c,Rd}$	807	kN	
Vertical deflection	δ	14.9	mm	
Vertical deflection resistance	δ_{max}	22.2	mm	

Table C.7: final results of hand calculations for selected beam B-18

Results				
Element	**C-14**			Section is Adequate
Design moment	$M_{y.Ed}$	6.6	kN.m	
Design moment resistance	$M_{b.Rd}$	286	kN.m	
Flexural buckling resistance	$N_{b,z,Rd}$	1989	kN	
Combined bending + axial compression		0.62		

Table C.8: final results of hand calculations for selected column C-14

To examine the reliability of implementation S-BIM, it must have the ability to handle whole parameters described above. All the described parameters are present for the evaluation of tests performed for simply supported timber beam.

C.2 PROCEDURES OF TEST 3 BETWEEN TEKLA STRUCTURES AND REVIT

In this following, the procedures of exporting 3D steel structure as a BIM model from Tekla Structures to Revit via different files formats (*.dwg, *.ifc, *.stp). All the procedures consist of indirect link (Tekla export file to specific type format).

Export to Revit via DWG file (TEK $\xrightarrow{DWG}$ RVT)

- Using **import CAD** ribbon under **Insert** into Revit

1) The model appears as a block, thereby there is no ability to modify the structure by the user.
2) No analytical data could be transferred via DWG.

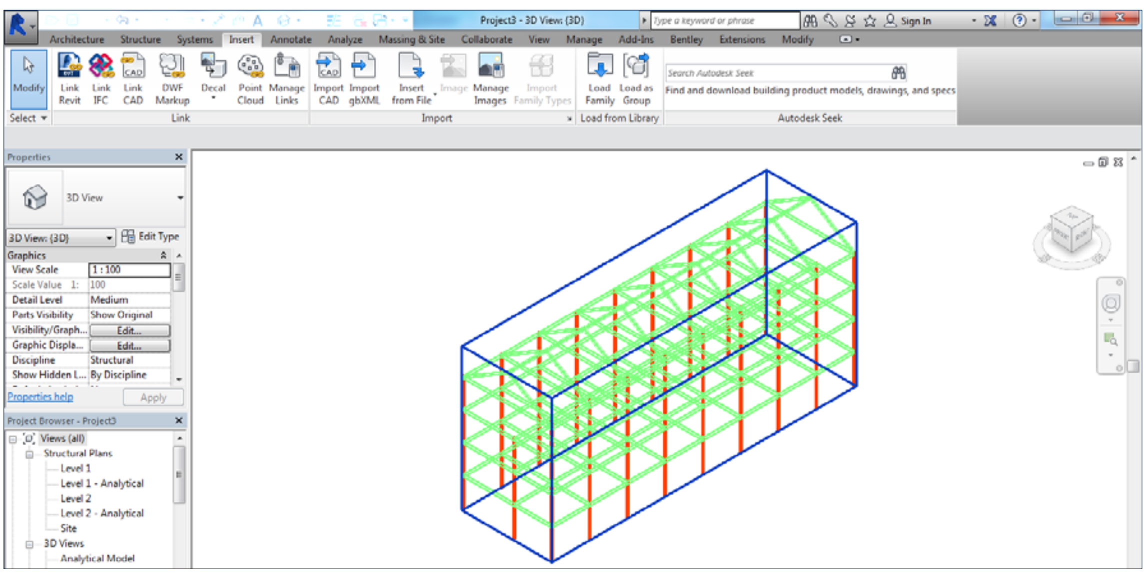

Figure C.2: The transferred 3D model via DWG in Revit

Export to Revit via IFC file (TEK $\xrightarrow{IFC}$ RVT)

- Using **file/open/ifc** ribbon inside Revit. (Choose IFC coordination view 2.0)

1. No errors, no warnings happen through transfer process
2. All members are transferred.
3. Each member appears as an object with its correct length, material profile and its right location, thereby there is ability to modify the structure by the user.
4. No analytical data could be transferred via IFC.

Export to Revit via CIS/2 file (TEK $\xrightarrow{CIS/2}$ RVT)

- Use ***Extensions*** ribbon inside Revit for *Import/Export CIS/2*

1. No errors, no warnings happen through transfer process
2. All members are transferred.
3. Each member appears as an object with its correct length, material profile and its right location, thereby there is ability to modify the structure by the user.
4. No analytical data could be transferred via CIS/2.

C.3 PROCEDURES OF TEST (3)

The procedures regarding with table 4.3 in section 4.6 results are described in this following.

Indirect link from RSA to RVT via CIS/2 file (RSA $\xrightarrow{CIS/2}$ RVT)

- Use ***Extensions*** ribbon inside Revit for *Import/Export CIS/2* to import CIS/2 file through *Analytical elements*.

1. No errors, no warnings happen through transfer process
2. All members are transferred.
3. Each member appears as an object with its correct length, material profile and its right location, thereby there is ability to modify the structure by the user.
4. No analytical data could be transferred via CIS/2.

Indirect link from RSA to SPro via CIS/2 file (RSA $\xrightarrow{CIS/2}$ SPro)

- Use normal indirect link for export/import CIS/2 file format transfer process.

1. All members are transferred
2. Columns profiles HEB260 are missing, However the user can add them manually.
3. Each member appears as an object with its correct length, some material profiles and its right location, thereby there is ability to modify the structure by the user.
4. Not all analytical data could be transferred via CIS/2, loads are missing.
5. Unknown message about missing members through transfer.

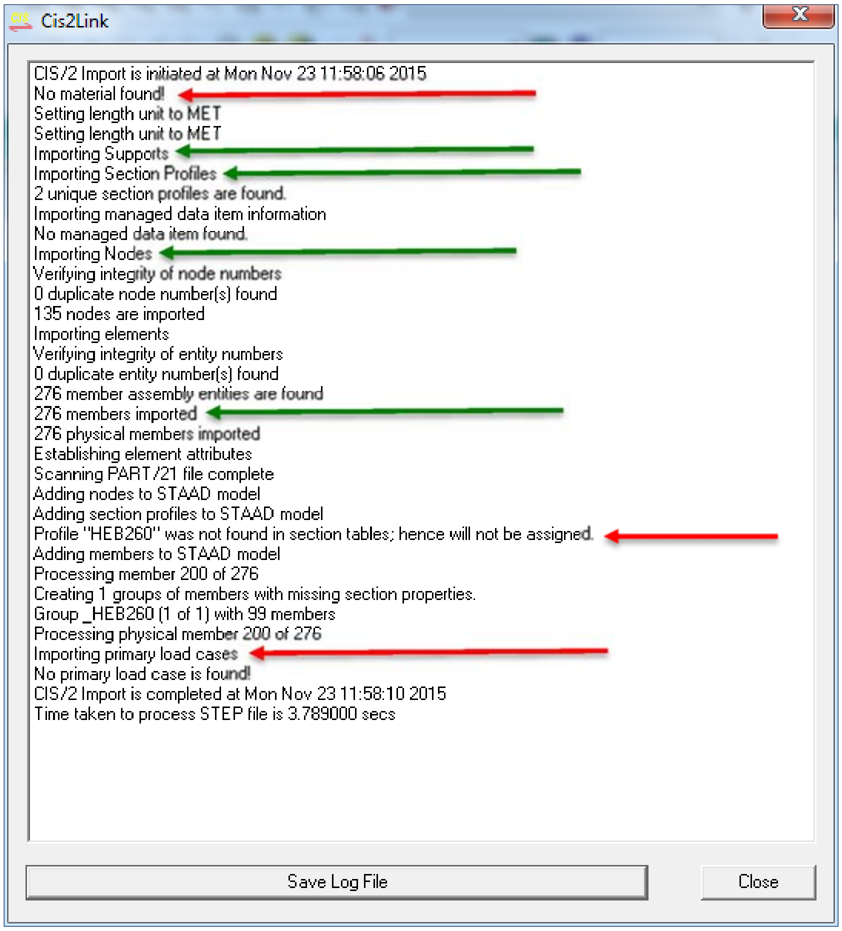

Figure C.3: Cis2 link message during exporting CIS/2 file into SPro.

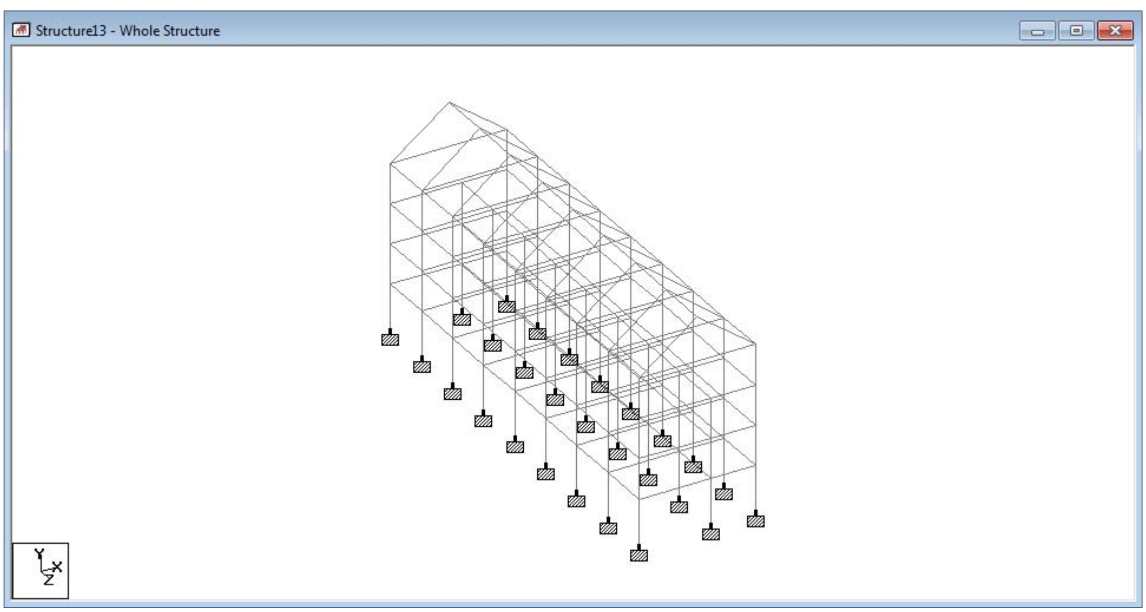

Figure C.4: The 3D steel structure modelled in SPro via CIS/2