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Interoperability between architectural BIM models and structural analysis software

Master Thesis

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Synopsis:
This thesis investigates interoperability between architectural BIM models and structural analysis software. Different architectural modeling tools and structural analysis tools are investigated for its capabilities in exchanging models through IFC and direct links. The tested software applications are:

- Revit Structure 2012 and 2013
- ArchiCAD 16
- FEM-design 9.0 and 11.0
- Robot Structural Analysis 2013

Tests of models exchanged through direct links have shown better results compared to models exchanged through IFC. It is found that the considered architectural software applications use the IFC Model View Definition “Coordination View” which has proven not to be suited for exchange of architectural models to structural analysis software applications.

Preface

"Interoperability between architectural BIM models and structural analysis software" is made as a Master Thesis in Civil Engineering on the Technical University of Denmark. The thesis is made from the 1st of February 2012 to the 15th of August 2012.

The study of this thesis has been supervised by Associate Professor Jan Karlshøj from DTU – Department of Civil Engineering.

Attached to this report is a CD-ROM with model files which have been investigated through the project period. Throughout the report references to the models are given; an overview of the CD-ROM content is given in appendix H.

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Abstract

The scope of this thesis is to investigate in which degree architectural BIM models can be used for structural investigations. The first chapter of the study clarifies the theoretical advantages connected to the use of BIM. In the first section BIM theory is explained in general and implementation challenges are discussed to address the need for using architectural BIM models for structural analysis.

In chapter 2 the focus is oriented towards the collaboration in project coalitions. Particularly the collaboration between architects and structural engineers is studied. It is defined which roles architects and structural engineers have had in projects using traditional planning approaches. New approaches better suited for BIM-based planning and some of the challenges in interoperability for architectural and structural BIM models have been introduced. The software applications Revit, ArchiCAD, Solibri Model Viewer, Robot Structural Analysis and FEM-design are presented as the BIM tools used for testing interoperability.

The third chapter introduces a case study used for investigation of practical interoperability capabilities. Building 324 is under construction at DTU campus and an indoor bridge structure from the project is presented as the BIM model used for the case study. Six different model exchange scenarios are set up and it is defines which information should be exchanged in them.

Chapter 4 goes through the processes in exchanging information from the architectural BIM models to structural analysis software applications. The tests which have been made are documented and test results are investigated. For each section a sub conclusion is made to sum up the results which have been found in the appertaining exchange scenario. The descriptions included in the chapter outline the processes, while detailed descriptions of each step of the exchange is given in appendixes. The investigations show that exchanging models through direct links can be based on an analytical model representation while an exchange through IFC is based on the Model View Definition “Coordination View” and therefore exchanges geometry based on centerlines. The ability to exchange material properties, loads and boundary conditions varies for the different exchange scenarios.

In the fifth chapter the results from the exchange scenarios are gathered and discussed. It is clarified how the test results facilitates the transitions from the traditional planning approaches to the BIM-based planning approaches. Finally it is discussed which future development is needed to reach a point where architectural models can be used in structural analysis software without the need for modification.

The conclusion of the thesis is that it is possible to use architectural models for structural analysis, but in the considered cases some modification must be made in the structural analysis software. Exchanges through direct links haves shown the best results, but improved IFC implementation is seen as the best path for future development.

Contents

Chapter 1

Introduction

This chapter introduces Building Information Modeling (BIM) from a historical perspective to give an understanding of the tasks related to the implementation of the methodology in the construction industry. Furthermore it is described what BIM is today and how it shall be used to gain full advantage of the method. Based on the description the challenges connected to a successful implementation are outlined and it is stated how the implementation can derive advantage of a common exchange schema.
Sections 1.2 till 1.4 describes the vision of BIM and not necessarily the current performance of the BIM tools.

1.1 Scope of thesis

Many challenges are connected to implementation of BIM working methods and the transition between different phases in a project process. Until this point it has been described in general which advantages and implementation challenges are connected to the BIM method. This report will focus on handling a small part of the challenges related to the interaction between architectural and structural BIM models.

The scope of this thesis is to test different exchange scenarios using IFC and direct links. The tests will focus on the ability to exchange data related to structural issues, such as geometry, material type, material properties and structural relations. The exchange scenarios are based on a part of a real project to create the most realistic results. The goals of the tests are to investigate the challenges connected to the procedure and define if architectural BIM models used for structural purposes give advantages in the design process. The testing of the exchange using IFC is compared to exchange of models using direct links.

Besides defining the challenges in the BIM working methodology the thesis will discuss which challenges are related to implementing engineers earlier in the project phase and which demands should be meet by the project coalition related to reusing BIM models for other purposes than they are initially made for. This will mainly be reflected by the work with structural and architectural models.

1.2 Building Information Modeling

BIM is an integrated digital method used for managing the lifecycle of a building. The method is used as a project planning tool for predicting costs, planning construction methodology and time estimation. The overall goal of BIM is to substitute the traditional planning, construction and operation methods in the construction industry by increasing the information level throughout the building lifecycle, ensure lower costs, increase quality and lower environmental impacts. The BIM method is in a developing phase and is not yet used in its full extend.

Practically BIM is a digital building model which contains information of a building project linked to the planning phase. 3D objects, such as walls, pipes etc., are the visual representation of the BIM model while information regarding the specific objects is attached. Time scheduling, cost estimation and facility management are denoted the 4th, 5th and 6th dimension, respectively.

BIM differs from the traditional building methods in the visual expression and in the way information is handled. 3D modeling requires that all objects are considered while the traditional plan and section drawings do not represent objects which are not placed in the sections. Using digital BIM tools the need for information, regarding placement each component, is needed earlier in the construction process in order to ensure the ability to affect the design with the lowest possible cost (described in chapter 2.1). The difference between the traditional construction method and the BIM method is a change that affects all practitioners in the building industry and a complete change in practice is essential to reach the overall goal of the BIM concept.

1.3 BIM history

The background for using BIM in the planning process lies in the history of the construction industry. Traditionally the planning of building projects were handled with paper based drawings describing building geometry using plans and sections. When creating building drawings by hand there were many man-hours in making changes and updating drawings. Therefore the transition from the paper based drawing procedure to a CAD-based (Computer Aided Design) drawing procedure was introduced in the early 1980s, when new computer technology became available. At that time digital working methods were already used for several years in the air craft and car industry, actually it was introduced in the mid 1950s in the US Air Force [1]. At first the digital work included graphical 2D representations, while 3D modeling as we know it today was first developed in the 1960s.

The first CAD software was commercially available by Autodesk in 1982 [2] and called AutoCAD. The first versions were able to make a digital presentation of the traditional hand drawn drawings, but no additional information could be added to the models. Therefore the building procedure was not changed due to the use of CAD. Even though there were no major changes in the construction industry the CAD software showed a value in decreasing the required man hours in the drawing processes.

In the early stage of CAD implementation computer force was an issue which influenced the implementation speed. Development of computer hardware went fast and parts of the industry saw a large potential in the products, but were intimidated by the rapid development. It was often seen that hardware was outdated in a short period and many saw advantages in waiting until hardware could cover the needs for a longer period of time to ensure profitability of investments in the hardware [3].

In 1987 ArchiCAD was released. This was the first program which was able to create both 2D and 3D drawings and is considered to be the first BIM application on the marked [4]. From that point on software have developed further and the possibility to attach information to the objects in building models is present in today’s software.

BIM software has developed since the 1980s and has to some extend been implemented in the industry in recent years. Studies have shown that the labor productivity has almost not increased in the construction industry from the time when digital working methods were first implemented until today. It seems that this tendency should be different since other industries have increased productivity. Figure 1.1 compares the labor productivity in the construction industry and non-farm industries [1].

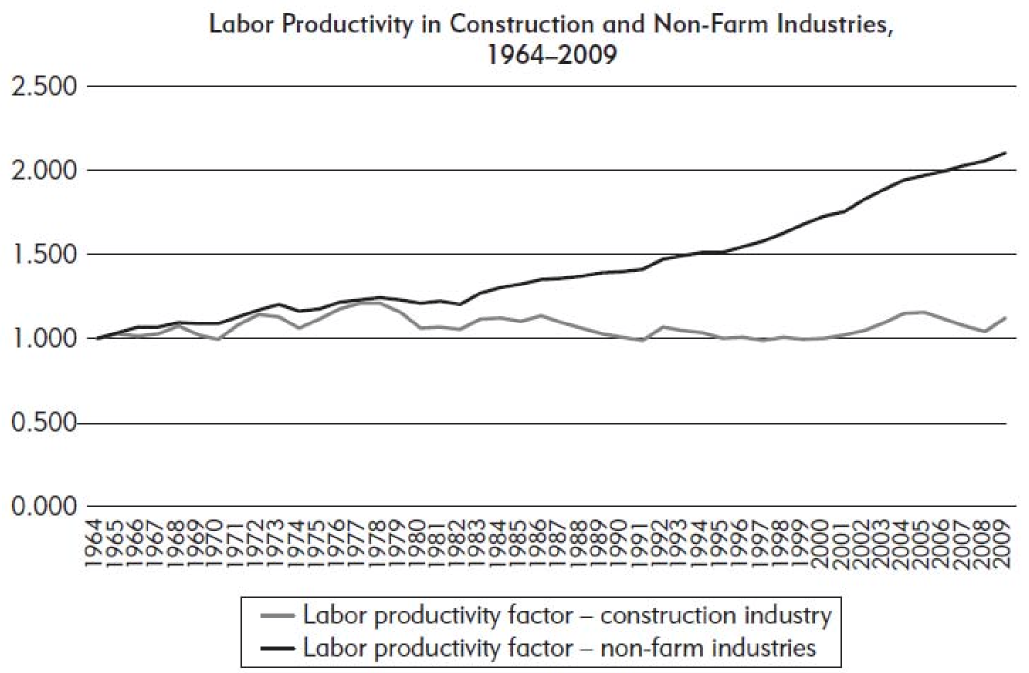

Figure 1.1: The diagram illustrates the development in labor productivity from 1964 until 2009 in the U.S. It shows that the productivity in the construction industry has not developed in the same speed as is the case for other non-farm industries. The diagram is based on research by Pail Teicholz at CIFE (Center for Integrated Facility Engineering).

The figure shows how other industries have managed to increase labor productivity in the last decades while the construction industry lies in almost the same level as in the 1960s. Assumed that the increase in other industries is affected by the technological development it seems that there is a huge potential which the construction industry has not yet utilized. In the following sections the technological advantages in using BIM are described; advantages that might help to increase the productivity in the industry.

1.4 BIM concept

BIM is used to digitalize the construction process. The method involves a construction process where a digital information model, shared through a BIM platform, is the basis of the project. In principle all project participators use the platform to extract information needed for their specific task and then update it when a task is handled. Theoretically this ensures the highest possible level of detail in all project periods, but there are conflicts related to responsibilities, contracts and economy that complicate the process.

The configuration of the platform differs depending on the project stage. A tender project is typically specifications of building requirements while the conceptual design involves a 3D model that represents the physical appearance of the project. The information attached to the BIM model are denoted the 4th, 5th, and 6th dimension. The dimensions describe time, cost and operation which are the tasks besides construction that are considered in the lifecycle of a building. In figure 1.2 a graphical description of the tasks are shown.

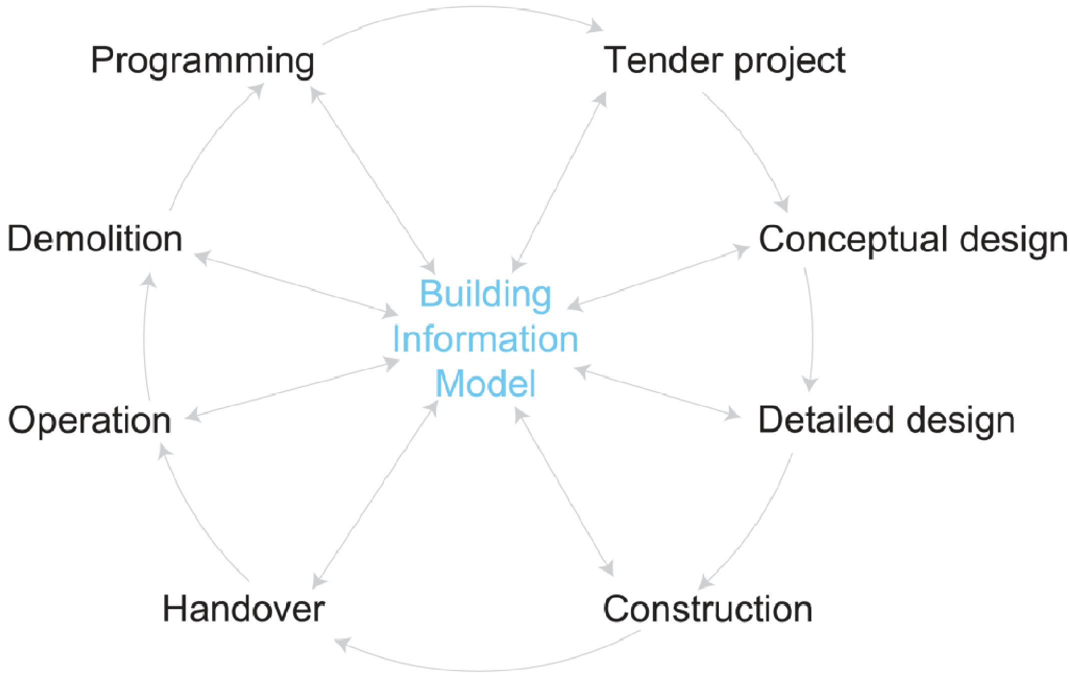

Figure 1.2: The figure describes an integrated building process where all tasks are handled with BIM. In this case BIM describes a common platform which can be accessed by all project participants and not necessarily one model only containing the actual building.

The following section describes a theoretically optimal process, ensuring full benefit of the BIM method, knowing that technical complications, lack in interest and other issues regarding the BIM implementation might mean that full benefit of the method is not practical possible in the present developing phase. It will later be discussed which challenges are related to BIM implementations and why it is still not common practice to use it in its full extend.

A **tender project** is made when a need for a building occurs. A developer describes the needs in the project and adds the information to the digital BIM platform, in figure 1.2 described as "Building Information Model". All project suggestions are then delivered digitally to the platform as **conceptual designs**. Since information about the building demands are given digitally all incoming suggestions are checked and evaluated in comparison to the demands before a conceptual design is chosen. The **detailed design** phase, done by the awarded contractor, starts with knowledge of the overall geometry and the demands that should be met in the design. All physical components are modeled in this phase ensuring compatibility in design parameters and all documentation is gathered in the BIM model. Contractors, engineers and architects are all working on the project in this phase to ensure that no mistakes are made when reaching the actual construction phase. The **construction** phase is planned using the digital platform; building components are ordered, time schedules are handled and the construction methodology is determined. Through construction all models are updated in accordance with the actual work progress and final structure ensuring that all documentation is accurate and available for the **handover**. This phase is the transition from planning and construction to the actual operation and use of the structure. A BIM model is handed over with information of all operation relevant documentation and it can be transferred to systems used for operation. When **operating** the building the digital model is maintained in order to ensure a complete documentation of costs, materials and other relevant information. The information is used when **demolishing** the building in the end of its lifetime. The gained knowledge ensures that materials can be reused in later projects and lifetime costs can be evaluated and make a basis for decisions made in new projects. Figure 1.2 denotes this **programming**.

The BIM method differs from the traditional building methods in a theoretical perspective, which is described above, since all tasks are handled digitally. The procedure does not completely reflect the projects which are handled with BIM in real life since software tools are not available to handle all parts that are described. The potential of the programming part can only be reached when having a number of BIM projects to base knowledge on and technical issues in the detailing process does complicate the work. Never the less there is reason to believe that more cost effective design and higher quality can be reached using the BIM method. This is derived from the MacLeamy curve, shown in figure 1.3. The curve is a way to show how the BIM method differs from the traditional building method.

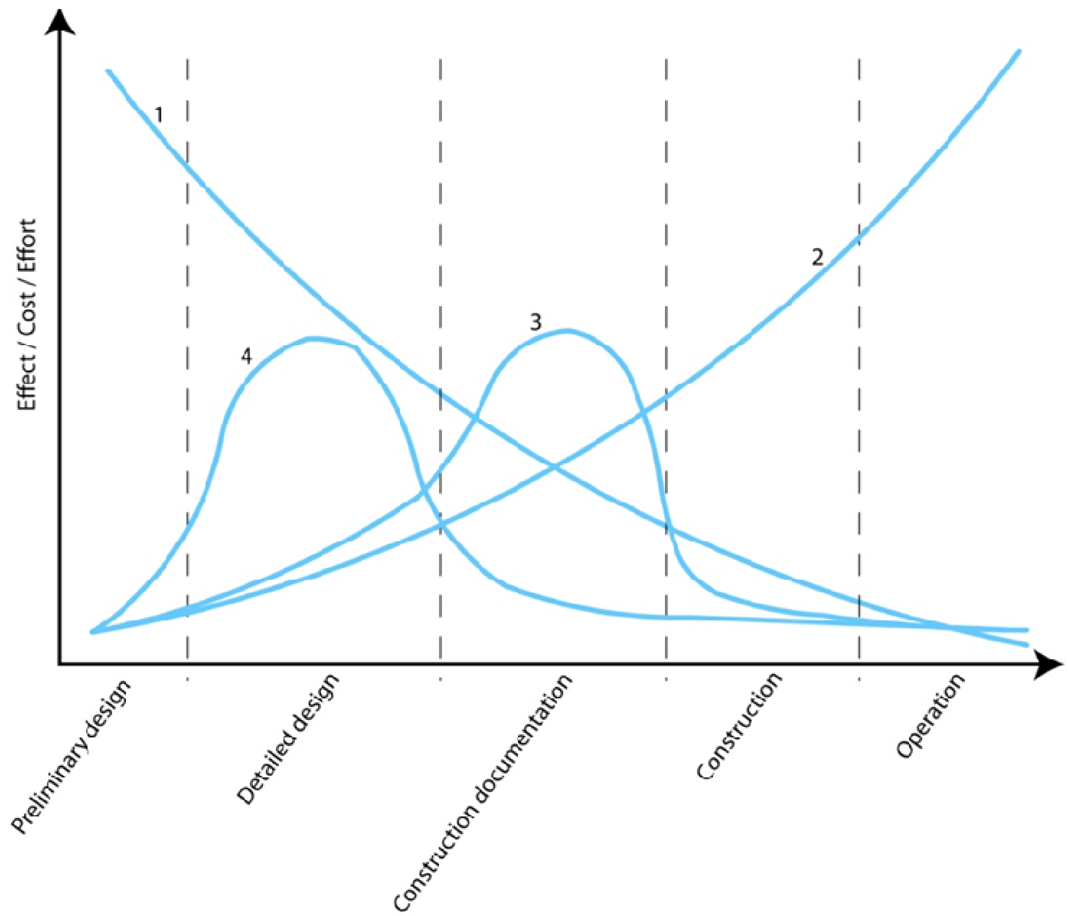

Figure 1.3: 1: Ability to impact cost and performance, 2: Cost of design changes, 3: Workflow with traditional building methods, 4: Workflow with BIM methods (Own illustration based on [5]).

The figure shows the ability to impact costs and performance in a project when different times in the project are considered. In the preliminary design period the project coalition has the ability to affect the design at a very low cost since nothing is finally decided yet. As the project period moves forward the costs due to a design change increases and finally in the construction phase it is close to impossible to implement changes since it will affect the design that has already been build. The advantage of BIM is that knowledge can be moved to an earlier phase of the building project. This ensures that changes can be made relatively cheap compared to the older drawing methods, but there are expenses in moving from the traditional method to the BIM method.

The information is stored in a BIM model and should be there early in the process. This means that some working hours are moved from the documentation phase to the detailed design phase. The benefit hereof is final projects that are more consistent and thoroughly prepared.

1.4.1 Tender project

A BIM based project starts when the developer makes the tender project. Here it is stated which purpose the project has, how large it should be and what the developer wants to achieve with it. This is the stage where it is defined that all project related material should be delivered digitally and ICT (Information and Communication Technology) specifications are made for the project. The specifications are made as a setup for digital communication and can be used if it is agreed in the project start. It is up to the developer to decide which of the specifications that should be used in the project.

When making a tender the developer describes the needs connected to the project, the description is the guideline for the architects when planning the conceptual designs. With BIM the project demands are given digitally with a description of the level of detail needed for the developer to compare incoming design suggestions. This procedure ensures that all proposals are delivered in the same form and the information attached to the suggestions can be handled digitally.

Information that could be relevant in this stage of a project period is quite simple. Areas, cubic meters and room functions could be some of the demands that should be delivered with the conceptual designs. When delivering this information with a digital building model the developer has the opportunity to check that all demands are met and facilitates comparisons of incoming proposals.

This method differs a lot from the traditional method were 2D drawings and visualizations are delivered as project proposals. With a digital tender project it is demanded to deliver a 3D model that includes the information which is stated in the tender project. This gives the developer a visual understanding of the project. The information attached to the model can be used for cost estimation and a comparison of incoming proposals can be made including like for like comparisons.

The method does give some advantages for the developer, but does also increase the work load of the architects in an early project stage where it is still not certain which project should be realized. The workloads will be larger until the tools are implemented and incorporated in the normal working procedure. To gain full advantage of BIM in tender projects interoperability and digital data exchange should be implemented in the design process. Besides technical issues there are some risks which should be taken into account when implementing new method. When using new tools there are many uncertainties and the workload might be different than what is first expected.

ICT specifications

In Denmark ICT specifications [6] specify how IT can be used in construction projects. The specifications are an offer to the project coalition which enables them to set up communication on a common basis. The specification contains general information about how to handle communication, CAD, tender and delivery. A specification is available for each of the four areas describing general practice considering the working procedure of the project. When projects start project specific additions to the specifications are made to ensure that the communication is suited for the actual project. It should be stated in the specifications when a project should be delivered using BIM.

Interoperability with Industry Foundation Classes or direct links

There are different ways to handle interoperability in a project depending on the software used and the agreements stated in the ICT specifications. Some software types support simple import and export of a number of formats while others are more locked, meaning that the software should be chosen carefully to ensure successful interoperability. This can be an issue that limits the construction industry which is why buildingSMART (see chapter 2.3) has developed IFC (Industry Foundation Classes), a neutral file sharing scheme supported by major AEC (Architecture, Engineering and Construction) software applications.

A common file sharing scheme gives all project participants the possibility to get the exact information which is needed, at the time it is needed, which is why IFC plays an important role for BIM. Besides the possibility of using IFC for communication between different software packages there is a possibility to use direct links. Direct links are available in many of the large software applications and are used to convert information to a "language" which is compatible by the software that receives the information (see chapter 2.4).

1.4.2 Conceptual design / Project proposal

The project proposals changes with BIM since the traditional methods are exchanged with new tools that offer the possibility to share information early in the conceptual design phase. In BIM projects the conceptual design models must contain information about some general questions which are relevant for all projects. Areas, cubic meters, room functions, access roads and the like are some general information that might be asked for.

The architects are challenged with a whole new aspect of their work and new tools must be learned to be capable of handling the changes. This means that some time is taken from the traditional sketching phase and moved to a more technological and locked modeling phase. To change working methods that are so ingrained in architects and designers are a large challenge since it is not just technical issues that should be changed but also the minds of those who have used the traditional methods. Never the less there are several advantages for both developers and for the architects. Architects are presented with a new way to express ideas for a project with a larger accuracy than earlier ensuring that the best architectural building concepts are realized in form of actual buildings. Some might argue that the new methods destroy the architectural creativity since sketching is limited to the functions available in the sketching software. Again it is a challenge to convince the whole project coalition that the advantages of BIM exceed the challenges and limitations which cannot be avoided when implementing new tools.

The level of detail in this period of a project is quite low. Areas, cubic meters, heights and settlement percentages are some of the information that could be derived from a BIM model at this stage. These are all information that gives the developer a possibility to compare the suggestions which are made on the same tender requirements. To use digital models this early in the process does not offer much information about engineering issues in the building projects, but simple calculations can be made already in this phase. With some experience about energy use in rooms used for specific tasks simple calculations can show the costs connected to the building volume. This gives the developer a possibility to affect the design in this stage with relatively small economical consequences. Also the structural system can be considered since for instance materials and span lengths are defined. The need for a detailed design is still not present, but a design can easily be evaluated by making a list if structural elements and compare span lengths and materials with earlier experiences or simple estimation.

The developer gets the possibility to investigate the difference of the proposals not only as rendered views and sketches of plan drawings, but as actual numbers describing the economical effects which might be just as important as the building expression. Facility managers get lots of material that can be used to estimate costs connected to the long run. Maintenance cost can roughly be estimated since the use of the rooms can be defined and the areas are present. Often these estimates are made in a simple calculation worksheet and it is therefore important that the information can be extracted directly from the model which is handed in as project proposal.

With BIM the conceptual design offers 3D presentation, the traditional renderings are replaced or supplemented with conceptual models that offer a whole new perspective to the decision process. It is possible to explore a project in 3D viewers where the developer can take a “walk” and “feel” the space in the project. Earlier two dimensional plans where a large part of a project proposal and the information where limited, especially for developers who might not have experience in reading building drawings. Besides 3D viewers which can be used on PCs it is possible to use 3D models in simulators, giving developers the possibility to experience the building sizes in a realistic manner.

Tender projects which are handled digitally give some extra work for the project coalition since 3D models shall be made, information must be attached and decisions of many details shall be made. This procedure takes time and some argues that the time consuming procedure takes the focus away from the design which is really important while others see a large potential in the digital methods and see an improved quality in the building process.

1.4.3 Detailed design

The detailed design process differs a lot from the traditional working method when working with BIM. All BIM objects are modeled in order to ensure that there are no clashes and to ensure that the model is consistent. Some objects are modeled in every detail while others are modeled more roughly. An example is windows which can be modeled with all details if it is needed, but in most cases it is not necessary with this high level of detail instead this information can be attached as a description. What is the color code? Does the window open right or left? The detailing level should be agreed on in the project to ensure which information is needed. This simplification of the model ensures a minimum work load and simplicity when using the model.

To use BIM in the detailed design process does mainly mean that all project participants can work in an integrated process. The use of integrated models is shown in figure 1.4.

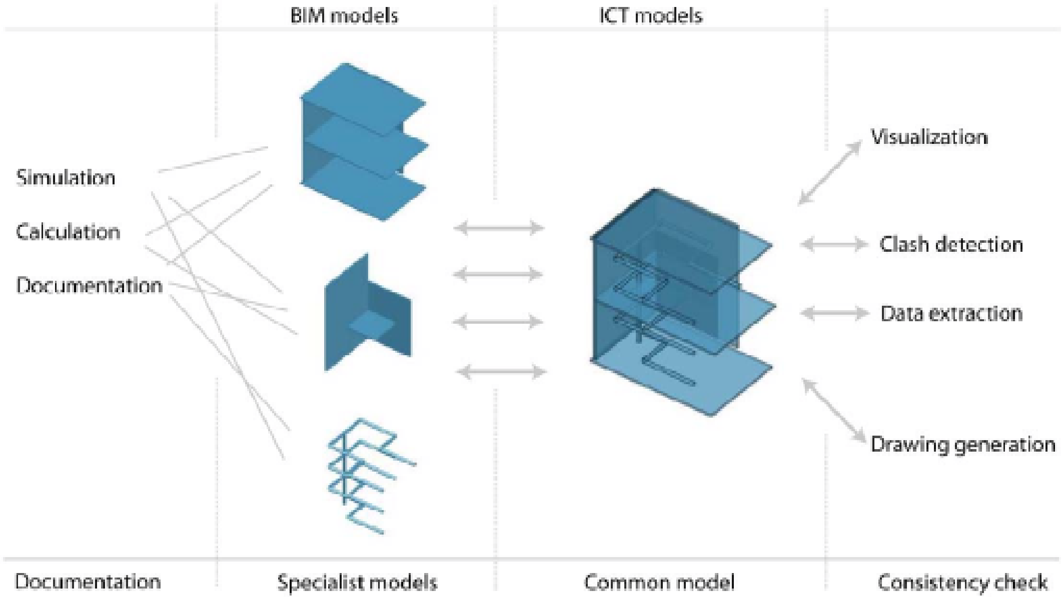

Figure 1.4: Illustration of integrated design process using BIM applications for special subjects and ICT for sharing information in a common model space. The right hand side of the illustration shows how consistency is reached by using the common model while changes are made in the specialist models. Two-way communication enables this working procedure.

As figure 1.4 states the working procedure includes data exchange between different models. Arrows are pointing in two directions meaning that modeling made in one program should affect other models when they are updated. This two-way communication is more theoretical than practical since the interaction in programs is not handled automatically for all BIM applications. This is one area that should be developed further to ensure interoperability between in the models.

Using the BIM method in the detailing process gives some advantages since clashes can be detected before construction starts. By gathering the models and investigating them in clash detection software it is possible to see where there are space problems. In some cases the problems are actual clashes, but it is also possible to check that all structural components are connected in the model. In comparison to traditional working methods it should be said that 3D modeling assures that all details are considered. In traditional section or plan drawings it is possible that some connection details falls outside the section drawings and are therefore not considered before made on site.

Visualization is another tool that is used also in the detailing process. When changes are made due to structural configurations, material properties or the like visualization can be made where the new expression is shown. The developer can use these ongoing visual presentations to see the process and to interfere if something does not correspond to the wishes.

Theoretically the documentation is made when the common model has all information attached, but this is still not the case in actual construction projects. This procedure demands that all project participants use the BIM applications and the model is updated throughout the project. Besides there are demands from the government to deliver BIM models as documentation for a building project.

Handling the detailed design with BIM is a large task since project participators should work in BIM platform and update the common model with the knowledge gained in specialist software. The challenge in this phase is to share the models and keep all relevant material after the data exchange. IFC offers the possibility to get all information from one program to another, but the support of IFC differs in different BIM applications. In the developing phase of BIM and using IFC for data exchange a lot of work is put into maintaining models and to ensure that all relevant data is stored. Challenges regarding the data exchange scenarios in a detailed design process will be describes later in the report.

1.4.4 Construction

Theoretically there are many differences in the construction phase that are changed when comparing the traditional building method with the BIM method. Most of the changes are related to planning which is actually done before the construction phase begins. Here the following topics are affected:

Time scheduling	- Visualized planning - Adjustment of time consumption related to site - Overview
Drawing material	- No conflicting versions - Paper prints on site
Procurement lists	- Planning of delivery times - No manual work - Elements related to building coordinates
As-build drawings	- Digital handover - Newest drawing material available

Table 1.1: The table shows the tasks affected by the BIM method in the construction phase and mention the change compared to the traditional building methods.

Since it is possible to model all temporary elements which affect the construction time the time scheduling is one of the issues which can be controlled in detail with the BIM tools. Drawing material can have the same form as in the traditional method but it is also possible to make 3D plots enabling the workers to visualize the construction better. Traditionally drawing sets were updated several times during construction, but this procedure can be simplified with BIM. Having a plotter on site enable workers to get the newest updates of drawings on the time it is needed. This saves work connected to printing new drawing sets, but does also assure that the newest versions are used at all times.

The planning does not only affect the time scheduling, also procurement lists can be handled digitally. By ensuring that delivery times of materials are suited with times where space is available on site, work can be made faster since space is available for the workers instead of used for storage of materials. Also no double handling is required.

Finally as-build drawings and other documentation can be handled easily when operating with a BIM model. The number of mistakes should be reduced since class detections can be made before clashes appear on site. The as-build drawings are rather simple to make since the geometry of a BIM model is made as objects which are constrained to each other. This ensures that if one element is moved the elements it is locked to will move with it or the specific object can be changed to symbolize the realized physical appearance. As-build drawings are not made as paper drawings but simply as the changed BIM model which is the documentation of the project.

The following section outlines the benefits which are connected with having a BIM based construction phase, based on the keywords of construction given in table 1.1, while implementation challenges are discussed in chapter 1.5.

Time scheduling

Just like other parts of the construction procedure the time scheduling can benefit from BIM based planning. Information about the time needed to build different components is attached to the model and a schedule is formed with this knowledge. The schedule will be much alike the time schedules which are used in the traditional building process (Gant charges), but the scheduling can be made more precise with BIM since all building components are considered. As stated earlier all objects should be modeled meaning that the time scheduling is made with a spatial overview ensuring that all components are considered and no surprises appear in the construction phase. A large problem on building sites is time consuming changes that are not planned in the original time schedule therefore it gives some delays when changes are made, this can be avoided with BIM, at least in theory.

Changes cannot be avoided completely since needs can be changed in the building period, delivery delays might happen, weather delays etc. The BIM tools does not provide solutions for all these factors that are not handled completely by the building coalition, but visualization of the construction process makes it easier to see how time schedules can be changed with the BIM tools. Additional construction time can for example be added in periods where bad weather typically appears.

By making a BIM based time schedule it is possible to make a quite precise time estimate since information is attached to specific building objects in the BIM model it can be specified where the objects are placed in relations to the time schedules. This means that installation time of elements which are placed on a higher storey for example can be planned to have a longer construction time than the same element on a lower storey. This ensures that there is accounted for the time it takes to get the materials to this position. Since the working times are longer for areas where more workers are present in the same time this is also a thing which can be handled in the planning process. In most cases it will be preferable only to work on one thing at each location, but it might not be possible if the delivery date cannot be moved and delays have occurred. The main point is that the economical effect of placing more workers in the same place on site is given in the BIM model and it can thereby be decided if the process is suited for the project. By evaluating economical consequence in all situations it should be possible to reach a lower total cost for a construction project.

Drawing material

The technical drawings are the basis of the construction on the site. Traditionally new versions of drawings have been printed for the contractors when changes have been made. With many changes in a project this means that there are several drawing versions available which leads to problems in communication. The communication should at all times be based on the newest drawing material which takes some work to ensure that the newest versions are printed and handed out to everyone. Besides the physical issues there is a lot of work in updating drawings in a construction project. Traditionally drawings have been made as 2D plans and sections, which are made without relations to each other. This means that a change that affects all drawings should be changed in all drawings manually, taking a lot of time.

Procurement lists

Theoretically there are many advantages in having a BIM project when procurement lists are made. When having a digitalized model the project coalition is able to send production drawings, based on the BIM model, directly to the producers and the original building drawings can be made to fit the exact measures which are given in the BIM model. This seems like a perfect way to minimize the working process and to minimize human mistakes since building elements should be documented to have the right proportions in the BIM model and this is the only reference for the producers. Even though this seems like a perfect utilization of BIM there are several problems related to the procedure, since all traditional methods should be renewed and contracts describing responsibilities should be updated. Also production relations are not implemented in a BIM model since producers organize their production to fit the production capacity in the best possible way.

The problems are mostly related to the working processes of the building element suppliers. If a steel element factory are working with an IT system which is not compatible with the BIM software the only way to implement BIM is to exchange the system or develop it to support the BIM models. Technological this seems like a manageable task, but the component firms should be encouraged to do it which seems most likely if the costs can be reduced. The fabrication companies are responsible for the products they deliver and their working processes are optimized to fit the own systems. Consequently it is necessary to demand the suppliers of a building project to use the BIM models and it takes time to educate and develop the supplier systems to manage the working procedure. Also the level of detail should be considered when using BIM models for production, since the architects might not consider product specific details which could give errors in a production.

These aspects should all be considered and it might not be possible to implement the theory, but there are definitely development possibilities that should be further investigated.

As-build drawings

The traditional procedure is to deliver as-build drawings when a project is handed over and going from the construction phase into the operation phase. As-build drawings are the newest versions of the technical drawings used in the construction process. The drawings are made to have a documentation of the way the building is actually made since the information is needed for renovating, modernization and facility management.

With BIM the actual as-build drawings are replaced with the digital model which is handed over when the building phase has ended. This model is fully updated since it is also used for construction purposes. Since the model contains a full and precise description of the geometry and material use it is relatively simple to continuously adjust the model when changes are made in the operation phase. Thereby the model can be used not only when renovating the building but also when the building eventually should be torn down. Theoretically all information about the building is available and it can be evaluated if there is an economical or environmental advantage in reusing some structural elements or materials.

1.4.5 Hand-over / Operation

When handling the transition from construction to operation BIM tools offer a direct transfer from the common model to FM (Facility Management) software. In the tender project it is stated which information should be present at this time and there should be no extra work connected to start up the management of the building. Since the tools are new for the project coalition it is not certain that the building cost will be lower for the developer. The operation of the building is therefore a subject which can convince a developer to demand BIM in the building phase since the operation should be handled easier and thereby lower the costs in the long run.

When going to the operation phase BIM can be implemented in the FM programs. Some tasks which can be supported by the FM systems and thereby the BIM models are:

Space	Space management Space allocation Interior layout Moving Furniture
Operations	Maintenance (interior, exterior, installation etc.) Supply (Heating, electricity, water, waste) Cleaning
Service inspections	Technical installations
Investment	Own / Lease Rebuild

Table 1.2: FM tasks which can be handled through FM systems [7].

Table 1.2 shows some tasks which can be facilitated using a BIM model and exists in most large companies who are typically the developers in large construction projects. The list might vary when dealing with specific specialized companies.

The following sections will specify which needs are connected to handling the tasks given in table 1.2. It is stated how a BIM model can ease the work connected to each of the tasks.

Space

To manage a space in a large building is an issue which is very important to handle in order to reach the highest efficiency possible. For office buildings this includes a complete utilization of the space and a reasonable area to spare for allocation.

Working space is often efficiency evaluated in regards to having a certain number of people working on a certain area. The efficiency depends on the working procedures, if work is done in groups, how large are the groups and the like. Most companies are adjusting the number of employees and the size of groups in order to fit into the current marked situation. Therefore a design of an office building should never be expected to look the same in the entire lifetime which is a very long period compared to a marked situation. The BIM model offers room descriptions, areas, usage percentage and other relevant information related to the adaption process. Having the model and in the entire building operation phase applying information of the usage of every square meter makes it possible to visualize how possible changes can be made and at which cost.

Operations

When discussing operations of a building it is maintenance, supply and cleaning which are the major tasks. With BIM a maintenance program can be made ensuring that all building components are treated well and the life span corresponds to the building life time. When having a maintenance program the material quality can be decided based on the estimated life span of the building. Besides material choices there are advantages in evaluating operations early in the process since choices can be made to suit the actual functions which should take place in the buildings. This leads to an operation and maintenance program that ensures the lowest life span cost of the building. Since a BIM model is an object based model it can be attached with information of every kind. This means that operations can be done according to the guidelines given by the suppliers and the quality of the building is lasting. The model organizes the information and descriptions are stored in the model, at each building component.

Cleaning is one of the most extensive and cost consuming tasks when operating a building. The cleaning is often organized via time schedules which are followed the same way every week for consistency. The work can be done either by a cleaning company or by staff connected to the specific building. Handling cleaning processes digitally gives a possibility to store long run costs of specific rooms with different materials. This knowledge will enable facility managers to affect the building costs when choosing new materials in renovations.

A BIM model could also include information about the use of specific rooms. If for example the model is synchronized with time schedules of the building users it can be planned that cleaning is only done when specific rooms have been in use for a number of hours. This ensures less cleaning and thereby a reduction of operation costs.

Service inspections

Inspection of all technical installations is a part of maintaining a building and should be done in certain intervals to ensure functionality and legal requirements. By handling inspections digitally a part of the work load is reduced. An example could be that a control system connected the ventilation shows an error that needs to be fixed and the landlord should call a specialist to come and fix the problem. By handling the problem digitally a picture could be taken and automatically sent to the specialist for whom it is to decide if a specialist is needed for the job or if a simple operation by the landlord is sufficient.

This is just one way of handling a problem digitally, but a system could just as well be handled all digitally by sending direct messages to specialists when errors occur without including the daily landlord.

There are products available to handle these digital service inspections. Dalux offers mobile reporting using smartphones or tablets [8], where pictures, movies and descriptions can be uploaded directly to a FM system. This method includes GPS coordinates which enables landlords to locate mistakes precisely and remove simple location mistakes.

Investment

When managing a large building it is important to use the space efficiently to ensure the lowest long run costs. In times where all square meters are not in use it can be beneficial to rent out some areas and share maintenance costs with the renters. When renting out property location and utilization of specific building areas influences which rental prizes are taken. A BIM model enables the facility managers to investigate changed flowcharts when dividing areas and thereby ensure the workability of the space. Also new fire plans, cleaning schedules and the like can be updated efficiently.

A long life span of a building can lead to changed needs for which reason reconstruction might be considered eventually. When considering reconstruction it should be seen as an investment and the planning is therefore a vital aspect for ensuring profitability. With knowledge of cost connected with specific spaces based on the former operations a design can be made the most beneficial way. BIM does in this case ensure knowledge connected to operation costs but can also be used when doing the actual remodeling of space.

1.5 Implementation challenges

There are several challenges related to the transition from traditional working methods to the BIM methods. The transition includes workers, but also planners who should organize their work with new tools. New systems might be relatively simple to implement if only one task is a part of the change, but with BIM the advantage lies in the integration of different systems written in the same model. Information flow relies on the functions BIM tools offer and the correctness of the included information throughout different stages. This is of high importance for assuring profit.

Technical challenges such as using common file formats and defining responsibilities for different project participators is connected to the tasks that lies in the future implementation of BIM, but the first obstacle to overcome is to convince developers that projects should be made with BIM. The traditional bidding procedure ensures that developers are ensured a cost estimate on a construction project before a detailed design is made which enables the developer to determine budgets. The value in BIM is to make decisions in the entire design situation, but a challenge lies in convincing the developers to demand BIM projects and thereby ensure a lower cost considering the entire life time of the building.

The technical challenges of BIM are both related to communication and actual technology. Many software applications are available and cover a large part of the tasks which are needed in a construction project, but details handled in a specific application has no value if it is not communicated in a way that enables all relevant project participators to see and understand the information. To some degree software used in the construction industry should ensure that information is shared with relevant information attached, but if the responsibility lies on an information receiver everything might be modeled and created again to ensure that the information is correct. An example could be steel fabricators who could produce elements based on a common BIM model, but are responsible of the delivered steel components. Therefore it might be safer to redraw models and thereby ensure that all conditions are evaluated correct. Adjustments on site are more expensive than adjustments in models which make it difficult to encourage project participators, such as steel fabricators, to rely on common models.

Education of staff is another issue that complicates the implementation of BIM. Companies who have based their development on the traditional methods might not be capable of handling a BIM project at first since the entire working process is replaced. Education of staff and tests of BIM tools in ongoing projects are some tasks that should be made to prepare the staff to BIM.

Implementation of BIM is a huge communication task since many of the same building components modeled in a common model should be used for many different tasks. Figure 1.5 shows a simple, but very descriptive example of a communication task.

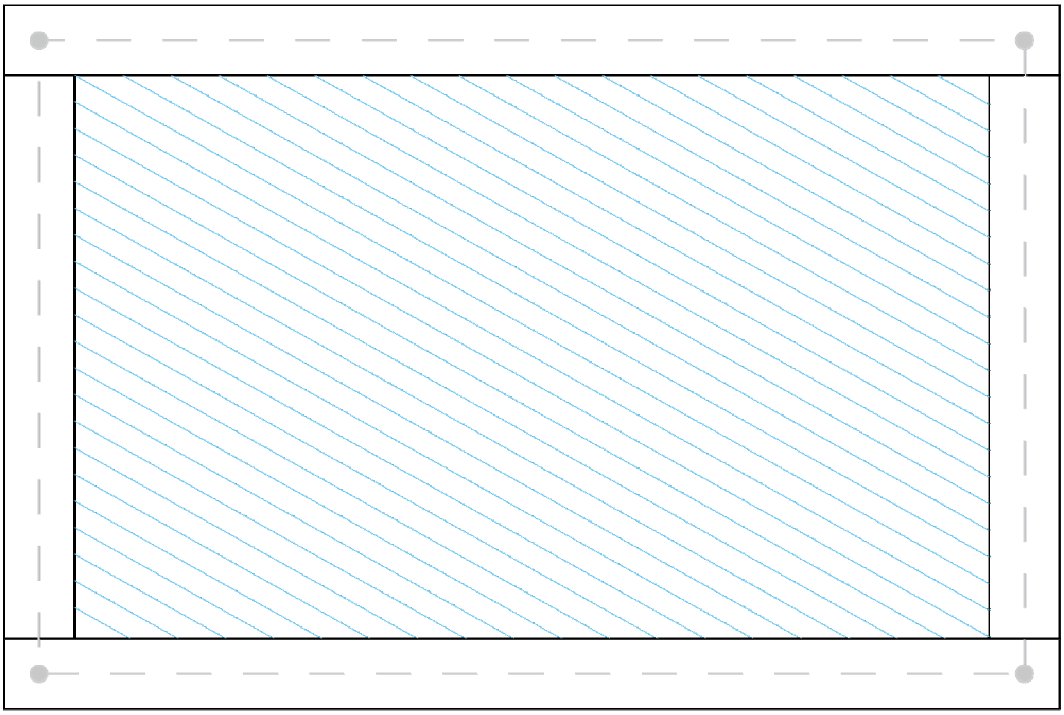

Figure 1.5: Example sketch for explanation of different needs to a simple rectangular room. The floor area is marked with blue, the centerlines are grey while the walls have a black tone.

The room has a floor area marked with blue which describes the interior area. This area could be used for calculating how many square meters of floor is needed or calculating the costs of maintenance and cleaning, but the area marked here does only describe which area is needed for a limited part of the BIM users. For estimation on total costs in an early phase of the project the whole area including the walls should be used. If rooms lie up against these walls the important area might include half of the wall area for each room and a new situation is present. Considering the walls, there are also a number of issues that complicates the way they are modeled. The grey lines are the center lines of the wall elements and could be the lines that a structural investigation is based on. Here they are shown in the center of a simple wall element, but the situation will change if the wall does not have the same surface on each side since the center line will move if it is based in the total width of the wall. The wall connections introduce another issue related to communication. The center lines are connected, but do not correspond to the length of the walls. If a model is used for planning fabrications of elements is should be assured that the actual lengths are considered and not the lengths of the centerlines.

Using a rectangular room as an example clarifies some of the difficulties in a simple manner. The challenge in agreeing on where to measure areas might not be the most difficult task, but it shows that a BIM model should include a lot more than one simple representation of each element if it should be used for several tasks.

With the assumption that the BIM tools are capable of handling all information needed for all project participators there is still some obstacles to overcome in order to benefit from the tools. The responsibility of correct model information should be addressed before it is reasonable to believe that project participators will rely on information from a BIM model. If the users of the model information cannot be guaranteed that the information corresponds to their needs it is more than likely that the project material will be remodeled or investigated further before it is used and all benefits are lost and further mistakes can happen as work will be done in several models.

Exchange of data should be handled successfully to ensure the lowest risk of making mistakes. IFC is one way of ensuring a common language that can be handled by everyone in a project group, but there are also a number of direct links between different software applications. An implementation task is therefore to make agreements on the way digital data are handled throughout the construction period. Can agreements be made in a way that enables all project participators to rely on the common material a large part of the task is solved. The project participators can familiarize themselves with the IFC data exchange as well as the functionality of the direct links in the software applications in smaller projects or test projects to capture lessons learned and prepare for a big scale project where the real benefits can be seen.

Chapter 2

Collaboration in the construction industry

This chapter describes different construction procedures from the planning phase until hand-over. The Design-Bid-Build, the Design-Build and the Integrated Project Delivery approach are all explained and it is defined how they facilitate the use of BIM. Also challenges related to interoperability between architects and structural engineers are defined. It is defined how direct links and IFC theoretically facilitates interoperability and the software used in the following chapters is described.

2.1 BIM – A change in practice

The transition from the traditional working methods to BIM based planning is a large challenge which is well defined in the BIM handbook:

> *"Building Information Modeling (BIM) can be considered an epochal transition in design practice. Unlike CADD, which primarily automates aspects of traditional drawing production, BIM is a paradigm change" [1].*

To address the transition to BIM-based methods as a paradigm change illustrates how comprehensive the procedure is and how many aspects of the construction industry is affected by the changes.

For the architects the transition to BIM does mainly involve a change in the time where certain information is needed. The traditional tender procedure demands relatively simple models or drawings where many considerations are left until the competition has been won, while the BIM projects demands that all spaces are determined and that the constructability is considered. The affect of this transition differs from architect to architect. Some companies have been using 3D modeling for years in order to construct spatial illustrations giving the developer insight in the considerations behind the chosen designs while others have limited their work to simple 2D drawings and the use of picture editing for producing illustrations.

Engineers are also affected by the transition to BIM methods. Estimations on energy use, evaluation of structural design and optimization of structural elements are some of the issues which should be implemented in an earlier phase than what has been the case in former projects where traditional methods have been used. Digital tools should be updated in order to suit the BIM working methods. Engineering software should be capable making estimates and calculations based on information from a BIM model in an early phase to ensure that as many aspects as possible are considered in the first designs.

To gain full benefit of the digital tools which are available in the construction industry changes in the construction procedure should be considered. The traditional Design-Bid-Build (DBB) and the Design-Build (DB) procedures are the most common in the construction industry and are explained in detail compared to BIM in the following sections. Also Integrated Project Delivery (IPD), a collaboration form, specifically developed to support the advantages of BIM is considered.

2.1.1 Design-Bid-Build approach

The DBB approach is the most common for public construction projects and covers a large part of private construction projects as well. In 2002 the approach covered almost 90% of the public and around 40% of the private projects, making it the most common building approach for public projects [1].

The main stages in the DBB approach are given in figure 2.1. The DBB approach can be divided into 7 stages; Program, Schematic, Design, Bidding, Design detail, Construction and Operating. The professions which are considered in the figure are restricted to the largest professions who take part in construction projects – Developer, Architect, Engineer, Constructor and Facility Manager.

The figure shows who take part in making the construction program which provides the basis of the project. It shows that engineers, constructors and facility managers are included in the project after a specific design is chosen by the architects. One limitation for the DBB approach is that the tender should be won before detailed design is considered which leaves out the possibility for specialists in specific topics to influence the project when it is economical reasonable according to figure 1.3 in the introduction.

Program: The program is the first phase considered in the project. Here the developer makes a written report containing a list of requirements for construction project. Typically it is defined how many square meters are needed, which functions should be there, how rooms should be placed according to each other, which constrains that are related to the construction site and what building codes should be used. The developer might have an advisor for describing building codes and other technical tasks.

Schematic: In this phase architects are included in the project. Plans, building models and visualizations are made and the building concept is determined. The phase might include several proposed projects since the tender has not yet been won by one specific part. The goal of this specific phase is to find the most promising design solution. Before moving to the next stage the project developer decides on the best suited proposal for further process.

Design: The chosen design is further developed and precise dimensions and appearance is decided. The level of detail achieved in this phase is what contractors and engineers should place their bids upon. Besides making construction drawings contractual relations are defined. These are used to clarify the content of the bids that are placed in the next phase. Engineers are typically included in the project in this phase since constructability of the project shall be assured.

Bidding: Based on drawing material, drawings and descriptions bids, to win the project, are placed by contractors. Typically the cheapest offer wins since the drawing material offers a specific description and only building procedures can vary for the contractor.

Design detail: Having the contractor in place the details of the project are developed. All materials are chosen and time schedules, procurement lists and building topology are made in collaboration with the contractor. Since the largest decisions regarding the space for installations, structural materials and the like are chosen in the design phase the contractor does not have the possibility to change anything major in the project, at least not at a low cost since changes can be expensive in this period of a project. In some cases the work on ground level might have started before the detailing in the upper stories is even considered.

Construction: When going to the construction phase the roles are changing. Architects and engineers have made their project contribution and it is up to the contractor to do what drawings and descriptions states. Architects and engineers are still responsible for following up that the work is made according to the project plan.

Operation: The transition from constructing to operation is typically based on a day where the entire project is delivered. From this point on facility managers get the responsibility for maintaining the building and thereby ensure the quality. The responsibility includes maintenance according to descriptions delivered with the project in order to assure guarantee on the building components.

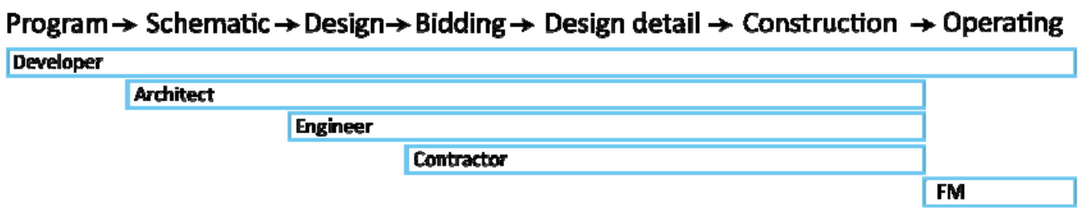

Figure 2.1: Stages in the DBB approach and those who are connected to the specific stages. The bidding phase marked with blue to address that this phase is the one excluded in the DB approach.

There are several aspects in the DBB approach that does not suit the BIM methods, which supports the statement, that "*BIM is a paradigm change",* since the most used building approach in public projects does not seem suited for it.

Figure 2.1 shows clearly that engineer, contractor and facility manager is taken into a building project late in the project. Therefore their competences and experiences cannot be implemented in the original project. Architects are responsible for making the schematic design and decide on the spaces which are reserved for MEP and HVAC while the structural configuration is based on assumptions. Actual calculations and dimensioning are left for the detailed design where engineers are attached to the project. Also constructors are not a part of the project and the building topology cannot be discussed in this phase. The procedure forces the contractors to remodel the structure when planning, this procedure being both time consuming and a source for making mistakes.

Since different professions are included in different steps during the process there will always be details which does not appear in the written material and discussions about contractual responsibilities is therefore a part of the DBB approach. Many actors are present and the contracts are a large part of the administrative work in the process. This section has considered engineers to be only one part, but there might be several engineers involved in the project since most companies only offer one part of the engineering tasks.

One might ask why DBB is the most common building approach with this kind of disadvantages. The reason seems to be due to competition between bids on all part of the job, which gives the developer a possibility to choose the cheapest solution for the wanted project. Never the less it must be said that this approach has been dominant in times where the BIM tools, which are known today, have not been present and the life time costs, early energy estimations and the like has not been seen as design criteria, which were possible to handle or had such a big impact on the project economics.

2.1.2 Design-Build approach

The DB approach is developed to overcome some of the challenges connected to the bidding procedure in DBB. Figure 2.2 illustrates how the bidding phase is removed compared to the DBB approach.

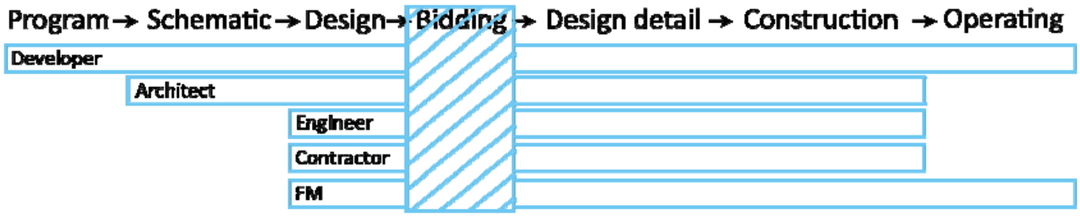

Figure 2.2: The difference between the DBB approach and the DB approach illustrated by excluding the bidding phase.

Removing the bidding phase means that the project coalition can be determined earlier in the process. The procedure allows one large contractor to take part in all decisions considering the project, which means that only one contract should be made for the entire project. Using this approach a general contractor must be able to handle everything from architecture to building management programs to ensure that decisions are made on the best basis possible.

To remove the bidding phase from the process gives the developer a smaller chance to ensure the cheapest bid since one general contractor gets the responsibility for all sub-contractors. The value for this procedure is connected to the time where decisions are made. To take an example; fire engineers are participating as consultants already during the first schematic design where choices and changes can be made at the lowest cost possible ensuring the project to reach a high quality and consistency in the project material. Escape rules can be discussed since room connections are already established at this point. A relocation of a room with a particularly high fuel load might better fulfill the escape rules. Thereby expensive fire resistant materials can be saved and the regulations are still fulfilled. Also the sizes of fire cells can be discussed in an early stage. A small reduction in room size might lower the considered fuel load to a point where fire insulation can be reduced. If the change has no architectural or structural effect a change can be made and costs related to insulation material is reduced.

From a BIM perspective the DB approach offers the opportunity to apply all available tools since the bidding procedure does not prevent a part of the project coalition from participating in the early phases where value can be added to the project. Should one obstacle for this approach be mentioned it is the opportunity for the developer to make changes after having made an agreement with the general contractor. When a general contractor is hired early in the building process a total price will be agreed on and the developer is therefore left with large economical consequences if changes are made in the construction phase. However, having one general contractor can be beneficial for ensuring that a project is delivered at the right time. Day fines for non-delivery and bonus for early delivery might ensure that the "risk / reward" situation is worth taking.

2.1.3 Integrated Project delivery

IPD follows the intentions of BIM quite close. The main goal of the collaboration form are to move from the traditional approaches to an integrated approach where the developer and facility manager is included in the project from the very first phase in order to get all aspects included in the initial design. The construction phase which is known from the traditional approaches is not considered in IPD since they are seen as barriers for the integrated design [9].

Using IPD the BIM tools should be used from the early stages until the project is going into operation. This ensures that the interests of the developer are followed since a great advantage of the BIM tools is to consider long run costs of energy consumption, maintenance issues and the like. Many developers might also have an interest in showing respect to the overall environmental impact, which in a building project can be done by using sustainable materials and assure the lowest waste percentage of the material, which is practical and economical feasible. A way to reduce the material use is by using project specific prefabricated elements whereby only assembling will be done on the construction site and no excess should be present. In the work with 3D models and visualizations BIM facilitates the prefabrication of elements and is therefore essential for projects with focus on the environmental aspect.

2.1.4 Implementation of BIM considering building approaches

The building process approaches which have been introduced goes from a traditional approach where traditional tools have been used to an approach where BIM applications have been considered when developing it. IPD requires a project coalition with a great knowledge of BIM interoperability and specific BIM tools. This makes it complicated since implementation of a part of the tools where value adding is proved will be the most normal implementation procedure.

Implementation of BIM being both a change in the contractual relations and a change in design- and operations tools makes the implementation a long process. To gain full advantage projects should be made using IPD but to reach a point where a project coalition can take part in IPD the BIM tools must prove efficient on projects made on basis of DBB and DB.

2.2 Collaboration between Architects and Engineers

In chapter 2.1 some building process approaches have been discussed and interoperability in the processes has been found necessary for the utilization of BIM. The time where collaboration of different groups of the project coalition are supposed to share information is different depending on the construction approach, but for all approaches it is seen that collaboration is necessary to achieve the advantages that are connected to BIM.

This section seeks to describe the information which should be shared in a given time of the project period between architects and structural engineers. In the schematic design where the first design decisions are made and where the knowledge on materials and building topology is still not decided to the point where all decisions are made and the engineering effort is on documenting the structural behavior, energy consumption etc.

Using the traditional DBB approach the information flow from architects to engineers has, to some extent, been one way, meaning that the schematic design is made in a project period where engineers have not been included in the process. When structural engineers are included in the project the cost of making design changes has increased, leading to solutions only chosen to limit the costs instead of reaching the desired quality in the building.

Having used the DBB approach for most building projects there are some challenges in adjusting software to another level of detail. Taking structural analysis, as an example, FEM (Finite Element Modeling) software is developed to prove and document design of structural elements which is needed when following the DBB approach. To move from DBB to DB, IPD or other integrated design processes the detailed calculations are not needed for the preliminary designs since final decisions have not yet been made (will only be the case if the detailed calculations cannot influence the costs of the project). Never the less there is a need for structural understanding of suggested designs since this will also give a better possibility see potential problems that will occur during construction.

In an integrated design process there is a value in limiting the times that similar building components are modeled since mistakes are reduced and working hours are kept on a minimum. However, a precondition for reducing mistakes is that components should still be modeled in way that satisfies the needs for all project participators using the models. To make architectural models that are useable in structural engineering software requires models with a higher level of detail giving the architect more modeling work in an early phase, assuming that the modeling software requires more information to elements used for both architectural and structural investigations. The following chapters describe the content in architectural and structural models to establish a basis for the investigations of the data exchange between the parts.

2.2.1 Design with BIM

Architecture has, in traditional projects, been visualized using hand drawings in paper based formats. The transition to computational modeling of conceptual designs have been under some critique due to the limits that are present in the digital modeling tools. Using the BIM tools designers must stay within boundaries made by the available structural elements. Conceptual design tools such as Google SketchUp and Rhinoceros are available but are not yet seen as BIM tools since the generation of 3D models are the main purpose of the programs. A more complicated but definitely a part of the BIM software package is the Revit software from Autodesk where conceptual models also can be made. The building mass can here be created and divided into different stories, rooms and facades when the detailing level increases.

It is a possibility to make special forms in a BIM application but generations of real complex shapes is still not possible in BIM software [1]. Even though there is a lack in conceptual design tools many projects should be realized using BIM in the future since the advantages of BIM are also present for not that special geometry designs.

The present limitations of the BIM software might give some challenges connected to the architectural freedom in the initial design phase, but the reuse of information is a point that BIM projects can benefit from also in the initial designs as described in chapter 1.3. When the work with BIM progresses the architects will create a library of building parts that have been modeled digitally and the time consumption for modeling a building for review (only considering a low level of detail) will be minimal compared to the traditional approach with actual cardboard models and picture renderings. It should be said that it is not realistic to believe that all components can be stored in a library.

2.2.2 Model exchange for architects and structural engineers

The levels of detail in architectural models change when the work progresses towards a final design. Traditionally the first models are hand drawings that only describe an overall geometry where considerations regarding fabrication of structural elements and the like are not considered. Using the BIM tools the possibility of making free hand sketches and lines is not supported since the transition from sketch to construction model should happen by increasing the level of detail. The modeling process differs from one software application to another, but in general the same challenges occur.

In traditional CAD software buildings were presented as plan and section drawings and to some extend a 3D model giving an overall understanding of the geometry of a project or a specific detail. With BIM all geometry is modeled and each building component contains some information needed for other details than the geometric representation. To use an architectural model for structural calculation does therefore require that the information needed in structural FEM software is included in the BIM application used to create the initial architectural model. A simple, but quite relevant, example could be the representation of analytical lines in a connection between a concrete wall and a slab. FEM software uses the analytical lines for representation of the connections and to connect building elements where loads are transferred from where it is assigned and to the supports. Analytical lines are typically placed in the center of the building components to have symmetry in the load added on the specific component. Figure 2.3 shows a representation of analytical lines.

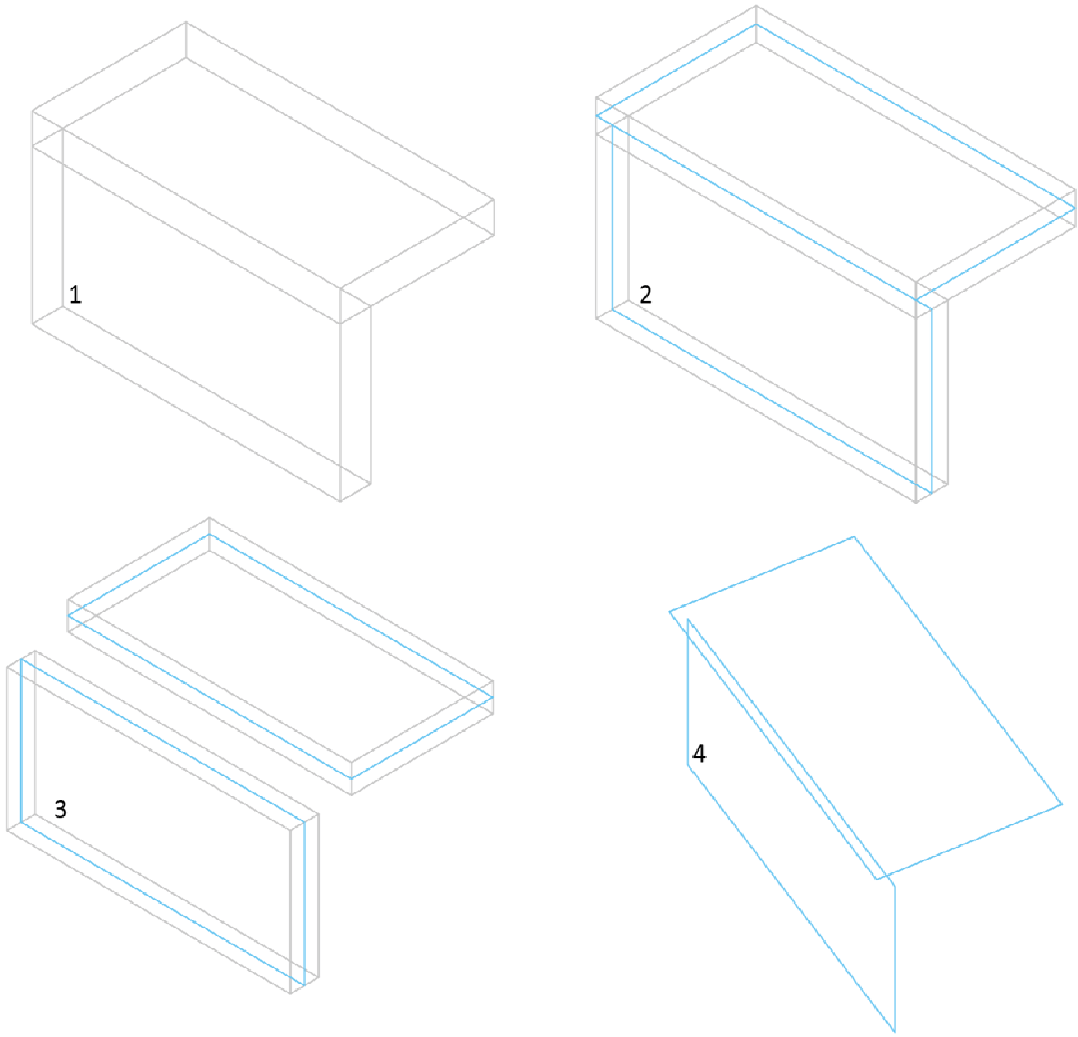

Figure 2.3: The figure illustrates challenges connected to the use of architectural models in structural analysis software. (1) shows a connection of a slab and a wall where the geometry seems to correspond to a real but simplified situation. In the second part (2) the analytical lines are added in the centerlines of the slab and the wall. The third picture (3) shows that the wall and the slab have a similar geometry but are oriented in two different directions, while the fourth part (4) shows the actual challenge when collaborating through different software. When moving the geometric representation of the walls it becomes clear that the analytical lines are disconnected.

This illustration clarifies that a model made in one software application can be useless in other applications if it has not been considered how the data exchange is handled. In the considered example it is assumed that the software application uses the analytical lines for calculations, but it could also be outer geometry that is transferred to a software application that is not suited for exactly this geometry. The main point is that quite simple interoperability issues might be difficult to handle. Also coordinate systems and load directions could be different in the software application which is why there should be focus on the process when planning an integrated design process.

2.2.3 Integrated design situations

The use of integrated design and the possibility to affect a building project in an early phase is related to exchange of models between different project participators. To reach the best possible solution an exchange scenario between architect and engineer could happen as shown in figure 2.4.

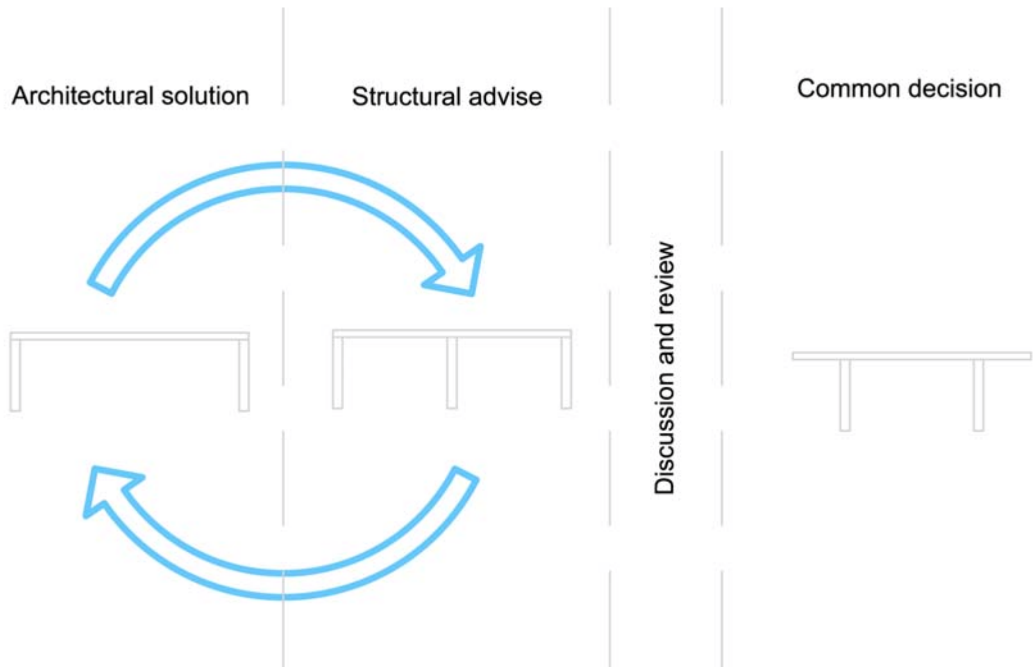

Figure 2.4: Schematic illustration of workflow in an integrated design decision about placement of columns with a fixed span length and slab thickness.

The theoretical workflow in a design situation includes a building model which is exchanged from an architectural software applications to a structural FEM program (illustrated with blue arrows) in order to find the best possible solution, here illustrated by a slab with a fixed span length with different supports. Different architectural solutions can be investigated and a structural advise given. Based on common discussion and review the best suited solution is chosen. This simple example shows the importance of interoperability and data exchange between architectural software and structural FEM software. The workflow of the integrated design process is facilitated by easy interoperability, since the process should be repeated several times at a very short time, to find the best solution possible.

To benefit most from an integrated design process as shown in figure 2.4 the demands for the BIM software is clear; Software must be able to handle two-way communication. The interaction between the software applications must be handled as smooth as possible. If manual work is needed when a model is exchanged from architects to engineers the process is more time consuming and the full potential related to cost in the BIM working method cannot be reached. In the same time responsibilities of changes should be agreed on which makes it more than a technical task.

2.2.4 Interoperability

Different software is used in the construction industry and the major task when using BIM is to combine models made in different software, compare results and make a project material where clashes and inconveniences are avoided in the construction phase. It is the phase where expenses can be reduced and profit gained.

After the construction phase the project material within BIM should be used when managing the building. This requires that the model data can be operated by FM software as well as the technical software used in the construction phase. Theoretically the best way of using digital tools in the AEC industry would include a common model which should be able to receive information from all softwares and make changes to already implemented information to ensure consistency in the material. This process should happen with no manual interference since this could cause mistakes in the process. This theoretical perfect procedure would require a software application capable of handling all parts of the construction process, from planning to operation. It seems that such an application will not be developed in the nearest future and the need for interoperability between different applications in the industry is therefore a present challenge on the development of BIM.

2.2.5 Communication path

Collaboration in the construction industry with model sharing in integrated design situations using the BIM tools give some challenges related to the traditional working procedures. Figure 2.4 describes how an integrated design process can be beneficial to the value and layout of a construction project in theory while the practical approach is described in this section.

When the initial architectural models are made are the design considerations the most important issue for the architects to find the best suited solutions. Typically many models are used and evaluated to find the best suited solution for a specific purpose. This methodology continues when further detailing are added to the models. Therefore software applications used in this phase must be able to handle frequent updates when new considerations are made. Figure 2.5 shows the procedure considering the architectural model updates.

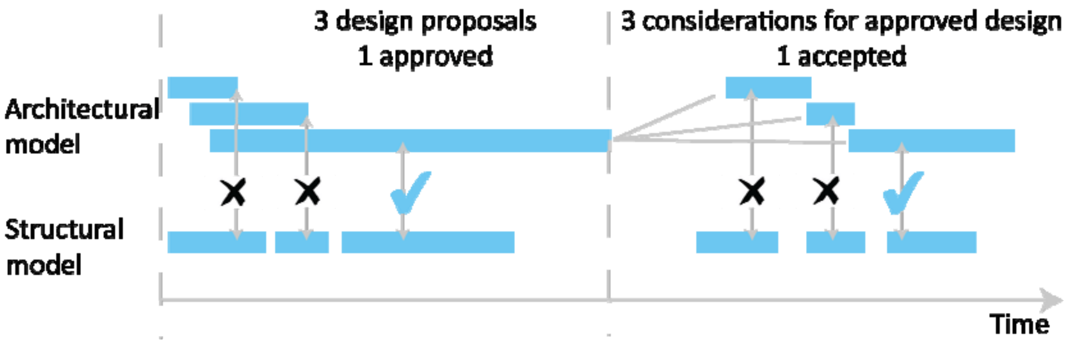

Figure 2.5: Illustration of the need for updating structural models in the design process and send reviews back to the original models. Different proposals can be investigated, but also considerations of one proposal. It is illustrated that the number of calculations is large and the exchange should be handled efficiently to gain advantage of the process.

As the figure states an architectural model is typically made in a process where different suggestions are tried to see if they are suited for the project. When changes are made an update is made in the structural model as well and new calculations are made. When all updates follows this procedure a huge number of calculations should be made to keep track with the architectural development which is of course not optimal. Therefore there is a great challenge in making agreements of model exchange before the startup of a project. Designs with structural challenges can be evaluated early in the process to investigate if the structural challenges can be solved in way that does not interfere with the architectural layout. Some architectural solutions might not have structural issues that are relevant to consider before going into a detailed design process. The communication path should be agreed on in order to ensure efficiency in the work and still have the benefits of an integrated design process.

In figure 2.5 an example with three architectural proposals are shown. One model exchange for each of the proposals might be sufficient for choosing one of them. When deciding on one of the proposals (in this case Proposal 3) the model exchange goes into its next phase. Different considerations are made to develop the proposal and each consideration demands structural investigations. This model exchange situation introduces some demands to the architectural and structural software applications in order to reduce modeling time and avoid unnecessary data exchange. In situations where architects are considering different solutions for a specific detail it might only be this detail that should be examined for its structural behavior and therefore the only detail that should be present in the data exchange. Exchanging only a part of a model ensures that potential mistakes are reduced and changes in design can be reviewed and compared in the architectural software applications. IFC and direct software links are investigated as model sharing tools in this thesis.

2.3 BuildingSMART – IFC

The IFC format developed by BuildingSMART is one way of exchanging information and to ensure interoperability in the industry. The major software applications used in the industry supports the IFC format which makes it a tool suited for interoperability issues. Until a point where modeling and planning can be made in one common software application the IFC format can be used when importing and exporting models and model information and to make consistency checks. For structural use the material properties and geometry are the most important information to transfer together with the analytical lines, but also relations to surrounding objects are relevant to ensure model consistency.

IFC is developed by buildingSMART former known as IAI (International Alliance for Interoperability). IAI was established in 1994 [1] under the name Industry Alliance for Interoperability as an industry consortium with the purpose to provide guidance in C++ codes for new applications. In 1997 the name was changed to International Alliance for Interoperability and was made a non-profit organization. The goal of the organization at that time was to make a neutral data model considering all parts of the building lifecycle. Again in 2005 the name of the organization was changed, this time to BuildingSMART which is still the name used today.

There are possibilities to share information using other formats or direct interfaces between the major software applications but the advantage of IFC lies in the registration as an International Standard [10]. Software applications using the IFC logos, shown in figure 2.6, are certified by buildingSMART.

Figure 2.6: IFC trademark used by certified software applications [11].

The purpose of IFC is to enable everyone connected to a construction project to share information using a common schema. This includes everyone from the early design stage to delivery of a project, then demolition, when the building life span ends. The ability to share information about activities taking place in the operation phase as well as information about geometry on specific building components is what makes IFC a match for the BIM working methods.

This section will describe how the IFC schema is made to understand the theoretical idea behind IFC. The different levels, domains and resources are described since they make the basis for the sharing of digital building models. The coding of file structures behind the user interfaces is not considered in this thesis.

2.3.1 IFC schema

The IFC schema defines how the data structure is handled in the IFC files. Figure 2.7 shows the IFC schema and a description of the four layers within it. The layers are a "Domain layer", an "Interoperability layer", a "Core layer" and a "Resource layer", which all make as basis for the communication. Each of the layers contains entity definitions divided into smaller subgroups. An entity is a collection of properties/attributes such as geometry or cross-section data.

The Domain layer contains entity information divided in different roles which are present in building projects. The roles are described in the figure with circles. The second layer introduces interoperability to the schema. The purpose of this layer is to enable modeled objects to appear inside different domains. An example is a wall which should be considered in a number of domains, the structural analysis domain for the static examination of the project, the architectural domain for representation of geometry and the structural elements domain for planning the building process. Next is the core layer which defines non-physical objects such as space and annotation while the "kernel" focuses on relations, groups and project participators. The resource layer is the final layer which contains general information about a project such as materials, quantity, cost and profiles.

The main idea of dividing the schema in layers is to reuse information from the top layers which are more general than the layers in the bottom of the schema. The value is that specific building components do only contain information about itself, but the heritage in the schema defines more general information used for interoperability in different software. The IFC schema contains 653 entities, 317 property sets.

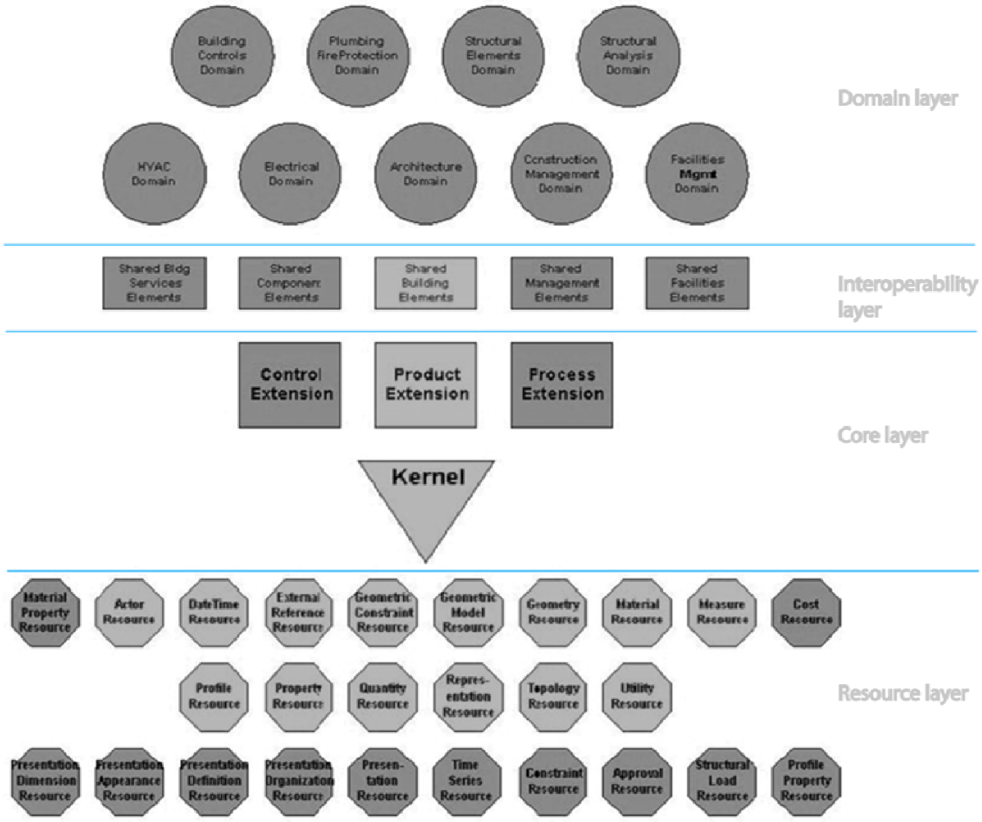

Figure 2.7: Illustration of the IFC schema. The layers described in the text are shown in horizontal lines and with description in the right hand side. The layer descriptions are added to the original drawing from [12].

2.3.2 MVD – Model View Definition

A model used for more purposes contains information about several issues regarding different project participators it is therefore needed with a coordination of the model data to ensure that the correct information is taken for the purpose it should be used for. To handle the coordination Model View Definitions (MVD) are used. MVDs are parts or subsets of the IFC schema in figure 2.7 chosen on basis of the need to the model requirements. Three MVDs are available on the BuildingSMART website [11].

- **IFC2x3 2.0 Coordination View** designed for planning in the construction phase.
- **IFC2x3 Structural Analysis View** for structural analysis such as loads, load combinations, support conditions and materials.
- **IFC2x3 Basic FM HandOver View for** operation phase, room boundaries, furniture and equipment are typical exchanged.

The newest version of IFC is the version 2x4 which offers over 800 entities, 358 property sets and 121 data types [1]. This ensures that standard elements which are used in the AEC industry are possible to model and exchange through the IFC format. This Master Thesis uses the IFC version 2x3 since this version is implemented in the FEM software applications which are considered.

2.4 Direct links

IFC is developed as an open source exchange format where all software providers can use a common schema. The alternative to IFC is model exchange through direct links. Direct links are, in this context, additions to the architectural software developed to translate information in the architectural software to information suited for a specific structural software application.

Since direct links are developed to suit exchange from only one software to another all standard building components from the software applications are typically exchanged without problems. An assumption for a successful exchange of the standard elements is of course that they are present in both applications. If a structural element is only available in a component library connected to one of the software applications it is the add-in (the additional program that handles the direct link) that should translate an element to a custom component.

Considering the advantages in making an exchange add-in, only suited for one specific exchange, gives some advantages since specific problems can be solved, but there are also some disadvantages in using a direct link instead of a common exchange schema. The direct link only allows one structural software application to be used, while IFC assures that the same model can be used for calculations in different structural software applications. It should be said that these considerations are based on the assumption that both exchange methods have reached the same level of development.

2.5 Model exchange

The communication path, described in chapter 2.2, introduces some demands to BIM models depending on the stage they are in. Architectural models should be made with respect to structural demands to ensure that remodeling is not needed when analyzing the structural behavior in structural analysis software applications. When model exchange is required in a project period an exchange path should be decided on and the level of detail in the models should fulfill the demands from all users of the building models. In general a model exchange scenario could follow the topology given in figure 2.8.

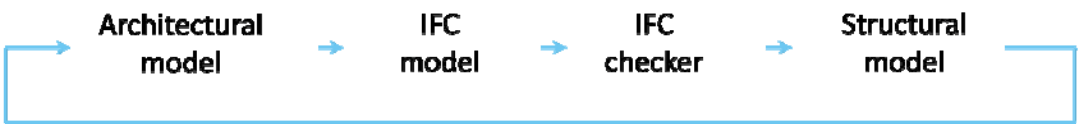

Figure 2.8: Illustration of model exchange scenario between architectural models and structural models without specification of software applications. Here IFC is used for the exchange. The same scenario could be set up with a direct link.

The architectural model is made in a suited software application and structural considerations are implemented in the model. Materials and geometry are the minimum required input for the architectural model since it should be used for FEM analysis. The architectural model is exported to IFC which changes the model information into a general language which is understood by the structural software application it is send to. To ensure that all information in the IFC model is present the model could be reviewed in an IFC model checker. This procedure ensures that all relevant information (information which should be agreed on in the project specific ICT specification) is available when the model is used in the structural analysis application.

In the presented exchange scenario no steps are illustrated between the structural model and back to the architectural model. Identification of components that should be changed after a structural analysis is an issue that should be treated in the stage between the structural model and the architectural model. This issue is not discussed in this thesis, but is definitely a problem that should be solved to gain full benefit of the model exchange procedure.

2.6 Software applications

There are many software applications that support IFC since it is an open source file format, but there are some demands that should be fulfilled to get a certification. A software certification is bound to a specific MVD [11], which ensures that the software can be used for the purpose it is certified to. Some additional IFC properties might be implemented in the software applications as well and other capabilities might be available. An architectural model can for example be used for structural analysis without analytical lines if the analytical software application is able to translate the geometry and establish new analytical lines.

In the following sections emphasis will be on software used in this thesis to clarify the clamed exchange capabilities, both considering direct links and IFC.

Two major architectural BIM applications which are considered are Revit from Autodesk and ArchiCAD from GraphiSoft. Both applications are capable of handling large BIM models. For structural calculations FEM-design from Strusoft and Robot Structural Analysis from Autodesk is used. For investigation of IFC files Solibri Model Viewer is used.

2.6.1 Autodesk Revit

Autodesk offers a wide range of software applications for the construction industry. The capabilities of the software applications spans from 3D animation with focus on visual effects to CAD software for simple drawing generation. The Revit products are developed for BIM-based projects and cover a large part of the planning process connected to construction projects. The Revit software applications are Autodesk® Revit® Architecture, Autodesk® Revit® Structure and Autodesk® Revit® MEP. The applications can be set up in a design suite with the ability to combine the three models made in the specialist Revit software. In figure 2.9 it is shown how a project is set up using the Revit® applications that are considered here.

Revit® models are established by a number of objects that have a geometrical representation, where information is attached. These objects are addressed as “Revit® families”.

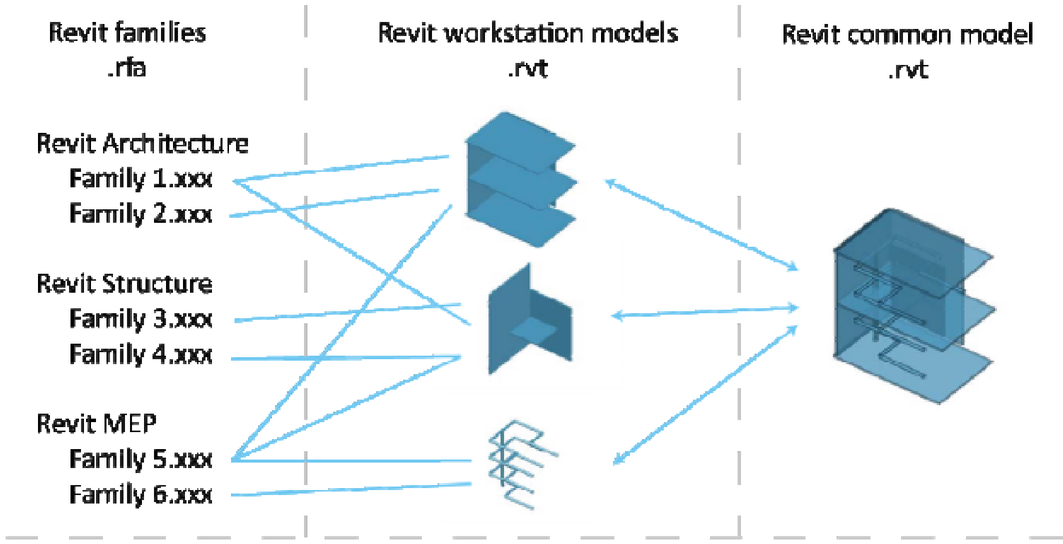

Figure 2.9: Illustration of interoperability inside the Autodesk® Revit® product suite. A common model is placed on as server and copies can be used as "worksheets" on local PCs. Standard and custom Revit® families can be loaded into the models from the component library.

As illustrated in figure 2.9 a common model is made from input by different workstation models. The models addressed as workstation models in this thesis are models which are locked by an administrator and only unlocked for changes made by specialists in specific areas.

This master thesis does mainly focus on Revit® Architecture and Revit® Structure, but as figure 2.9 shows a similar scenario will be present for models containing families that are not structural, here illustrated by plumbing diagrams. Some families can have properties that are used for more than one task. Structural walls do for example have en architectural purpose as well.

The native models used for the exchange scenarios in chapter 4 are made in Revit® Architecture. Any changes made to the architectural model will therefore be made in the architectural application. Architectural models from Revit® Architecture can be opened directly in Revit® Structure where structural considerations can be handled. Here load cases, boundary conditions and load combinations can be added.

There are different ways to set up an IFC export from Revit® Structure. Through an application it can be decided which elements should be exported through IFC. A standard setup is made for the IFC export, which can be used if there are no special needs. Alternatively the user can decide to translate elements to IFC elements by knowing the classes they should be imported into. The export procedure enables a project coalition to establish its own schema for the data exchange. This ensures full control over the exchange scenario since irrelevant information can be left out of an export. Revit® Structure is certified for the MVD "2.0 Coordination view".

Besides the possibility to exchange models through IFC there are direct links between Robot Structural Analysis (RSA) and FEM-design which are the considered analytical software. The direct link to RSA automatically transfers components while the link to FEM-design requires a mapping process where manual interpretation is required.

The speed in the development of BIM means that new versions of the software are presented quite often. The exchange capabilities of models is a focus area with many new developments and features wherefore several editions of a given software is available on the marked at the same time. This is the reason why two versions of the Revit® software are used for testing capabilities in this thesis. The native models are made in Revit® 2012 while some of the investigated exchange scenarios are made in Revit® 2013.

2.6.2 GraphiSoft ArchiCAD

ArchiCAD is developed by GraphiSoft® and is major architectural software. ArchiCAD is certified for the MVD 2.0 coordination view and offers a range of possibilities connected to IFC interoperability [13]. A mapping interface is available to make exports suited for specific purposes. The ArchiCAD user interface uses both plan views and 3D views and gives the possibility to investigate element properties by marking them in the model. The available element property table contains general information about material and graphical representation, but also about IFC parameters.

For interoperability ArchiCAD relies on IFC. On the GraphiSoft web page FEM-design is suggested for interoperability through IFC. There is no direct link which indicates that GraphiSoft seeks to develop interoperability using IFC.

When exporting ArchiCAD models to an IFC file it is done with focus on which software receives the IFC file. The IFC file is then prepared for the exact software application which is considered. This is of course not optimal since the same file is not suited as a common model, but it might be preferable in the developing phase IFC is in.

2.6.3 Solibri Model Viewer

Solibri is a software used for checking and evaluating IFC model files made in other software. A model checker can be used for checking clashes between several models and make reports where it is stated which changes should be made to ensure consistency in a project. This thesis focuses on a free software application, Solibri Model Viewer version 7.1 which does not allow several models to be investigated, but has the ability to check IFC information connected to one model at the time. A free software program supports the thought of having different project participators to deliver a 3D model considering their area of competence and being able to ensure the correct information is available in the delivered model.

2.6.4 FEM-Design

FEM-Design is a structural software application developed by StruSoft who are providers of a range of design software. Implemented in the software are Eurocodes, which makes the software suited for documentation where the Eurocodes are used.

It is possible to create a model in FEM-Design, using custom components or predefined profiles that are stored in a component library. When importing models there is a number of possibilities depending on the software in which the original model is made. When using Autodesk software products a direct links allows all elements to be transferred into FEM-Design and a structural analysis can then be performed there. When transferring the model the materials are mapped meaning that the properties given in Autodesk are transferred to be understood in FEM-Design. The original model can then be used with a minimum of manual work connected to the process in FEM-design.

The IFC exchange is another exchange possibility supported by FEM-design. When opening IFC files in FEM-design there are three different ways to do it depending on which level of detail is needed in the FEM-design model. The “architectural view” import option is for cases where a visual representation is needed. Elements are imported as plates, shells, beams and columns, but there is no structural information attached to the model. The second import option is the “reference geometry view” where the lowest amount of information is present after the import. The geometry is shown, but no information is present for the imported model categories. Finally the third import option the “structural analysis view” is available. This view is only an option when the file, which is imported, is originally attached with structural information. This import option makes it possibility to keep structural information from the native format and use it to generate FEM-Design elements used in structural analysis. It should be said that these import options are those claimed by StruSoft.

The possibility to use models generated in other software is present, but FEM-Design does not support a two-way communication. The elements which are made in FEM-Design can be used for structural analysis, but a model transfer back to an architectural software application is not possible. It is therefore a manual task to change elements in the native format and then make a new export of the structural analysis to investigate if the changes are sufficient.

2.6.5 Autodesk Robot

Autodesk Robot Structural Analysis is an application with similar capabilities as FEM-Design, but more oriented towards detailed calculations of structural components and not overall static systems as FEM-Design. Modeling of custom components, standard elements and composite members can all be modeled in Robot or imported through IFC. Besides the IFC import option RSA has a direct link from Revit® for faster interoperability.

The direct link enables the applications to communicate changes in the model directly whereas an IFC model should be reviewed and the original architectural model should be altered manually. IFC gives the advantage that the same model is used for more than the structural area and this advantage should be greater than having a direct communication path if IFC should be used.

Investigations of RSA is included in this thesis since it is relevant to see how IFC data exchange performs compared with analytical software managed by a software vendor that also controls one of the major architectural applications on the marked.

Chapter 3

Case presentation

An available model of DTU Building 324 is used for testing different exchange situations. This chapter describes the process in testing model exchange scenarios and it is defined which properties are relevant to exchange when considering architectural models used for structural analysis. The exchange of models in different software applications establishes knowledge of the information flow possible when using IFC and direct links.

3.1 Case description

To establish a basis for data exchange needs in real projects DTU Building 324, modeled in Autodesk® Revit® Architecture 2012, is used to test the data exchange into structural analysis software. DTU Building 324 is at this moment under construction.

The basis for the exchange scenarios is an architectural model of DTU Building 324. Since the model is made for architectural purposes there is no consistency in the analytical lines and load cases. Also boundary conditions and load combinations are not defined in the native model. The planning and construction is Design-Bid-Build and does therefore not follow one of the approaches that are best suited for BIM. Despite the planning approach the available model contains the information needed in order to establish an exchange scenario suited for investigations of exchange capabilities of the chosen software.

3.1.1 DTU Building 324

DTU Building 324 is under construction on DTU campus as a central building connecting several institutes. The building is 4.500 m^2 designed for different studying purposes, office cells, open office areas, a reception as well as smaller conference rooms. The building is 3 stories where atriums break through the stories to connect them. Four stairwells are placed in the outer parts of the building and functions as load carrying walls as well as access ways. The facades are made as window panels with intelligent moveable solar shading for achieving optimal solar gain and daylight factor in the indoor environment. The stairwells include the office areas on the upper stories and they are connected with a bridge structure hanging from the roof in steel elements. Figure 3.1 shows a plan drawing where the stairwells and the bridge structure are introduced.

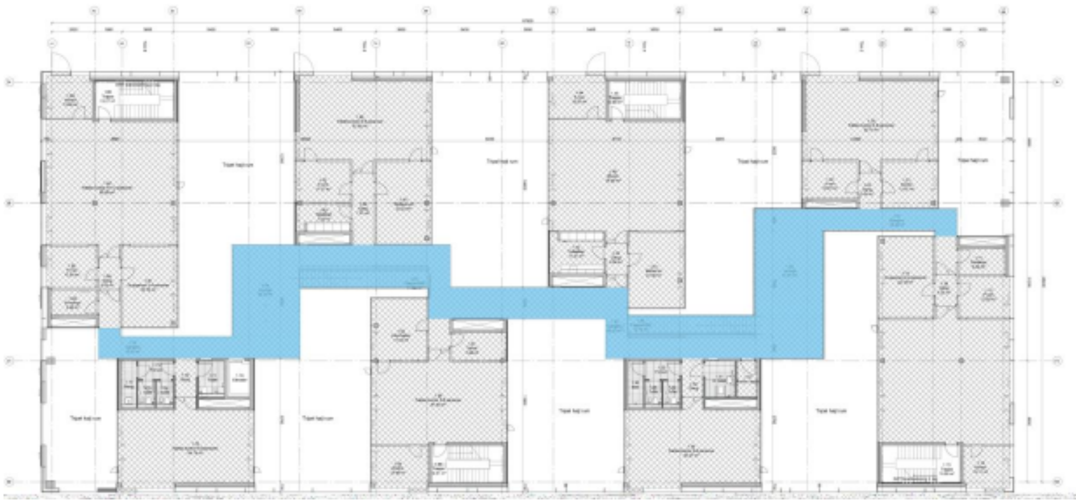

Figure 3.1: Plan solution for first floor. The bridge structure hanging from the roof is marked with blue.

Figure 3.2 shows the exterior design of the building. The main construction material is concrete which is used for the cores and the stairwells, and the rooms that lie in connection with these. Steel is used in the façade system and in the roof structure.

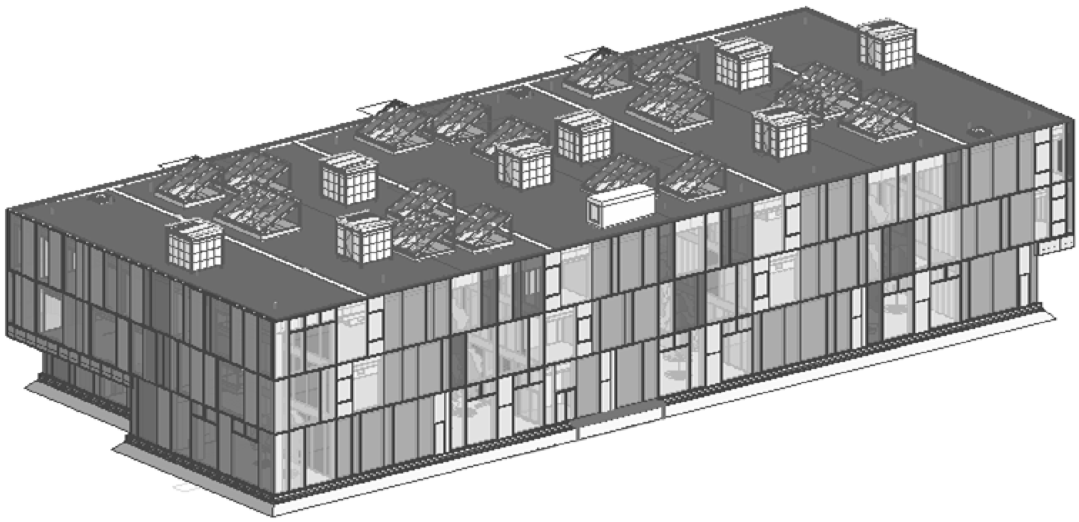

Figure 3.2: The figure shows a 3D illustration of DTU Building 324.

3.1.2 Structural configuration

The structural elements in DTU Building 324 are shown in figure 3.3. Steel girders are places in the roof construction to carry the bridge that goes through the entire building. Also the façade system is made in steel elements while the structural cores are prefabricated concrete elements.

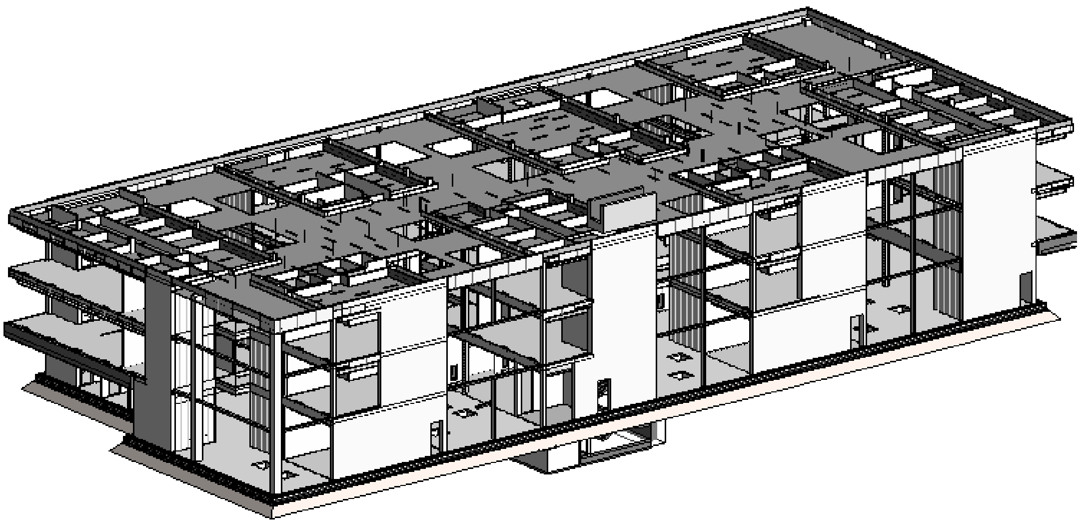

Figure 3.3: BIM model of structural elements in DTU Building 324.

The concrete cores are both acting as stabilizing walls for the wind load on the facades and for the vertical loads. The bridge gives an additional vertical load which is taken by the concrete cores. Figure 3.4 shows the two bridge planes and the steel members that transfers the loads to the roof structure.

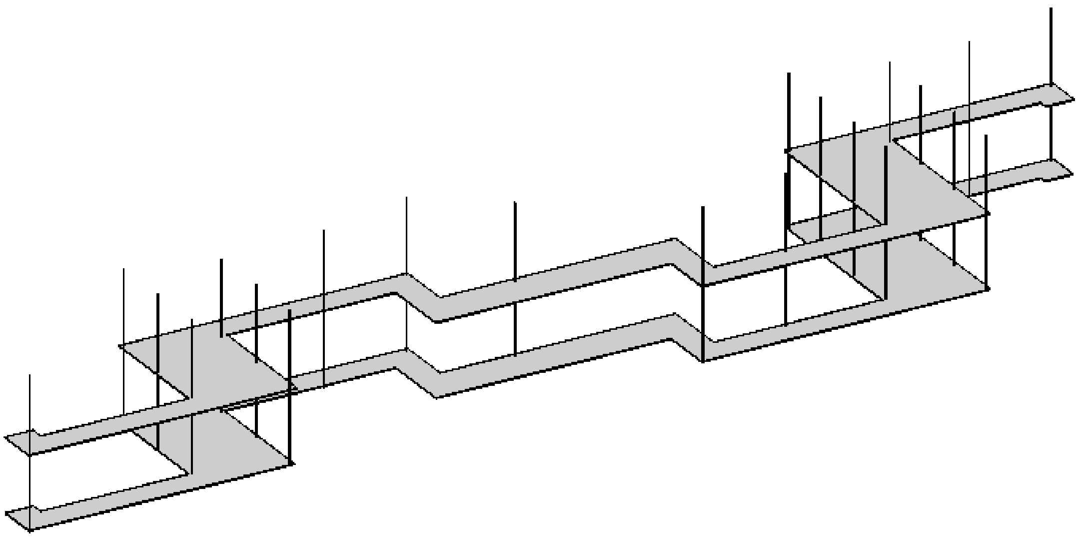

Figure 3.4: Illustration of bridge decks in the second and third storey hanging in steel members. The steel members are attached to girders lying inside the roof structure.

3.1.3 Bridge structure

When testing the software applications for its IFC capabilities the bridge structure will be used as an example. The structure is supported where the steel elements attached in the roof which ensures that it can be evaluated separately with the assumption that the roof structure has enough strength to transfer the bridge load to the concrete cores.

The bridge structure introduces some of the challenges in using an architectural model for structural analysis. The steel members are attached to the decks inside the deck boundaries since it suits the attachment system of the steel members. This is modeled in the architectural model, but for a structural analysis the steel members should rather be placed at the boundaries and attached to the analytical lines in the deck structure. The bridge figure does not clarify how the steel members are modeled, but this is another issue that should be considered before using the model for structural analysis. In structural analysis all connections are made as nodes and the steel members are only calculated when the end points are attached to the nodes. In the following chapters the bridge model in figure 3.5 will be used to test the exchange scenarios. For consistency the nomenclature of figure 3.5 will be kept the same throughout the thesis.

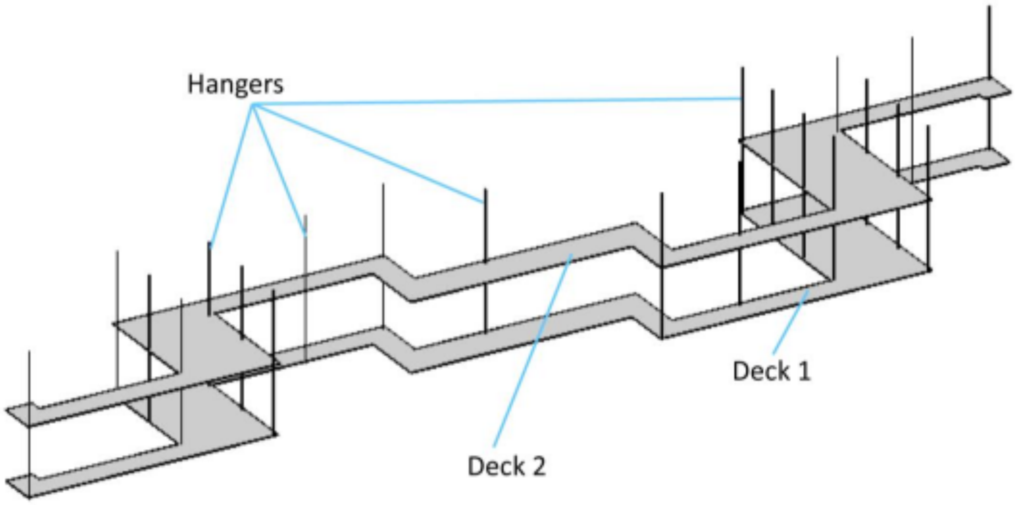

Figure 3.5: Description of elements in bridge structure used for further analysis.

3.2 Software specific exchange scenarios

In this section it is specified which exchange scenarios are considered and which software applications are used. It is defined how the bridge model is shared and in which stage of the exchange the model files are reviewed. The native model from Revit is used for data exchange through IFC to FEM-design and RSA, but also direct links between the software applications are investigated. Finally the Revit model is remodeled in ArchiCAD and an IFC-based data exchange to FEM-design and RSA is made. This ensures a basis for comparing the two architectural software applications.

The considered exchange scenarios are numbered as stated in table 3.1.

Exchange scenario number	Software considered for exchange scenarios
1	Revit → IFC ↔ SMV → FEM-design
2	Revit → *.r2f → FEM-design
3	Revit → IFC ↔ SMV → RSA
4	Revit → *.rtd → RSA
5	ArchiCAD → IFC ↔ SMV → RSA
6	ArchiCAD → IFC ↔ SMV → FEM-design

Table 3.1: The exchange scenarios are numbered in the table. The numbering will be used as reference in the following sections.

3.2.1 Exchange scenario 1

Exchange scenario 1 is based on the Revit model. The model is exchanged through IFC and imported into FEM-design. An illustration of the exchange scenario is given in figure 3.6.

Figure 3.6: Illustration of exchange scenario 1. The Revit model is exchanged to FEM-design through IFC. The IFC file content is investigated in Solibri Model Viewer. When no errors appear it is exchanged to FEM-design.

The original model is exported to IFC after a mapping procedure where the material properties, geometry, loads and boundary conditions are translated to the IFC property sets. To ensure that the mapping is successful and the file contains all relevant information the IFC file is reviewed in Solibri Model Viewer. It is documented which information is present before loading the file into FEM-design.

Having the model transferred to FEM-design it is investigated how the information from the IFC file appears and if it can be used in the same way as similar components from the FEM-design component library.

A successful design process corresponding to the situation shown in figure 2.4 requires that information about the structural analysis is communicated back to the Revit model. Since there is no direct link or IFC export options from FEM-design it cannot be handled here.

3.2.2 Exchange scenario 2

The second exchange scenario is based on the same model as scenario 1. Instead of using IFC for the data exchange the direct link between Revit and FEM-design is used. Figure 3.7 illustrates the exchange scenario.

Figure 3.7: Illustration of exchange scenario 2. A *.r2f-file is made based on the Revit model. The file is opened in FEM-design.

To ensure that all components are transferred to FEM-design the materials and profile types are mapped using the Revit to FEM-design add-in. The mapping names used in the mapping interface corresponds to the names in FEM-design.

Since the exchange scenario considers a direct link the *.r2f-file is not investigated before using it in FEM-design. A visual investigation in FEM-design will show if all components are exchanged successfully. As in scenario 1, FEM-design cannot exchange a model back to Revit even though it is a direct link.

3.2.3 Exchange scenario 3

This exchange scenario is based on the same Revit model as the first two exchange scenarios, but the structural analysis software is changed to RSA. The model is exchanged through IFC and investigated the in Solibri Model Viewer (the same IFC file as in exchange scenario 1). The exchange scenario is illustrated in figure 3.8.

Figure 3.8: Illustration of exchange scenario 3. The Revit model is exchanged to RSA through IFC after verifying it in SMV.

The main scope of this exchange scenario is to investigate how an IFC file performs, when the native model is made in a software program from the same software vendor as the structural analysis software. In theory the IFC file should be capable of performing superiorly since the application are from the same vendor.

3.2.4 Exchange scenario 4

In this exchange scenario a direct link to RSA from Revit is considered. The direct link connects two software applications from the same software vendor. The exchange scenario is illustrated in figure 3.9.

Figure 3.9: Illustration of exchange scenario 4. The Revit file is exchanged to RSA through the direct link.

It is expected that this exchange scenario shows a reliable exchange capabilities since the applications are from the same software vendor.

3.2.5 Exchange scenario 5

To achieve a frame of reference an exchange scenario is made with ArchiCAD as the architectural software instead of Revit. The native model is loaded into ArchiCAD using a direct link from Revit Structure. It is assured that all elements are reassigned to ArchiCAD elements before an IFC export is made since tests should clarify how differences in the original model affect the use in structural analysis applications. Figure 3.10 shows an illustration of the exchange scenario to FEM-design.

Figure 3.11: Illustration of exchange scenario 6. The ArchiCAD model is exchanged through IFC to RSA.

As in the other exchange scenarios the content in the IFC file is investigated in Solibri Model Viewer to document eventual lacks in the exchanged IFC file.

3.2.6 Exchange scenario 6

The last exchange scenario corresponds to exchange scenario 5, but the structural analysis software is changed to FEM-design. The exchange scenario is shown in figure 3.11.

Figure 3.10: Illustration of exchange scenario 5. The native model is loaded in ArchiCAD and exchanged to FEM-design through IFC.

Since ArchiCAD does not offer the possibility to exchange models to RSA or FEM-design through direct links only the exchange scenarios through IFC are considered.

3.3 Information exchange

Regardless of which exchange scenario is considered the same parameters should be exchanged to facilitate a structural analysis in the receiving software and get a direct comparison. Here it is stated which information is relevant for the considered exchange scenarios.

Geometry: The geometry is crucial for the data exchange since the sizes, span lengths and element placements are included in the geometry. The geometry is in some exchange situations guidelines for the placement of analytical lines and the nodes that connect the analytical lines. The geometry also includes the ability to recognize standard building elements in the receiving software.

Material properties: Exchange of material properties ensures that structural investigations can be made based on an architectural model without assigning material properties to each component after an exchange. The material properties are relevant to include in an exchange to a structural software application for ensuring a fast investigation of the structure and to minimize the probability of making mistakes.

Boundary Conditions: Boundary conditions are important for a structural investigation and to establish them in a common model ensures that all calculations are based on the same structural assumptions.

Loads: Loads cases and load combinations are made on basis of the codes used for the project. To establish load cases and combinations ensures that all calculations are made on the same basis. In the same time it reduces the times loads are added to different models and should therefore also reduce potential mistakes.

3.3.1 Preparation of architectural model

For all exchange scenarios the information reviewed in this chapter should be transferred from an architectural software program to structural analysis software. Table 3.1 shows the exact information that should be exchanged when testing the capabilities of the software applications based on the bridge from DTU Building 324.

Geometry	Hangers	-	Level
		-	Diameter: 50 mm
		-	Length: Varying (see model)
		-	Coordinates
	Decks	-	Level
		-	Thickness: 180mm
		-	Coordinates
Material properties	Hangers	-	Steel
		-	Strength s275
	Decks	-	Concrete
		-	C35/45
Boundary conditions	Hangers	-	Pinned in top of hangers
	Decks	-	Roller supports on some edges
Load	Hangers	-	Self-weight
	Decks	-	Self-weight
		-	Permanent surface load 2 kN/m2

Table 3.1: Information included in architectural models used for testing exchange capabilities.

3.3.2 Choice of properties evaluated in exchange scenarios

The level of detail in the architectural model is quite high considering the architectural purposes, but the information related to the structural performance is limited. Never the less the properties which are included in the tests are sufficient for investigating structural behavior in an early project phase and to estimate the capabilities of the investigated exchange scenarios. Having considered both the geometry of a custom component as well as a component from the component library, in form of the deck and the hangers, most common linear geometry components are therefore considered. Material types and material properties are also investigated and if these can be transferred successfully it is likely that material information can be shared in most cases. However, if the properties differ from the materials that are available as standard materials in the software, it might be a different case. This situation has not been considered in this thesis.

Loads and boundary conditions are included in the architectural Revit model. In both cases the scope is to investigate if it is possible to establish a structural basis in a common model and thereby assure that all calculations are made with the information entered in the architectural model.

Chapter 4

Case study

This chapter contains an investigation of the exchange capabilities of the pre-defined software described in chapter 2.6. The investigations are based on six exchange scenarios that are described in chapter 3.2. An outline of the process is included in this chapter while a detailed description of each scenario is given in the enclosed appendixes. The information that is exchanged is listed in chapter 3.3.

4.1 Method of analysis

For investigation of the exchange scenarios the following methodology is used. The architectural model presented in chapter 3.1 is the basis in all exchange scenarios. Adjustments to the architectural model are presented for each exchange scenario. These are made to prepare the models for structural analysis since the architectural representation does not correspond to a suited analytical model.

After having modified the architectural model it is exported to IFC or to a specific file used for direct transfer to an analysis software. In exchange scenarios where IFC is used the file is investigated in SMV to ensure that all relevant information is attached. If mistakes or lacks in the information is found in SMV architectural model is altered and the exchange is made again in order to fix the problem. Exchange files used for direct links cannot be reviewed before they are opened in the analytical software. For these scenarios an investigation is made in the analytical software and the exchange is repeated if information lacks are found.

The final step of the tests is to use the imported IFC files or direct link files for a structural analysis. Information needed for the calculation is added if the exchange of all information has not succeeded and a calculation is performed. Again the process is repeated if there are issues that make the analysis perform badly.

The investigation seeks to clarify the capabilities of the exchange tools and not to investigate the structural design of the bridge structure. Calculations are performed to ensure the functionality of the imported structural elements, but the results are not investigated further and should not be seen as documentation of the structure.

Experiences gathered when making the exchanges are shown in result tables after each scenario and a sub conclusion considering the specific exchange scenarios is included. The scope of the sub conclusion is to summarize the gathered experiences while comparisons of the software applications are made in section 4.8. All model files are attached in appendix H.

4.2 Exchange scenario 1

The bridge structure used in the data exchange is modeled for architectural purposes and does therefore need some modification to be useful for structural analysis. Loads and boundary conditions are added to the model before making the data exchange. A surface load is added to the deck while all hangers are supported in the end connecting the bridge structure to the roof. These supports a simple supports meaning that rotation is allowed in all directions, but no movement. The decks are connected to the concrete cores on some edges corresponding to a situation with a simple line support.

As stated in chapter 2.6 Revit is certified for the MVD "2.0 Coordination View" and it is therefore not expected that an exchange of analytical lines of structural elements, loads and boundary conditions are possible to include in the export. Never the less these are modeled and it is tried to include them in the export since the certification does not proscribe the software vendors to include more IFC exchange possibilities.

4.2.1 Process outline

Preparation of Revit model and investigation of IFC file content

The native architectural model is modeled in Revit and does only contain architectural information. The model is enclosed as;

- REVIT2012_originalmodel.rvt

This model is adjusted to fit a structural representation of the bridge. The hangers are moved to the edges, a surface load is added to the decks, boundary conditions are defined and analytical lines are connected in nodes. The adjusted model is enclosed as;

- REVIT2012_adjustedmodel_vers1.rvt

An IFC file export of the adjusted model is made using the standard export option in Revit. The standard export considers the elements that are possible to include. It has been tried to export analytical lines using IFC mapping names that functions with corresponding components. This test shows that only components that fit into an IFC resource that is supported by the standard export in Revit are supported. The exported IFC file is reviewed in SMV to ensure that all components are exchanged. The review shows that no loads or boundary conditions are included in the IFC file. Reviewing the file also shows that the hangers are represented in different colors in SMV and must therefore contain different information. A new version of the adjusted model is made where the hangers are changed to a new family. This family is made with the knowledge that it should be used for structural purpose and should therefore be transferred successfully. The new version of the adjusted model is enclosed as;

- REVIT2013_adjustedmodel_vers2.rvt

Again the model is exported to IFC and reviewed in SMV. The contents of the IFC file is specified in table 4.1.

Type	Family	IFC information
Building components	Hangers	The IFC material is steel, but there are no properties available (strength, environment etc. All hangers keep information about level attachment as well as the geometry. However, the information is different in some of the hangers.
	Decks	Deck geometry is transferred as well as concrete material information. Location of analytical plans is not included in the IFC model.
Boundary conditions	Pinned	The pinned supports are not transferred to the IFC model.
	Roller	The roller supports are not transferred to the IFC model.
Load	Surface load	Neither load nor load direction is available in the model.

Table 4.1: Information attached to IFC file based on the original Revit Structure model.

Only geometry and some material information are included in the IFC file. This version of the IFC file is used for investigations in FEM-design.

The newest version of FEM-design (11.0) is tried for importing IFC files, but without success. The FEM-design support team is aware of the problems with IFC and suggests the use of direct links instead. An e-mail correspondence with the support team is attached in appendix G. The test of FEM-design is made in version 9.0 since this version seems to function. After importing the IFC file in FEM-design it shows that the structural elements are not connected in the nodes as it is in Revit. The use of MVD 2.0 Coordination View transfers the geometry as lines that represent the center of each element (the exchange does not consider how the elements are modeled in Revit). A new version of the model is made in Revit where all center lines are connected. This version is enclosed as;

- REVIT2013_adjustedmodel_vers3.rvt

The third version is used for further investigation of FEM-design exchange capabilities.

Investigation of the IFC capabilities in FEM-design

When using an IFC file in FEM-design 9.0 it is mapped during the import of the model. Material properties are attached to the corresponding building elements. The mapping procedure ensures that all elements are assigned material properties from the FEM-design material library, while material information attached to the IFC file is only used to ease the mapping process in FEM-design.

The geometry of the bridge structure is exchanged successfully but loads and boundary conditions have to be added to the structure in the same way as for components modeled in FEM-design. A screen dump of the model is shown in figure 4.1.

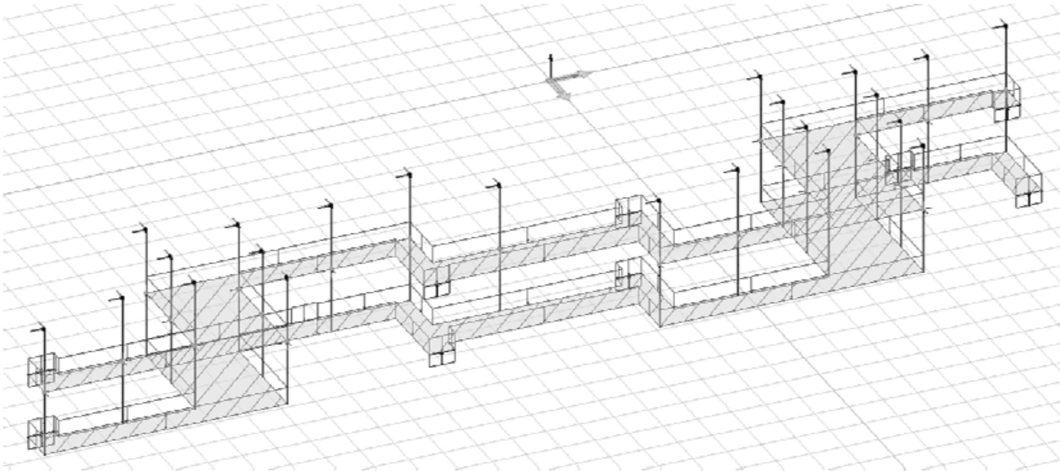

Figure 4.1: Screen dump of bridge model in FEM-design with a surface load added to the decks. Boundary conditions are specified for the hangers and the relevant edges of the decks are supported.

A calculation of axial forces in the hangers is made to prove that the exchanged components can be used for investigations of the structure. There are no problems related to a structural calculation; this is shown in appendix A.

4.2.2 Test results

Table 4.2 shows the results of the test of exchange scenario 1. Comments to specific parts of the table are assigned numbers and explained after the table.

	IFC file	FEM-design[1]
1. Geometry		
Level (Hangers)	✓	✓
Diameter (Hangers)	✓	✓
Length (Hangers)	✓	✓
Coordinates (Hangers)	✓	✓
Level (Decks)	✓	✓
Thickness (Decks)	✓	✓
Coordinates (Decks)	✓	✓
2. Material properties		
Material type (Hangers)	×[2]	×[3]
Material strength (Hangers)	×	×[3]
Material type (Decks)	×[2]	×[3]
Material strength (Decks)	×	×[3]
3. Boundary conditions		
Pinned hanger supports	×	×
Roller deck supports	×	×
4. Load		
Surface load	×	×
Load direction	×	×

Table 4.2: The table shows the test results for exchange scenario 1. It is specified which information is present in the IFC file reviewed in SMV and which information are exchanged to FEM-design. × tells that the information is not present while ✓ tells that the information is present.

1: The results are based on FEM-design version 9.0 while the newest version is 11.0. StruSoft are aware of the situation, but still only the older version is capable of handling IFC files using the Architectural import option (see appendix G).

2: A material tab is available in SMV, but the information is related to the Revit model. For a useful exchange the IFC model should include the same material information, but translated to an IFC type.

3: Material types and properties are not considered to be exchanged successfully, but the mapping procedure ensures that the information can easily be attached to the building component. This is a positive situation where the information is under control, but to attach a material from the FEM-design library requires manual work and could therefore be a source of mistakes.

4.2.3 Sub-conclusion

The investigation of exchange scenario 1 has shown some limitations related to data exchange with IFC for the considered software applications. It has been possible to exchange the bridge model and use it for structural analysis, but the exchange does not correspond to a theoretical optimal solution.

An IFC file based on Revit 2012 has proven that there is a mistake in the location of decks when they are exported to IFC. Using the 2013 version of Revit solves the problem, but it is an issue that complicates the exchange.

Since the Revit software uses the MVD 2.0 Coordination View the analytical lines are not exchanged. The investigation shows that the center lines are exchanged and the profile information is attached to the centerlines. Because of this situation the analytical model from Revit cannot be used before fitting the center lines corresponding to the analytical model. This is a major disadvantage since more models have to be produced and the advantage in using a common model for more purposes is not present.

The material exchange has not been exported successfully since everything needs to be updated in the mapping interface in FEM-design. Never the less this procedure is quite simple since a material description is available, but could be a source of error when handling models with an extensive number of components.

Loads and boundary conditions are not exchanged in this scenario, but are easily applied in FEM-design. This proves that the exchanged components are useable in FEM-design and the exchange related to geometry is successful.

Considering the FEM-design software, the exchange scenario has shown that the newest version of the software (11.0) has problems in opening IFC files after the mapping procedure. The FEM-design support team recommends that IFC is not used for interoperability before the import problem has been fixed. Never the less StruSoft promotes the IFC capabilities on their web page [14].

4.3 Exchange scenario 2

This exchange scenario considers the direct link between Revit and FEM-design. The scope of this investigation is to see if it is an advantage to use a direct link connecting the same software applications as in exchange scenario 1. It might be thought that the direct link has an advantage since the add-in can be fitted to the libraries in each software application, but the exchange scenario does include custom components that might set larger demands for the add-in.

4.3.1 Process outline

The model used for the exchange scenario is REVIT2012_adjustedmodel_vers2.rvt since it contains both an analytical and architectural representation. Exchanging this model will show if the direct link considers the modeling approach used in Revit.

The first step is to map the materials and profile types to ensure that FEM-design is capable of recognizing the components. Having mapped the information a *.r2f file is made; a warning tells that no valid material has been found for the hangers.

The hanger component is not in the standard FEM-design library and the name of a custom component with the same geometry and properties cannot be used to map the hangers. It is investigated if other column components available in both Revit and FEM-design libraries can be used or if the direct link has a problem in exchanging columns. The tests show that component types that are present in both libraries are successfully exchanged.

Due to this investigation it is not believed that the model exchange of the bridge will include the hangers, but the *r2f file is exported from Revit.

Investigation of model in FEM-design

Having opened the model in FEM-design it shows that the hangers are included in the *.r2f file as lines which makes it easy to substitute these with steel elements as in the Revit model. All boundary conditions are present while the loads have not been exchanged.

A displacement calculation is made as in exchange scenario 1 in order to prove that the exchanged components can be used in FEM-design. Hangers are replaced and loads are added before making the calculation.

Figure 4.2 shows the FEM-design illustration of the loads applied to the bridge after the calculation.

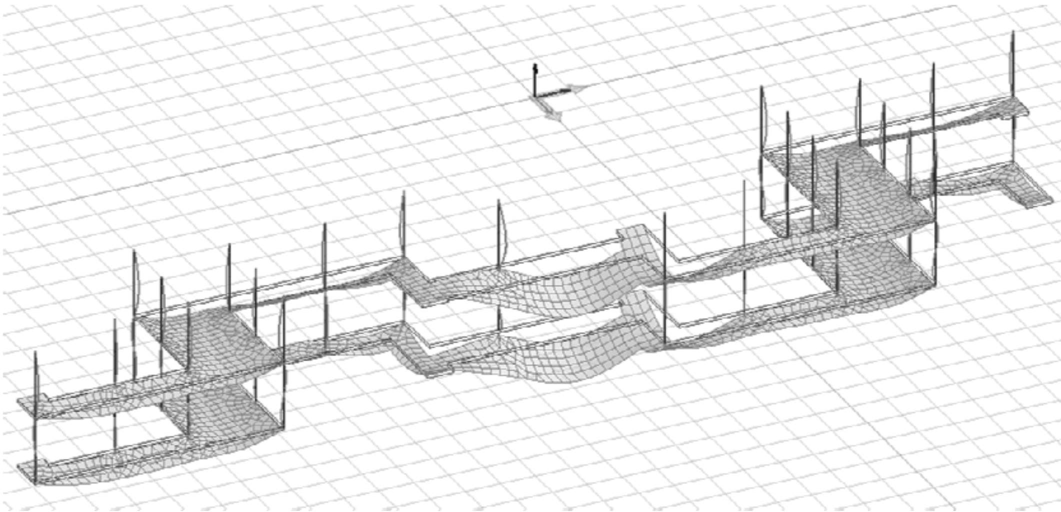

Figure 4.2: Screen dump of displacement figure based on model exchange in scenario 2.

The displacements are calculated successfully and it can be derived that the use of analytical lines are successful.

4.3.2 Test results

Table 4.3 shows the results of the test of exchange scenario 2. Comments to specific parts of the table are assigned numbers and discussed after the table.

	FEM-design
1. Geometry	
Level (Hangers)	✓[1]
Diameter (Hangers)	×
Length (Hangers)	✓[1]
Coordinates (Hangers)	✓[1]
Level (Decks)	✓
Thickness (Decks)	✓
Coordinates (Decks)	✓
2. Material properties	
Material type (Hangers)	×
Material strength (Hangers)	×
Material type (Decks)	✓
Material strength (Decks)	✓
3. Boundary conditions	
Pinned hanger supports	✓[2]
Roller deck supports	✓
4. Load	
Surface load	×
Load direction	×

Table 4.3: The table shows the test results for exchange scenario 2. It is specified which information is exchanged to FEM-design. × tells that the information is not present while ✓ tells that the information is present.

1: The hangers are not exchanged with all properties added, but the lines representing the hangers are easy to replace sine the coordinates are there. Therefore the model is useable even though the hangers are not exchanged successfully.

2: The pinned supports are exchanged with the correct coordinates even though the hangers are only presented as lines. This shows that the link is useful, despite the missing hangers, since the hanger supports works with the hangers that are modeled in FEM-design

4.3.3 Sub conclusion

Investigation of exchange scenario 2 has shown that analytical lines from Revit can be used in FEM-design. This makes it possible to use the architectural model for structural calculation, but it should be said that the analytical representation in Revit has to be investigated before an exchange. To use the original model of the bridge structure will not be successful, but the analytical lines could be established without moving the architectural components in Revit.

When exchanging the model there were some problems because the hanger material could not be included. In spite of this lack of information the analytical lines of the hangers are transferred and they can easily be replaced in with custom components created in FEM-design after the exchange. Although the hangers are not exchanged correctly the pinned supports are exchanged connected to the lines instead, which does not affect the calculations.

An error report is available when creating the *.r2f file which makes the user aware of the mistakes in the exchange. In this case it has been easy to identify the errors and correct the problems in FEM-design which makes the direct link useable for larger projects since it clearly states how the information is handled. No errors that were not identified in the error report have been identified.

Loads have not been transferred through the direct link and should therefore be applied in FEM-design. This is unfortunate since the load information in Revit cannot be used as common information. In theory all design information should be added in Revit and sent to different analysis software applications and investigated with the same load types as basis. The same loads will be used in any case, but adding loads after the model is exchanged will be a source of error.

Two column components that are available in the component libraries in both Revit and FEM-design have been tested; these have been successfully exchanged through the direct link. This test indicates that the exchange difficulties experienced for the hangers in the bridge structure is due to the fact that it is a custom component.

4.4 Exchange scenario 3

It is in this exchange scenario considered how an IFC file is handled in RSA. The considered IFC file is again from Revit. The overall scope of this scenario is to investigate the success rate of an IFC exchange when both the native model and the structural model are made in software from the same vendor.

4.4.1 Process outline

The investigation of exchange scenario 1 has shown that IFC export of Revit files uses the center lines as reference for the exchanged geometry. Having this in mind it is chosen to use SMV7.1_adjustedmodel_vers3.ifc when testing this scenario.

The IFC file is opened in RSA without going through any mapping process. Since there were lacks in the material information in SMV it is investigated which material information is attached to the components in RSA. It shows that both hangers and decks have the concrete material C12/15. The model also shows that loads and boundary conditions are not present exactly as seen in SMV.

To use the model for a structural investigation the material properties should be changed and loads and boundary conditions added to the structure. Having ensured that all properties are changed to the values given in chapter 3.3.1 a calculation of displacements is made.

There were no problems related to performing the calculation in RSA, for more details see appendix C. As stated in the appendix there are no problems related to making the calculation. The displacement figure corresponds to the figure in the other exchange scenarios and is therefore seen as a successful test of the components that have been exchanged. A screen dump of the displacement figure is given in figure 4.3.

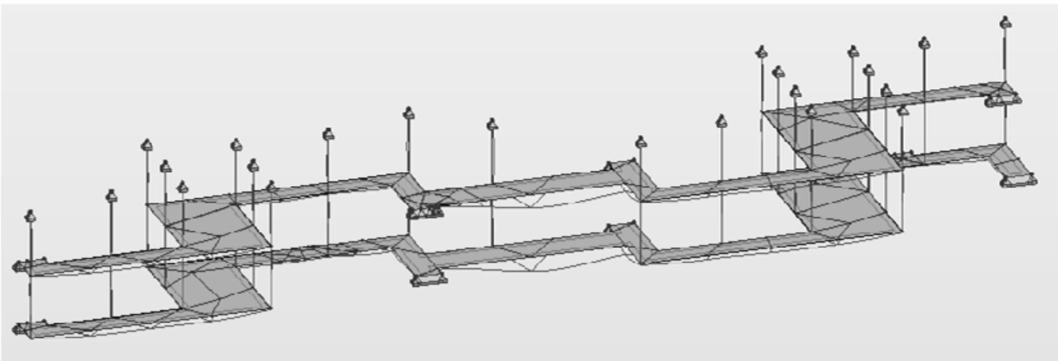

Figure 4.3: Displacement figure from RSA.

4.4.2 Test results

Table 4.4 shows the results of the test in exchange scenario 3. The results from the IFC file are the same as in exchange scenario 1 since the same IFC file is used for the investigation. Comments to specific parts are given after the table.

	IFC file	FEM-design
1. Geometry		
Level (Hangers)	✓	✓
Diameter (Hangers)	✓	✓
Length (Hangers)	✓	✓
Coordinates (Hangers)	✓	✓
Level (Decks)	✓	✓
Thickness (Decks)	✓	✓
Coordinates (Decks)	✓	✓
2. Material properties		
Material type (Hangers)	× [2]	×
Material strength (Hangers)	×	×
Material type (Decks)	× [2]	✓ [1]
Material strength (Decks)	×	×
3. Boundary conditions		
Pinned hanger supports	×	×
Roller deck supports	×	×
4. Load		
Surface load	×	×
Load direction	×	×

Table 4.4: The table shows the test results for exchange scenario 3. It is specified which information is exchanged to FEM-design. × tells that the information is not present while ✓ tells that the information is present.

1: The material type of the deck is concrete, but it seems that the type is a guess made in RSA since the same material is added to the hangers. Regardless of the origin of the material type information all materials should be reviewed after an exchange since it cannot be trusted that they correspond to those in the native model.

2: A material tab is available in SMV, but the information is related to the Revit model. For a useful exchange the IFC model should include the same material information, but translated to an IFC type.

4.4.3 Sub conclusion

The geometry of the bridge structure is transferred successfully. The sections of the components are available and it is possible to see the origin of the information (the IFC section names kept in the properties table in RSA). To transfer the geometry successfully gives an advantage in a project process compared to a remodeling of the structural components, but it is the centerlines that have been transferred and not the analytical lines. For every project it should therefore be evaluated if it is an advantage to use an architectural model for structural investigations when using IFC for exchanging models.

When evaluating if IFC is suited for data exchange in specific projects with RSA as the structural analysis tool it should be taken into account that materials are not transferred successfully. Therefore the material properties for components in Revit cannot be exported correctly and they should be adjusted in RSA.

4.5 Exchange scenario 4

This exchange scenario investigates the capabilities of the direct link between Revit and RSA. Since it is a direct link which is investigated it is expected that a calculation can be made on basis of the information given in the Revit model.

4.5.1 Process outline

Different options must be chosen when making an exchange through the direct link. The export interface does not include an option where the material properties in Revit are used. This is stated in appendix D. Therefore it is chosen to define the materials in RSA.

The model is exchanged to RSA and investigated. It shows that the materials have not been exchanged successfully, but geometry, loads and boundary conditions are kept in the same way as in the Revit model. After replacing the automatically generated material properties with the properties given in chapter 3.3.1 a displacement calculation is made. The calculation is handled successfully and it is thereby shown that a calculation can be made based on a Revit model, but that material properties should be changed in RSA.

Figure 4.4 shows the displacement figure from the calculations based on the Revit model and exchanged through the direct link to RSA.

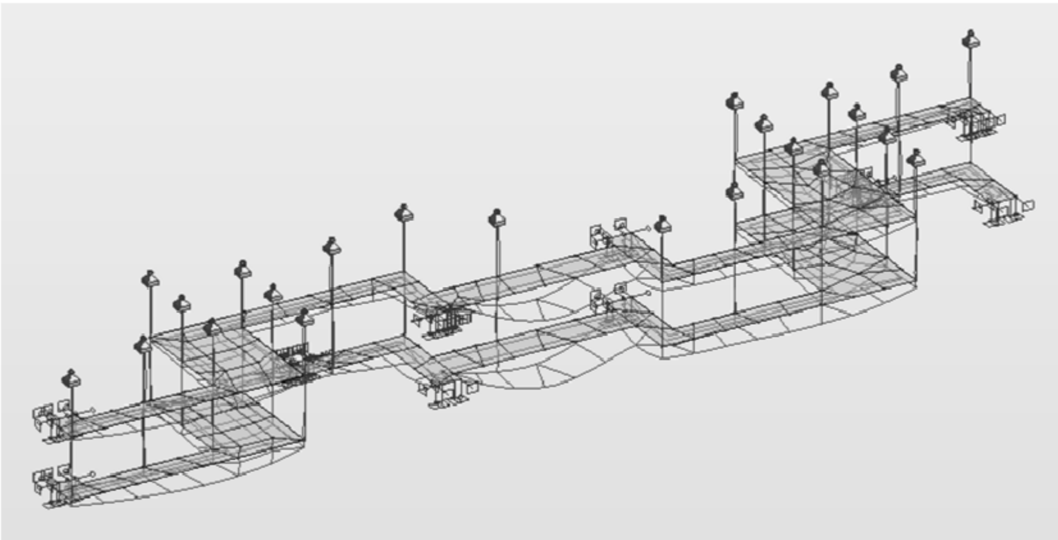

Figure 4.4: Screen dump of displacement figure.

4.5.2 Test results

Table 4.5 shows the results of the test of exchange scenario 4. Comments to specific parts of the table are assigned numbers and explained after the table.

	RSA
1. Geometry	
Level (Hangers)	✓
Diameter (Hangers)	✓
Length (Hangers)	✓
Coordinates (Hangers)	✓
Level (Decks)	✓
Thickness (Decks)	✓
Coordinates (Decks)	✓
2. Material properties	
Material type (Hangers)	×[1]
Material strength (Hangers)	×[1]
Material type (Decks)	×[1]
Material strength (Decks)	×[1]
3. Boundary conditions	
Pinned hanger supports	✓
Roller deck supports	✓
4. Load	
Surface load	✓
Load direction	✓

Table 4.5: The table shows the test results for exchange scenario 4. It is specified which information is exchanged to FEM-design. × tells that the information is not present while ✓ tells that the information is present.

1: The material properties cannot be exchanged through the direct link with the exact information that is given in Revit and is therefore not seen as a successful exchange. Never the less the material names from Revit are available in RSA and it is therefore quite easy to attach the material properties that correspond to the component names.

4.5.3 Sub conclusion

Investigations of the exchange scenario have shown that the material properties are the information that cannot be transferred through the direct link. All other information seems to be exchanged successfully. Since loads and boundary conditions are included a calculation can be made with a limited number of adjustments in RSA.

The investigation has shown that the material names are exported, but the material properties have default values given by RSA. To exchange the material properties have been quite simple since the names state which materials are actually considered. However, it might give more difficulties if the model is more complex than the bridge model considered here. Revit gives the possibility to attach material properties to the elements, but since the properties cannot be used for structural investigations in an analytical application from the same software vendor it seems to be an area that should be further developed. It should be said that there is no reason not to include the material properties in a Revit model since it can also be used for fabrication drawings and construction documentation where the material properties should also be present.

The exchange of loads has been successful and it makes it quite easy to investigate the model fast. To have the loads exchanged with the model will in a large degree facilitate the integrated design possibilities discussed in chapter 2.2.3. Especially when considering larger design changes early in a project it can relatively fast give a good estimate of the structural behavior when making some changes in the architectural model.

4.6 Exchange scenario 5

To investigate if the capabilities of IFC found in scenario 1 and 3 are related to the way IFC is implemented in Revit or to the MVD which is used, a scenario with another architectural software is studied. The bridge is remodeled in ArchiCAD and the properties of the elements are made as in the Revit model.

A direct link between ArchiCAD and Revit makes it possible to exchange the native model, but since the model is relatively simple it is remodeled to ensure that all components are attached with properties from ArchiCAD. The ArchiCAD model is enclosed in appendix H as:

- ACAD16_scenario5-6.pln

The architectural model is in this scenario exchanged through IFC to RSA while exchange scenario 6 investigates the capabilities of the IFC file in FEM-design. This makes a frame of reference for the other exchange scenarios.

4.6.1 Process outline

Remodeling of the decks and hangers has been made in ArchiCAD. Since the IFC setup shows that ArchiCAD uses the MVD "1.0 Coordination View" it is expected that the center lines will be used to create the analytical model in RSA when importing the IFC file. Therefore the modeling of the components is made as in the third version of the Revit model (where centerlines are adjusted to fit the analytical model).

The architectural appearance of the components is handled in a settings dialog for each component. Here the preferred material is chosen, but only for use in drawings based on the model. The appearance of the decks is chosen to be lightweight concrete while the hanger appearance is chosen as steel. This information is only related to the architectural presentation since there is no possibility to define material properties.

Loads and boundary conditions have been defined in the Revit model, but structural configurations cannot be added to the model in ArchiCAD.

To prepare the model for an exchange the bridge components are arranged in a structural layer. This ensures that these components will be included in an IFC file when exporting the model especially for use in structural analysis software. A thorough description of the export is given in appendix E.

Having exported the model to an IFC file it is investigated in SMV. Here it is seen that material type information is present for both the hangers and the decks. The material names in SMV correspond to the names in the appearance settings in ArchiCAD. It is not expected that a structural analysis application will be able to read this information since it is not oriented against structural use, but it might be possible to identify which components are considered by the name. This could be of use in larger construction projects. In this case the structure includes a few different elements and the need for identifying components is therefore handled without investigating the names further.

The investigation of the IFC model shows that the geometry of the structure has been successfully exchanged. Having concluded that the expected information is present in the IFC file it is used in RSA for a structural calculation.

The IFC model is successfully opened in RSA and loads and boundary conditions are added. Thereby the analytical model is prepared and a calculation of the displacements is made as for the other exchange scenarios. Figure 4.5 shows the displacement figure of the bridge.

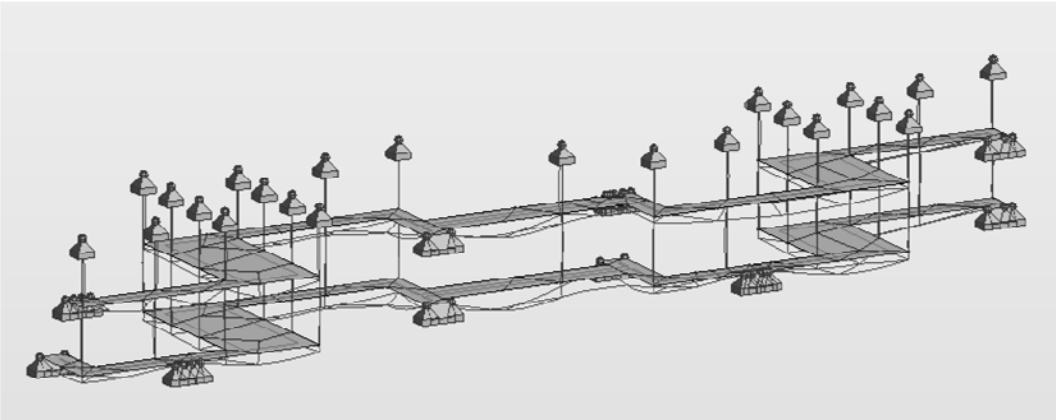

Figure 4.5: Screen dump of displacement figure.

The displacement figure seems correct and it is proven that the components exchanged through IFC can be used for analysis in RSA.

4.6.2 Test results

Table 4.6 shows the results of the test in exchange scenario 5.

	IFC file	RSA
1. Geometry		
Level (Hangers)	✓	✓
Diameter (Hangers)	✓	✓
Length (Hangers)	✓	✓
Coordinates (Hangers)	✓	✓
Level (Decks)	✓	✓
Thickness (Decks)	✓	✓
Coordinates (Decks)	✓	✓
2. Material properties		
Material type (Hangers)	× [1]	×
Material strength (Hangers)	×	×
Material type (Decks)	× [1]	×
Material strength (Decks)	×	×
3. Boundary conditions		
Pinned hanger supports	×	×
Roller deck supports	×	×
4. Load		
Surface load	×	×
Load direction	×	×

Table 4.6: The table shows the test results for exchange scenario 5. It is specified which information is exchanged to FEM-design. × tells that the information is not present while ✓ tells that the information is present.

1: No material types or properties are attached to the components, but appearance names from ArchiCAD are available and it can therefore be used to identify change the materials and properties.

4.6.3 Sub conclusion

For the investigation in this exchange scenario MVD “1.0 Coordination View” have been used when exporting IFC files from ArchiCAD. No differences has been observed in the IFC file caused by this version compared with MVD “2.0 Coordination View” used by Revit.

When the bridge structure is modeled the centerlines are connected to ensure that they correspond to the analytical model. This procedure ended in a successful exchange to RSA where the nodes were generated correctly. Never the less it does not give a perfect exchange in scenarios where the centerlines of the elements are not connected.

In ArchiCAD the IFC export is targeted towards a specific use. Here an export possibility focusing on analytical tools have been used ensuring that the components defined as “structural” are included in the export. This solution cannot be seen as a direct use of an architectural model for structural analysis, but the export tool does facilitate easy retrieval of information related to structural analysis.

There are direct links available that connects ArchiCAD with structural modeling applications and these can be used when defining loads and boundary conditions, but to use the modeling software as basis for structural investigations does not seem possible. The direct links have not been considered further, but collaboration with structural modeling applications could enable an integrated design process with ArchiCAD as architectural modeling tool.

4.7 Exchange scenario 6

This exchange scenario is made to investigate the performance of the IFC file made in ArchiCAD in a second analysis application. This investigation can show if the information in the IFC file are handled in the same way when using it in another analytical application than RSA.

4.7.1 Process outline

A thorough description of the process for this exchange scenario is given in appendix F while this section contains an outline where the main parts of the investigation are described.

The IFC file exported from ArchiCAD in exchange scenario 5 is opened in FEM-design 9.0. Earlier investigations have shown that version 9.0 is the most recent version that is capable of opening IFC files, which is why it is used for this investigation as well. When opening the file a mapping of materials is made and the information from chapter 3.3.1 is attached to the components. When mapping the materials it is observed that the names from the appearance settings in ArchiCAD are shown as IFC material names. These can be used to identify which materials that should be attached since only the element type can be seen from the IFC type.

When opening the model the geometry corresponds to the ArchiCAD model and the material types and properties have successfully been applied. Before using the model for analysis loads and boundary conditions are added. Finally a calculation of displacements is made to prove that the imported components can be used in FEM-design. Figure 4.6 shows a screen dump of the displacement figure showing that the exchanged components are useable.

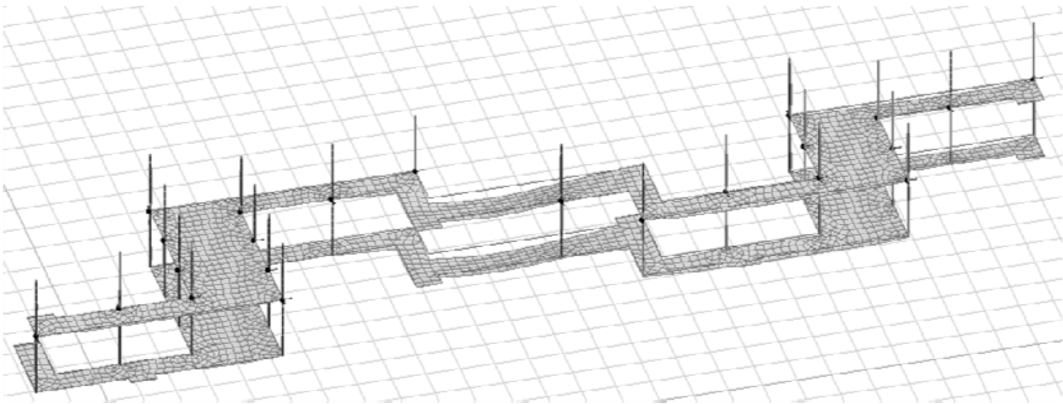

Figure 4.6: Screen dump of displacement figure from FEM-design.

4.7.2 Test results

Table 4.7 shows the results of the test in exchange scenario 6. Since the same IFC file as in scenario 5 is used the results for this part are the same.

	IFC file	FEM-design
1. Geometry		
Level (Hangers)	✓	✓
Diameter (Hangers)	✓	✓
Length (Hangers)	✓	✓
Coordinates (Hangers)	✓	✓
Level (Decks)	✓	✓
Thickness (Decks)	✓	✓
Coordinates (Decks)	✓	✓
2. Material properties		
Material type (Hangers)	× [1]	× [2]
Material strength (Hangers)	×	× [2]
Material type (Decks)	× [1]	× [2]
Material strength (Decks)	×	× [2]
3. Boundary conditions		
Pinned hanger supports	×	×
Roller deck supports	×	×
4. Load		
Surface load	×	×
Load direction	×	×

Table 4.7: The table shows the test results for exchange scenario 6. It is specified which information is exchanged to FEM-design. × tells that the information is not present while ✓ tells that the information is present.

1: No material types or properties are attached to the components, but appearance names from ArchiCAD are available and it can therefore be used to identify change the materials and properties.

2: None of the material properties have been included in the IFC file and can therefore not be used directly in the structural model, but the mapping interface in FEM-design ensures that no components are imported into the model without material information.

4.7.3 Sub conclusion

The investigations in this scenario show some of the same aspects that have been seen in the other exchange scenarios as well. The geometry is handled well and an evaluation of the exchanged structure can be made fast. This part facilitates an integrated design process. For the bridge structure there are relatively few loads and boundary conditions to add in the structural model, but for more complex structures it might be a process that takes too much time compared to the benefits in using the geometry. The alternative, where a structural model is made in the analytical application and then updated could be less time consuming for smaller changes, but a source of mistakes.

The mapping interface that appears when opening an IFC file in FEM-design gives the user an overview of the components that are imported and assures that all components are attached with material information.

Chapter 5

Discussion

The investigations in the exchange scenarios discussed are in this chapter. The capabilities of the different software applications are discussed and compared. It is also evaluated if an integrated design process is facilitated by the exchange scenarios investigated in this thesis.

5.1 Recap of scope

This thesis seeks to clarify if advantages can be achieved in the planning of construction projects when using architectural models for structural analysis. The exchange scenarios investigated in case study are evaluated in regards to the theoretical description of BIM.

This study has examined to which degree Revit and ArchiCAD facilitates the use of architectural models for structural analysis. In both cases exchanges have been made to FEM-design and RSA through IFC. In Revit there are direct links available to interact with both structural applications and these have been tested as well.

5.2 Discussion of results based on exchange scenarios

In table 5.1 is summarized which information has been exchanged in the six scenarios which have been considered. A comparison of the capabilities of the different software applications is made and a like for like comparison is shown in the table.

Scenarios	1 Revit IFC FEM	2 Revit *.r2f FEM	3 Revit IFC RSA	4 Revit *.rtd RSA	5 ArchiCAD IFC RSA	6 ArchiCAD IFC FEM
1. Geometry						
Level (Hangers)	✓	✓	✓	✓	✓	✓
Diameter (Hangers)	✓	×	✓	✓	✓	✓
Length (Hangers)	✓	✓	✓	✓	✓	✓
Coordinates (Hangers)	✓	✓	✓	✓	✓	✓
Level (Decks)	✓	✓	✓	✓	✓	✓
Thickness (Decks)	✓	✓	✓	✓	✓	✓
Coordinates (Decks)	✓	✓	✓	✓	✓	✓
2. Material properties						
Material type (Hangers)	×	×	×	×	×	×
Material strength (Hangers)	×	×	×	×	×	×
Material type (Decks)	×	✓	✓	×	×	×
Material strength (Decks)	×	✓	×	×	×	×
3. Boundary conditions						
Pinned hanger supports	×	✓	×	✓	×	×
Roller deck supports	×	✓	×	✓	×	×
4. Load						
Surface load	×	×	×	✓	×	×
Load direction	×	×	×	✓	×	×

Table 5.1: The table shows the test results for all exchange scenarios. It is specified which information is exchanged from the architectural software to the analytical software. × indicates that the information is not present while ✓ indicates that the information is exchanged successfully.

Geometry

All exchange scenarios have been fairly successful in exchanging the geometry modeled in the architectural software. Besides exchanging the hangers from Revit to FEM-design through the direct link all geometry of the components has been successfully transferred. In table 5.1 this is stated with ✓ in most fields, but the positive result does not tell the entire story. To succeed with an exchange through IFC it has been necessary to update the Revit model version 2012 to 2013 since the decks were not given the correct coordinates when exporting an IFC file. The update of models has not given any difficulties, but in larger projects it might cause confusion when the software in which the native model is made cannot be used for creating the IFC file.

ArchiCAD has shown promising results related to exchange of the geometry of the tested elements through IFC. Both the deck, which is a standard element, and the hangers are exchanged successfully. Investigation of the components in SMV shows that the coordinates are successfully transferred.

All geometry exchanges through IFC have been based on the centerlines, while the direct links have created a model based on the analytical representation when it is opened in the structural software. Since the centerlines of the architectural components might not correspond to an analytical representation IFC cannot be used, in such cases, without moving the components to fit the analytical situation.

Material properties

The exchange of material properties is quite important in integrated design situations. The value in integrated design lies in the ability to gain knowledge of different design options before determining a final design. To investigate different structural solutions it is important that an exchange of the models is made fast and with no needs for updating the model information. If materials are not exchanged it will delay an exchange since materials should be assigned in the analytical software before the required calculations can be performed and the architectural model evaluated.

In the tested scenarios the success in exchanging material properties has been limited. Only the direct link from Revit to FEM-design had successfully exported the material strength and type. Even though scenario 2 is successful in exchanging the material type and strength of the decks the direct link cannot be seen as a fully integrated tool in Revit as the material types have to be manually translated to the FEM-design language before the *.r2f file is made. Additionally only standard components could be exported this way.

Boundary conditions

In all scenarios where IFC has been used the boundary conditions have not been included in the exchange. The MVD “Coordination View” has been used in the scenarios with IFC and has shown that it is not suited for exchanging structural settings. IFC cannot directly be seen as unsuited for exchanging structural settings, but the MVD “Coordination View” can.

The two direct links that have been studied (scenario 2 and 4) have shown two be fully capable of exchanging the boundary conditions successfully. Exchanging models through these links does therefore require a minimum amount of work which facilitates an integrated design situation.

Loads

The tests have included an investigation of the exchange of loads. A surface load on the decks has been considered and it is evaluated if the load direction corresponds to the situation in Revit. It has shown that only the direct link from Revit to RSA includes the surface load. Since boundary conditions have not been exchanged through IFC it is no surprise that loads are not included as well, but it is surprising that the direct link to FEM-design does not include the loads.

For the bridge structure used in these exchange scenarios it is relatively simple to apply the loads when the geometry is exchanged, but it could be time consuming as well as a source of error when investigating a complex structure with a large number of loads and load combinations.

5.3 Assessment of software interoperability

In the previous section it has been summed up which information has been possible to exchange in the different scenarios. Here it is discussed how the direct links and IFC have facilitated the exchange of information.

5.3.1 Direct links

Direct link from Revit to FEM-design

The direct link from Revit to FEM-design, tested in exchange scenario 2, has shown the ability to exchange standard elements successfully after a mapping procedure. It has not been possible to exchange the hangers since these are not considered present in the material library in FEM-design. Even though the hangers have not been exchanged successfully it has been easy to place the hangers after an exchange since lines are transferred.

In theory it should be possible to make a structural investigation in FEM-design when the model is opened. Since the hangers have not been transferred this has not been possible. Never the less it has been possible to make a calculation based on the analytical lines which have been defined in Revit. Since the direct link is capable of transferring the analytical lines it is possible to make a structural investigation based on the architectural model.

The possibility to use the analytical representation facilitates a design process where structural investigations can be made fast and the best suited solution can be chosen, but the use of analytical models does also present a communication task that should be solved before the value in the process can be fully exploited. In this thesis the test has been based on a rather simple structure, but for more complex structures it might be difficult to for designers to adjust the analytical lines satisfactorily without guidance from the engineers who is making the calculations. It should be determined in every case if this communication will cause more confusions than benefits.

The same discussion appears when using the mapping interface in the add-on tool. The material names are translated from the Revit names to the corresponding FEM-design names. The interface requires that the user knows the way the materials are named in FEM-design in order to type in the exact name in the add-on tool. No drop down menus or the like are available which requires the user to have knowledge of both software. The seamless interaction between an architect and a structural engineer seems to be inhibited by this exchange procedure.

Direct link from Revit to Robot Structural Analysis

This direct link has shown some good results since it has been possible to include both loads and boundary conditions in the exchange and there has been no need to go through a mapping procedure before the exchange. Revit and RSA are made by the same software vendor and were therefore expected to show good results which were proved correct.

The exchange of material properties and types has on the other hand not shown to be successfully included in the exchange. When analyzing the structure in RSA all components must be reviewed to ensure that the material information is correct. That material information cannot be used in both applications is unfortunate and for complex projects it will give some challenges to update the structural model after the exchange.

5.3.2 Exchange through IFC

The exchange scenarios have shown different ways to handle the implementation of IFC, but in both Revit and ArchiCAD the MVD “Coordination View” has been used. This MVD is mainly thought as a way to collect the geometry from different models and investigate clashes while the “Structural Analysis View” should be used for sharing information related to structural considerations.

The use of MVD “Coordination View” has meant that the exchange of geometry has been related to the centerlines of the components. Therefore the architectural bridge has been adjusted to assure that the centerlines are connected in nodes corresponding to the analytical model. The procedure in adjusting the placement of the components, before making an exchange, cannot be seen as an actual use of an architectural model since the adjusted model could be a separate structural model. Never the less this is the MVD that is currently implemented in the studied software.

Also the loads and boundary conditions have not been included in the IFC files and these should therefore be applied after an exchange. Again a fact that complicates the use of a common model used as basis for structural analysis. It is of course a simpler task to apply loads than to remodel everything for each purpose, but it in the future development of the software applications it should definitely be incorporated.

To use an open source exchange format has shown some advantages in the tests. The IFC models have been investigated in SMV in order to study the contents before making a structural analysis. This eases the collaboration in a project coalition since a check in SMV can determine if the model information corresponds to the level of detail which is agreed upon in the ICT agreement.

Even though it has not been possible to achieve a completely successful exchange it has been tried to use the exchanged components for structural analysis to investigate the capability of exchanging information connected to each component.

Robot Structural Analysis

Both IFC models from Revit and ArchiCAD have been investigated in RSA and with very similar results. In both cases it has been possible to use the geometry of the exchanged components while material information, loads and boundary conditions have not been available after importing the models due to the fact that MVD “Coordination View” has been used. Based on these studies it cannot be said if RSA is capable of handling the information since it has not been possible to include it in the IFC files.

It should be said that RSA does not provide an import option where material properties can be defined. Instead the user needs to investigate all components and change the properties. Since the development and implementation of IFC has not reached a higher level one might wonder why RSA does not make the user aware of the fact that the software has guessed on random material properties and assigned these automatically.

FEM-design

Contrary to RSA, FEM-design handled the import of IFC files well in version 9.0. When opening an IFC file a material and component mapping interface is filled out to ensure that all information is successfully read. Thereby the use can control the model and the information contained in it.

In the mapping interface it is shown which material name is given in the IFC file and it can then be attached with a material from the FEM-design material library. The only difficulty in this procedure could be if the material was not present in the FEM-design library, but it has not been an issue in these studies. In the mapping interface the placement of the components is given in a list and if the IFC material name does not tell which material to apply to the components, it can easily be derived by investigating the components in the native model.

The exchange through IFC to FEM-design has shown some of the same lacks as seen in RSA but a major advantage in FEM-design is that it has been tried to find a way of handling IFC files and use the information in the best possible way.

5.4 Software versions

Testing the different exchange scenarios has revealed incompatibilities in software versions and it has been necessary to use different versions to be able to complete the investigations. Figure 5.1 gives an overview of the sequence the software applications have been used in to be able to complete the exchange scenarios. The blue arrows show the path that has been used to reach a successful exchange scenario.

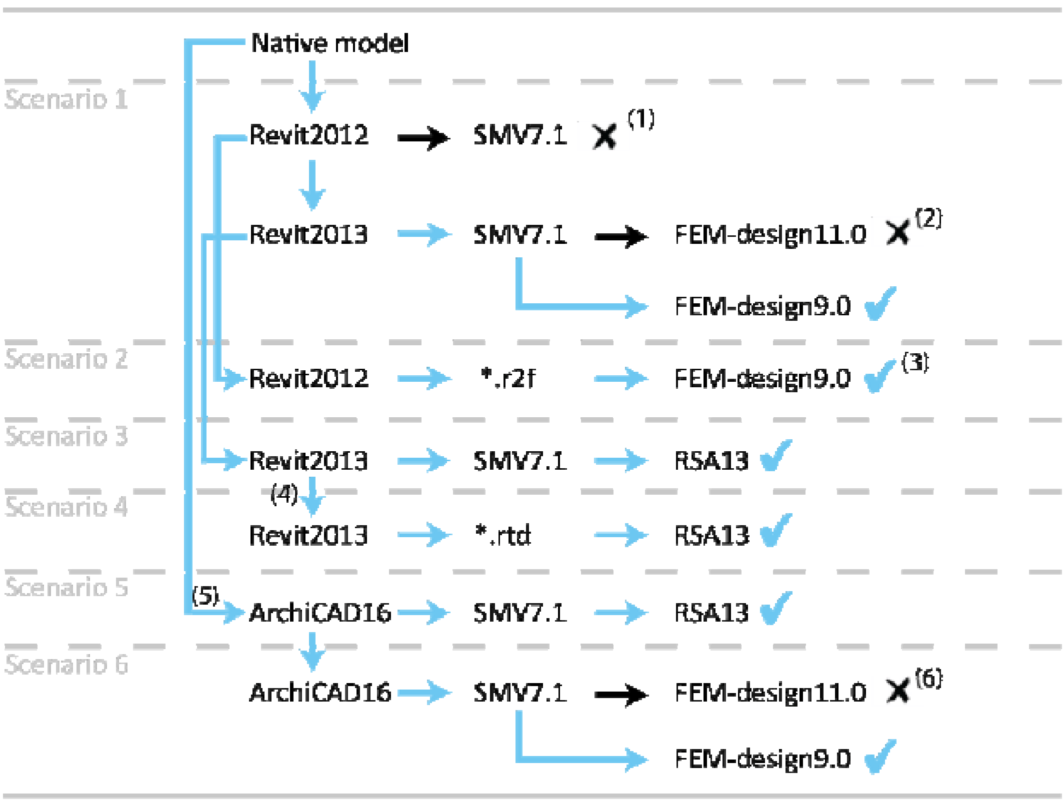

Figure 5.1: Overview of the sequence the software applications have been used in. ✗ shows that a software exchange has not performed satisfactorily and that another path is followed to complete the scenario. ✓ shows that an exchange scenario has been completed.

The following comments refers to the numbers given in the figure.

(1) The decks have not been successfully exchanged so the model is updated to Revit 2013 to solve the problem.

(2) This version does not support IFC for all models according to the FEM-design support group. Version 9.0 is used instead.
(3) The FEM-design version that the model is transferred to must be installed on the workstation.
(4) Revit 2013 is used since the link to RSA is already installed as default.
(5) The native model is remodeled to ensure that there are no properties from Revit included in the model which could be the case if an exchange was made instead.
(6) The E-mail correspondence with FEM-design support tells that some models might work in the newest software versions. This is not the case for this model and FEM-design 9.0 is used instead.

Figure 5.1 illustrates how the capabilities of the different software versions have been determining for the exchange path that has been used to complete the scenarios. The illustration only includes the software name and not the different versions of the models and still it can be difficult to keep track of the best communication path.

The investigations have shown that exchange problems have been solved in all cases, but for some it has been necessary to adjust the exchange path on the way. To use the investigated tools in practice and not only for testing the capabilities it will give some problems that the software applications cannot be trusted to have the capabilities as previous versions. Furthermore it is also necessary to Quality Control new software versions as it has been shown that capabilities have been lost with the upgrade of FEM-design, from version 9.0 to 11.0.

To succeed with exchanges to FEM-design it has been necessary to use an older version even though StruSoft claims, through advertising, that the software applications can handle import of IFC files. Also Revit 2012 showed lacks in exchanging decks correctly. This might be the only component type that cannot be handled, but exchange difficulties as these might reduce the benefits of using the tools and therefore these will not be implemented in the industry or at least the implementation time will be prolonged.

5.5 Software interoperability affects on BIM implementation

As stated in chapter 1.4 the value of BIM lies in gaining information early in a project phase to have the ability to affect a design at the lowest possible cost and thereby reach a higher quality of the final product. To reach this point the collaboration should go from the DBB approach to the more BIM oriented approaches DB and IPD. The software investigated in this thesis have shown some abilities that facilitate the transition to a BIM-based planning procedure, but they cannot be seen as fully capable of handling all tasks in integrated design of structural components. To reach the overall goal, increasing productivity in the industry for the benefit of both developers and the construction industry, a continuously effort in using the available BIM-tools should be strived towards.

The investigated scenarios have shown that the direct links are best suited for using a common model for structural analysis, since it has been possible to set up the analytical lines and use these in the structural analysis tools. Though the direct links have shown the best results for structural analysis IFC seems to have the largest potential. Theoretically IFC enables all project participators to base their design on a common model and with the same requisites. With the direct links the use of a BIM model is restricted to pre-defined professions where appertaining software applications are available.

This thesis has shown that both Revit and ArchiCAD rely on the MVD “Coordination View” which indicates that clash detection is the area which has been developed the most. Never the less ArchiCAD has an exchange option only for structural investigations but there are some challenges that have not been solved. It is clear that the MVD “Structural Analysis View” should be implemented to reach a point where more than geometry can be exchanged.

The BIM theory, described in chapter 1 and 2, defines the theoretical benefits of converting from traditional planning approaches in the construction industry. The theory emphasizes the benefits, for the life time of a given building, related to construction and life time costs. However, through the work done in this thesis, which has focused mainly on the use of BIM models for interoperability between architects and structural engineers, it has become very clear that there is a gab in the software development that must be fulfilled to gain benefit of the theory.

Chapter 6

Conclusion

The scope of this thesis was to investigate if architectural BIM models can be used for structural analysis. Investigations based in six different exchange scenarios have been made, where the use of direct links and IFC based data exchange has been evaluated. These investigations constitute the basis of the following conclusions.

The test scenarios have shown that an architectural model can be used for structural analysis when the exchange includes an analytical representation of the structure. In Revit Structure an analytical model can be made based on the architectural components. In ArchiCAD it is not possible to define analytical lines.

Direct links from Revit Structure to FEM-design and RSA it was possible to exchange the analytical representation of the model and use it for analysis. The link to FEM-design has some limitations for components that are not included in the FEM-design library, but incomplete information is easily adjusted in the application. Both direct links are successfully exchanging boundary conditions while only Robot Structural Analysis is capable of using the loads exported from Revit Structure.

The scenarios using IFC for exchange of models have all used the MVD "Coordination View" and the use of the exchanged models have shown that the centerlines of all components have been used as the analytical representation in the structural analysis software. To use architectural models exchanged trough IFC using the MVD "Coordination View" requires that all centerlines of the exchanged component are adjusted to meet where the nodes are in a corresponding analytical model. This means that the model is no longer correct in regards to being an architectural model.

The capabilities of Revit Structure related to IFC model exchange has been slightly improved from version 2012 to 2013. Only the newest versions of RSA and ArchiCAD have been used without any software compatibility issues. So development of these are not been discussed. The newest version of FEM-design, version 11.0, has revealed missing IFC capabilities compared to a previous version, this has been confirmed by the FEM-design support team. FEM-design 9.0 has been used instead and shown the expected IFC capabilities.

The conclusion of this thesis is that the direct links are better suited for exchanging architectural models since analytical representations are included in the exchange. Though the direct links have shown the best results in this thesis the recommendation is to implement MVD "Structural Analysis View" and thereby use IFC for data exchange instead of the direct links. This ensures that the structural engineer can choose the best suited software application without considering the software vendor in which they are produced. It should be noted that MVD "Structural Analysis View" is still in a development phase and has not been implemented in software investigated in this thesis.

The structural BIM-tools have not been able to make calculations based on architectural models without modifications. However, using architectural models is still seen as a focus area for future development. The theory studies have indicated a large potential in moving towards an integrated design procedure and a seamless use of architectural models for structural analysis does facilitate this.

The development of the BIM software has proven to be essential for reaching a point where architectural models can be used for structural analysis. That the newest version of FEM-design is incompatible with IFC shows a limited focus and willingness from StruSoft, while Revit Structure has shown better IFC performance in the newest version. In any case it is an area that should be further investigated to see if there is a general tendency from the software vendors to use limited resources in implementing IFC. This could for example be in cases where the same software vendor offers both a structural analysis and an architectural software application.

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Appendix **A**

Working process for exchange scenario 1

This appendix describes how the architectural model has been adjusted in order to use it for structural analysis. An overview of the model files described in this appendix is attached in appendix H.

A.1 Process description

A.1.1 Adjustment of architectural model for structural analysis

The original model is modeled for architectural purposes; therefore a linoleum floor is made on top of all concrete slabs in the bridge. The floor has no structural properties and should only be used for adding self-weight to the structure. In this case it is removed since the self-weight could be modeled as a load and the number of components to exchange is reduced. Figure A.1 shows a part of the original model where the floor is present.

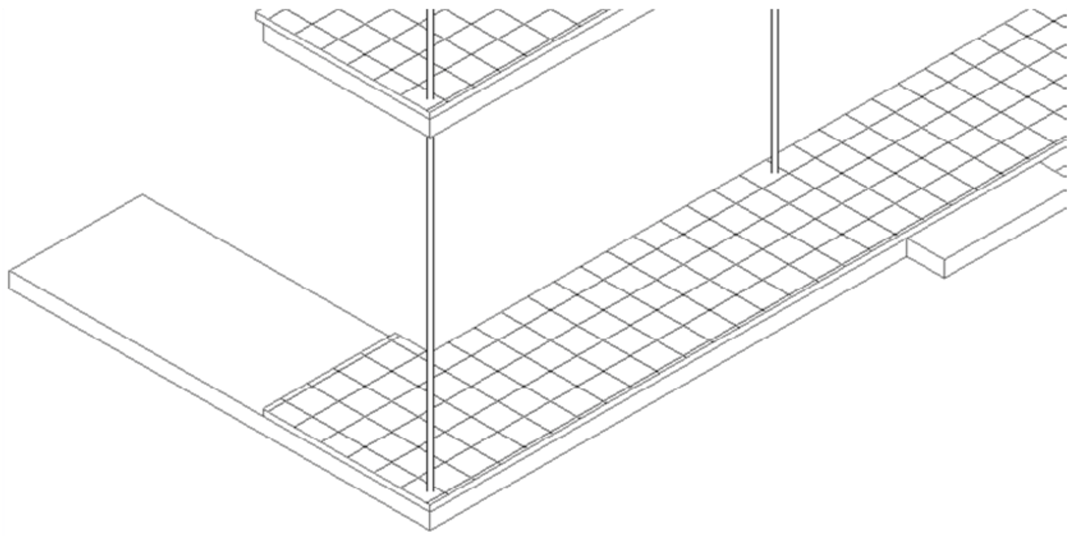

Figure A.1: Part of original Revit model shows where linoleum floor is still a part of the model. The linoleum has no structural function.

Figure A.1 shows that hangers are attached away from the edges of the decks. This seems reasonable for construction purposes, but a static model would typically be simplified when making a static analysis while details (such as the attachment of the hangers) would be considered separately. The part of the structure shown in figure A.1 would typically have a static system corresponding to the sketch shown in figure A.2.

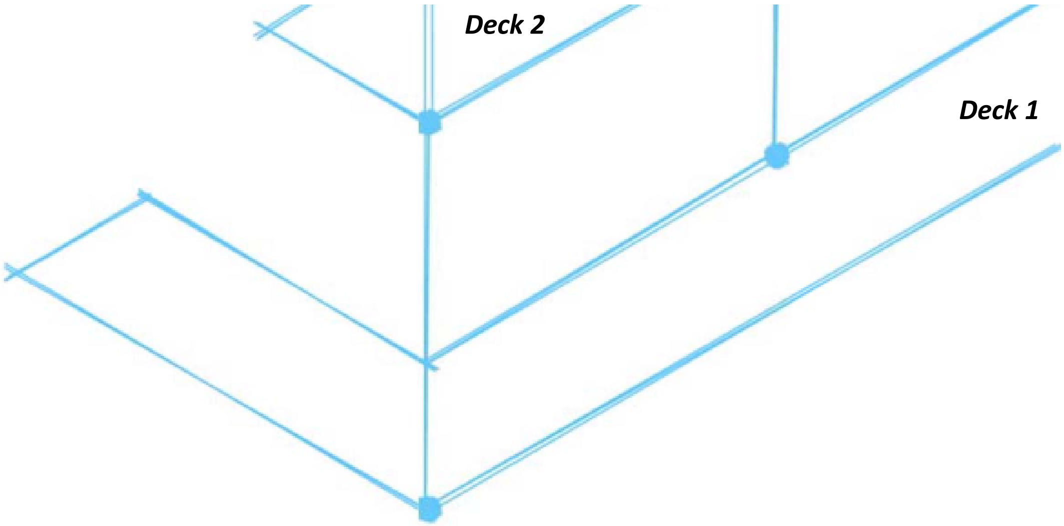

Figure A.2: Sketch of static system corresponding to architectural illustration in figure A.1.

The figures show that the hangers in the architectural model should be moved to the edges where nodes are generated or should be represented by analytical lines which are moved according to the static model. In figure A.3 it is seen how the analytical lines are placed in the original model.

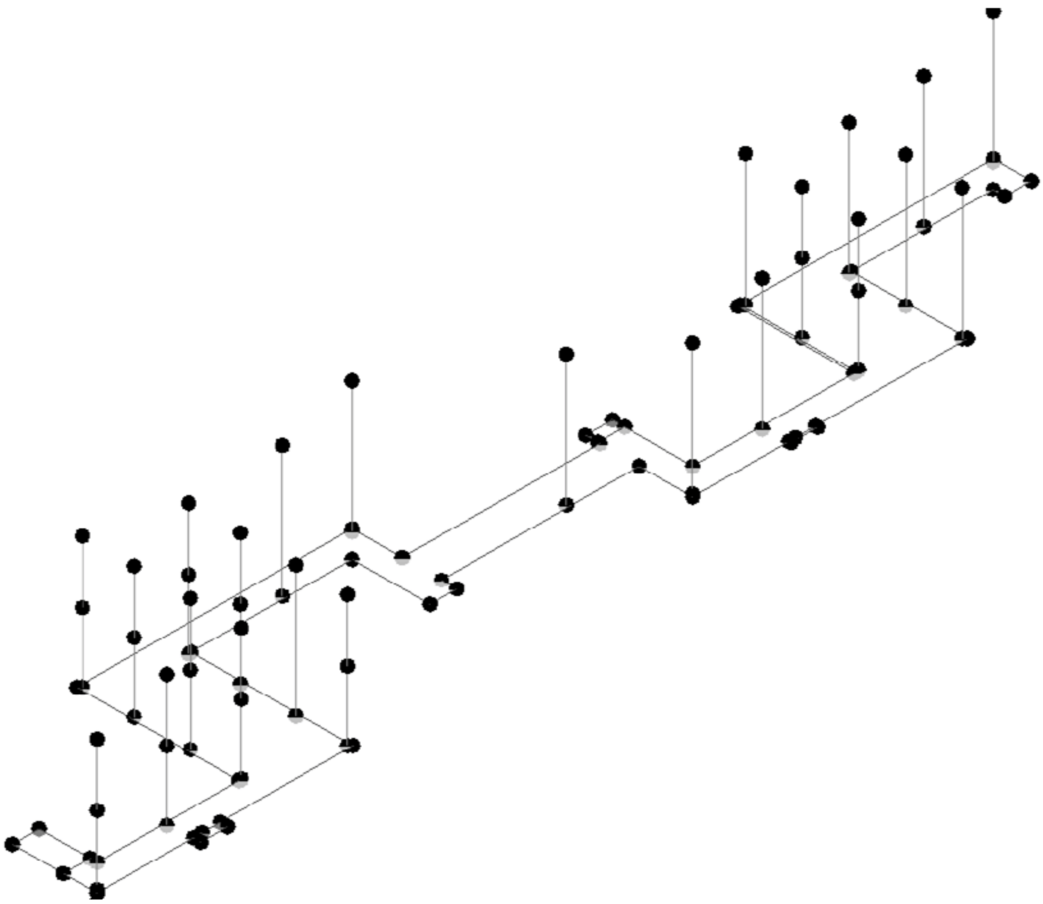

Figure A.3: Analytical lines before adjustment.

The figure shows that the analytical representations of the decks are placed on the same level and the nodes where the second deck lies are therefore not connected to the deck. What the figure does not show is that the analytical lines are placed higher than the decks and the nodes are therefore not attached to anything (see attached Revit file REVIT2012_originalmodel.rvt). All analytical lines are adjusted to correspond to a suited static model before an exchange is made. Besides adjusting the analytical lines all hangers are moved to the edges since it is expected that these are the only elements which will be exported using the MVD 2.0 Coordination View. Adjustment of analytical lines is made to test if they can be exchanged through IFC by modifying the mapping table in Revit.

Figure A.4 shows a view of the adjusted model which is used for the data exchange test. The model is attached in appendix H and has the file name: REVIT2012_adjustedmodel_vers1.rvt

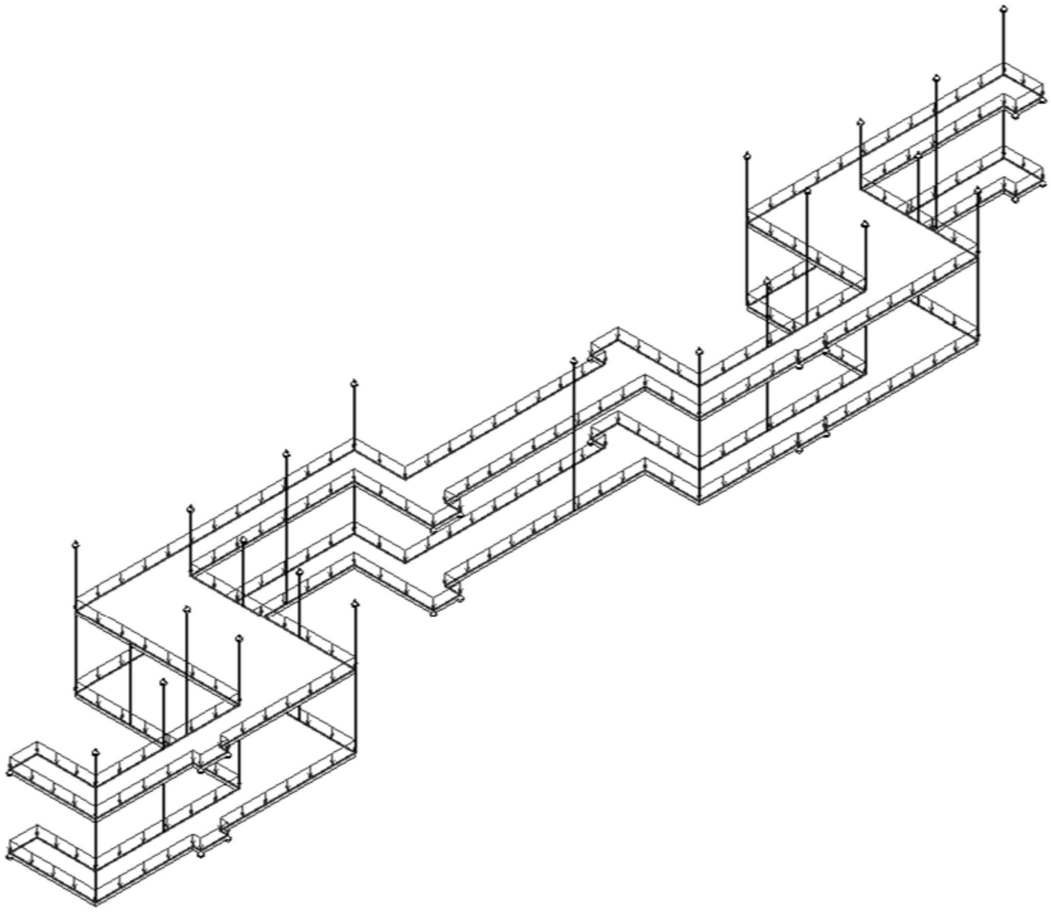

Figure A.4: Revit model adjusted to fit a structural representation and with loads and boundary conditions added.

Figure A.4 shows that the bridge structure is applied with pinned supports on the hangers, roller edge supports where the decks are attached to the surrounding structure and surface loads acting on the decks in a downwards direction.

All hangers have a diameter of 50 mm and are made of steel. Revit structure offers the possibility to attach material type information, but specific material properties are not attached to the building components. The decks are modeled as homogeneous concrete plates with a height of 180 mm. Both concrete decks and steel hangers have an architectural representation in solids, while the analytical model is made of lines connected in nodes, where the hangers are attached to the decks. Two support types are used in the model; 1) steel hangers are simply supported in the top to represent the roof structure which is considered to have sufficient strength to carry a part of the vertical load. 2) rolled supports along the edges where the bridge structure is attached to the concrete cores. The loads acting on the structure is its self-weight and a uniform distributed surface load. The surface load is applied in Revit Structure to investigate the ability of exchanging information of load conditions.

The following section goes through the process of creating a common IFC file based on the adjusted model (REVIT2012_adjustemodel_vers1.rvt) presented in this section.

A.1.2 Creating IFC file based on Revit model

In Revit the IFC export options defines which elements to export. The IFC export table is shown in figure A.5.

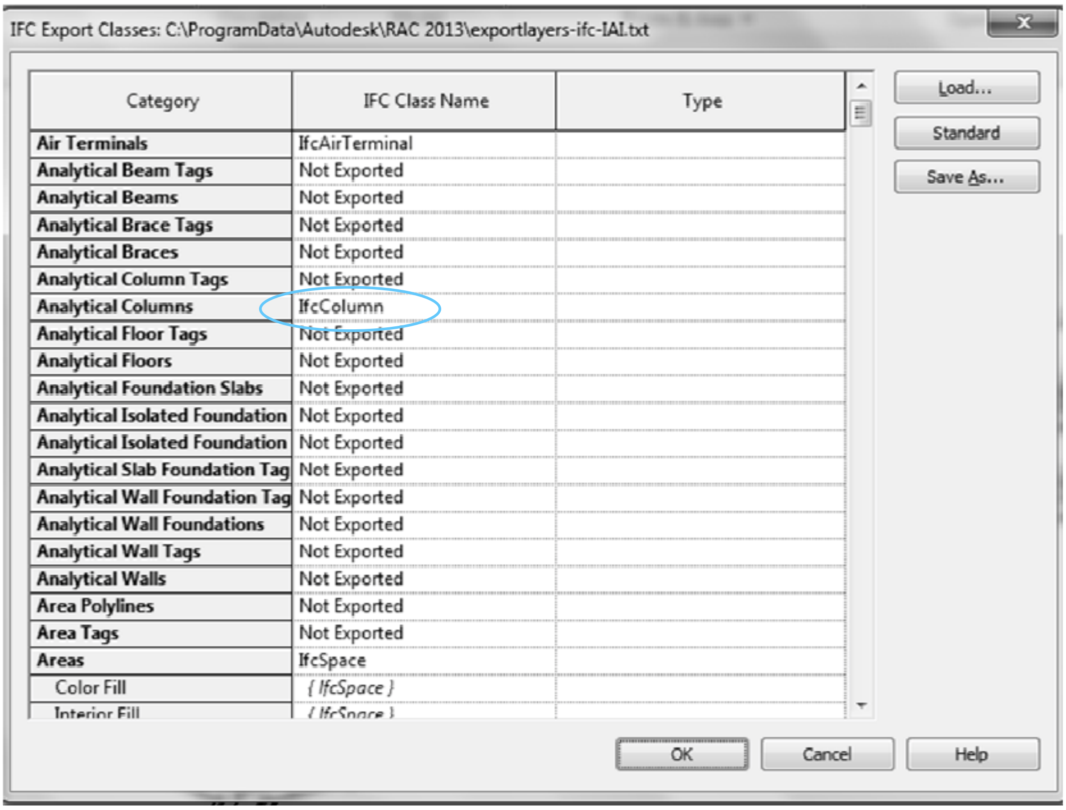

Figure A.5: IFC export table from Revit

The table follows a standard export suited for IFC export and does not include analytical categories as it is seen in figure A.5. It was tried to make an export where the analytical categories have been attached with IFC Class Names which are successful for other Categories, but it has not been possible to include the analytical Categories to the common IFC file. In the figure A.5 this is marked with blue.

The relevant IFC class names are given in table A.1.

Category	IFC class name
Analytical column	Not exported
Column	IfcColumn
Analytical floor	Not exported
Floor	IfcSlab

Table A.1: Category translation from Revit to IFC.

An export of the model REVIT2012_adjustedmodel_vers1.rvt is made with the standard IFC options given in the file exportlayers-ifc-IAI.txt [15]. The IFC file is attached in appendix H with the file name: SMV7.1_adjustedmodel_vers1-1.ifc.

A.1.3 Investigation of IFC file in Solibri Model Viewer 7.1

SMV7.1_adjustedmodel_vers1-1.ifc is opened in SMV to investigate the contents of the file. As illustrated in figure A.6 the hangers are placed separately from the decks.

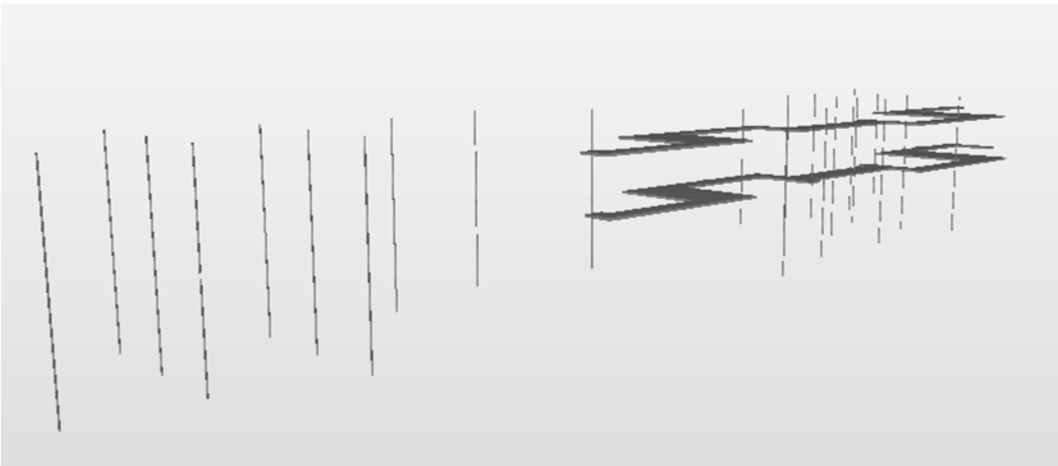

Figure A.6: Screen dump of SMV7.1_adjustedmodel_vers1-1.ifc opened in SMV.

This seems to be a software mistake according to an Autodesk forum [16]. The issue should be solved in version 2013; therefore the Revit model is opened in the new version, thereby upgraded, and a new version of the IFC file is made. Both models are enclosed as:

- REVIT2013_adjustedmodel_vers1.rvt
- SMV7.1_adjustedmodel_ver1-2.ifc

Investigation of the new version if the IFC file shows that the elements are placed corresponding to the Revit model, but the hangers are presented in different colors and might therefore include different information. Reviewing the components it seems that a part of the hangers have no profile type information included in the IFC properties. To ensure that the elements are the same a new Revit Family has been made and all hangers are exchanged with this family. The Revit Family used instead of the original hangers is enclosed as; REVIT2013_columnfamily.rfa. Also new versions of the Revit files are made, both in the 2012 version and the 2013 version. Both versions are updated since the add-ons, considered in the later exchange scenarios, are only installed on student PCs using the Revit 2012 version. The new versions are enclosed as:

- REVIT2012_adjustedmodel_vers2.rvt
- REVIT2013_adjustedmodel_vers2.rvt

Investigation of the new version includes the expected information when investigating the IFC file (SMV7.1_adjustedmodel_vers2.ifc). No loads or boundary conditions are available, but the visual look corresponds to the Revit model. This model is imported in FEM-design 11.0 to investigate the IFC capabilities.

A.1.4 Import of IFC model in FEM-design

When importing the model a mapping interface is shown in FEM-design. It gives the possibility to import the IFC information through a Geometry View or an Architectural view. Only the architectural view is relevant in this case since this gives the possibility to add material properties to the structural components, while the Geometry View import method only includes outer surface geometry of the IFC elements. Figure A.7 shows a screen dump from the IFC import interface in FEM-design.

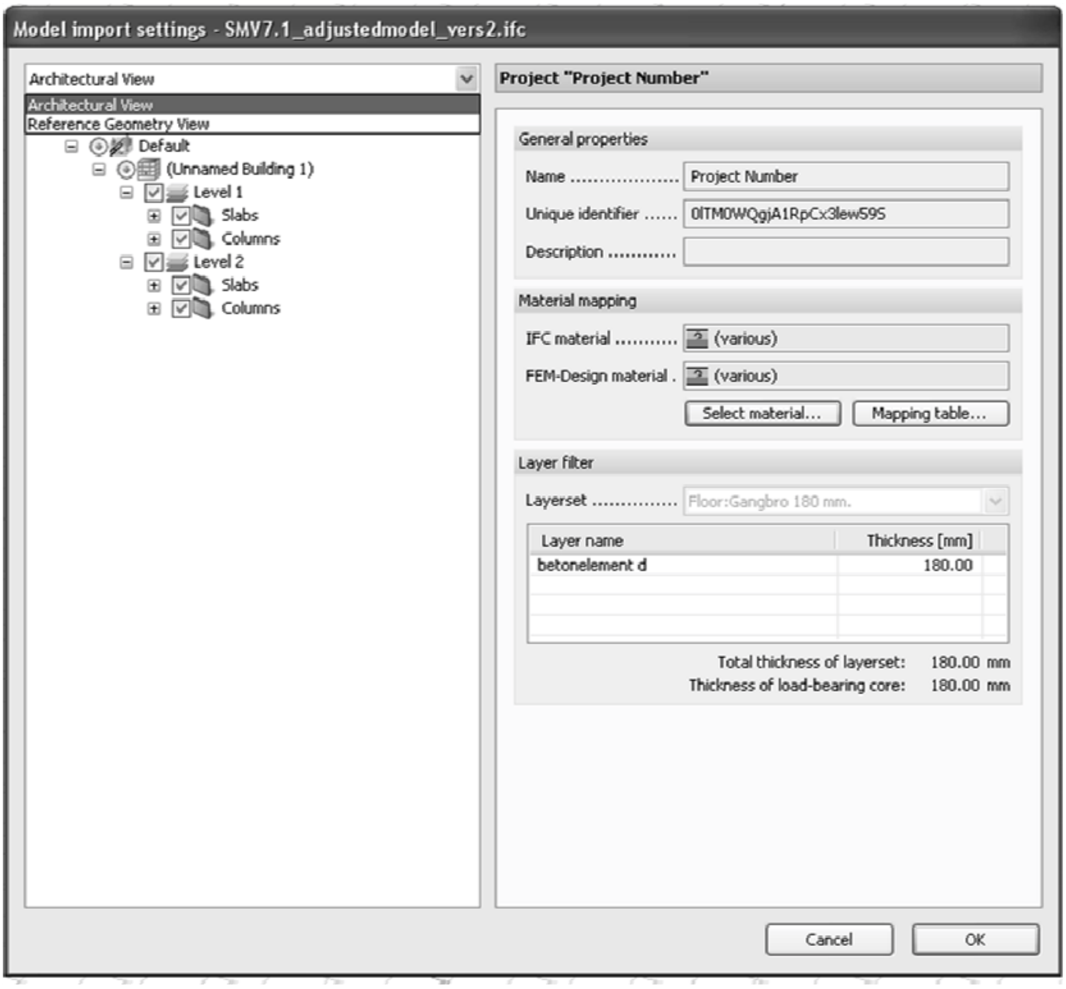

Figure A.7: Screen dump of import possibilities in FEM-design 11.0.

The import scheme is filled in, but the software crashes when all information is attached and the model is opened. This happens when using the architectural import method while it is possible to open a geometrical representation in all versions of FEM-design. Never the less the geometric representation cannot be used for anything, but drawing the corresponding FEM-design elements in the same places as the geometry which is imported. No information is attached and it is not possible to attach information to the imported elements since they are only imported as surfaces.

Through FEM-design support it has been tried to find a solution for importing IFC, but it has been stated that the newest versions of the software has problems with IFC. A mail correspondence with FEM-design support is attached in appendix G. Instead version 9.0 has been used for testing IFC capabilities since it is capable of opening the IFC files. The fact that an older version offers IFC capabilities that cannot be provided in the newer versions should be considered when comparing the analytical software applications, but the tests will be carried out without considering the versions further.

The IFC file SMV7.1_adjustedmodel_vers2.ifc is imported in FEM-design 9.0 and the mapping is made successfully. The exchange is successful in regards to the material that is attached to the corresponding components, but local coordinate systems in the nodes shows that the analytical lines generated in FEM-design does not correspond to the Revit model.

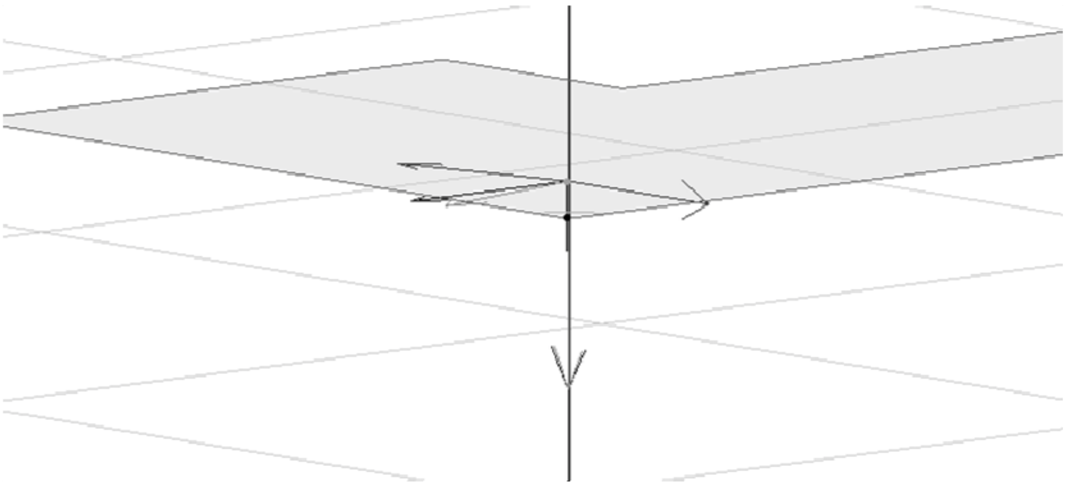

Figure A.8: Screen dump from FEM-design 9.0 illustrating that nodes are not placed identically to the native Revit model.

In figure A.8 it is seen that the coordinate system is placed above the deck; approximately in the height where the deck surface is in Revit. Therefore it is likely that the IFC export relates to the centerlines of each component and places and extra node where the hangers meet. A new version of the Revit model is made where the components are arranged so that the centerlines of all elements correspond to the wanted analytical representation. All Revit files and the IFC file are enclosed as;

- REVIT2012_adjustedmodel_vers3.rvt
- REVIT2013_adjustedmodel_vers3.rvt
- SMV7.1_adjustedmodel_vers3.ifc

The third version of the IFC file is imported in FEM-design 9.0 using the mapping interface. A screen dump is shown in figure A.9. The marked area shows the material mapping where the IFC material is not specified while the FEM-design material is chosen to be s275.

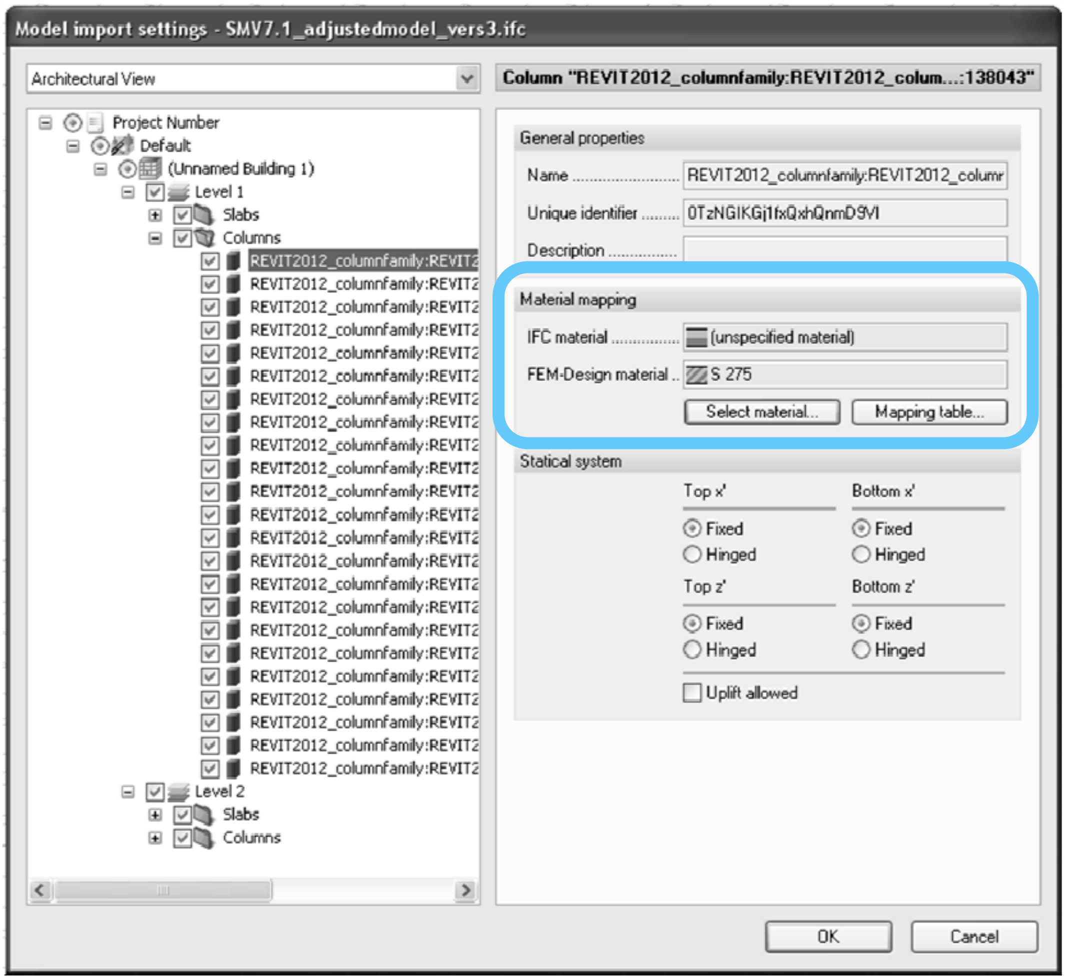

Figure A.9: Import settings in FEM-design 9.0. The material shows that no IFC material is chosen while the FEM-design material is s275.

Having mapped all materials the IFC file is opened in FEM-design 9.0. The nodes are now placed correct in relation to an analytical representation of the structure. The file is enclosed as:

- FEM9.0_adjustedmodel-vers3.str

Figure A.10 shows the model before adding loads and boundary conditions. Visual investigation of the model shows that all structural elements, modeled in Revit, are available in FEM-design 9.0 and that the geometry corresponds to the Revit model.

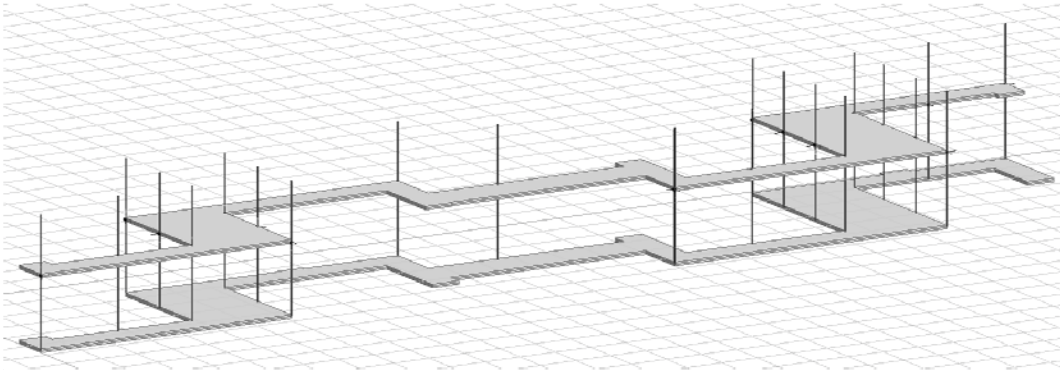

Figure A.10: Model imported to FEM-design before adding loads and boundary conditions.

Loads and boundary conditions are added to the model and load combinations are handled in suited tables. All information attached to the model can be further investigated in the *.str file attached to appendix H. A view after applying all information is given in figure A.11.

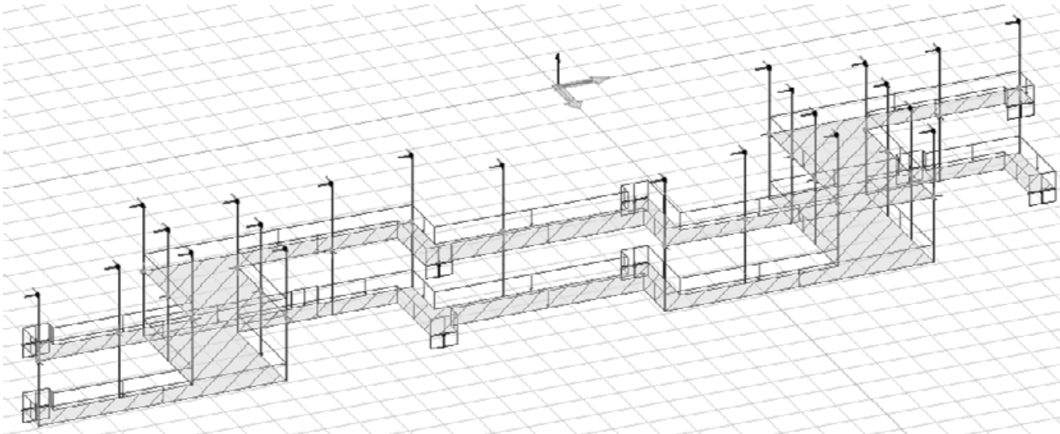

Figure A.11: FEM-design model after applying all information related to a structural investigation of the model.

A.1.5 Analysis based on imported IFC file

To ensure that the imported IFC components can be used for structural calculations a displacement analysis is made based on a fictive load combination. Since the materials are chosen in FEM-design there might be differences compared to the other software specifications and the results are therefore not completely comparable. This investigation is only made to ensure that the transferred components can be used for structural analysis.

The considered load cases are shown in figure A.12.

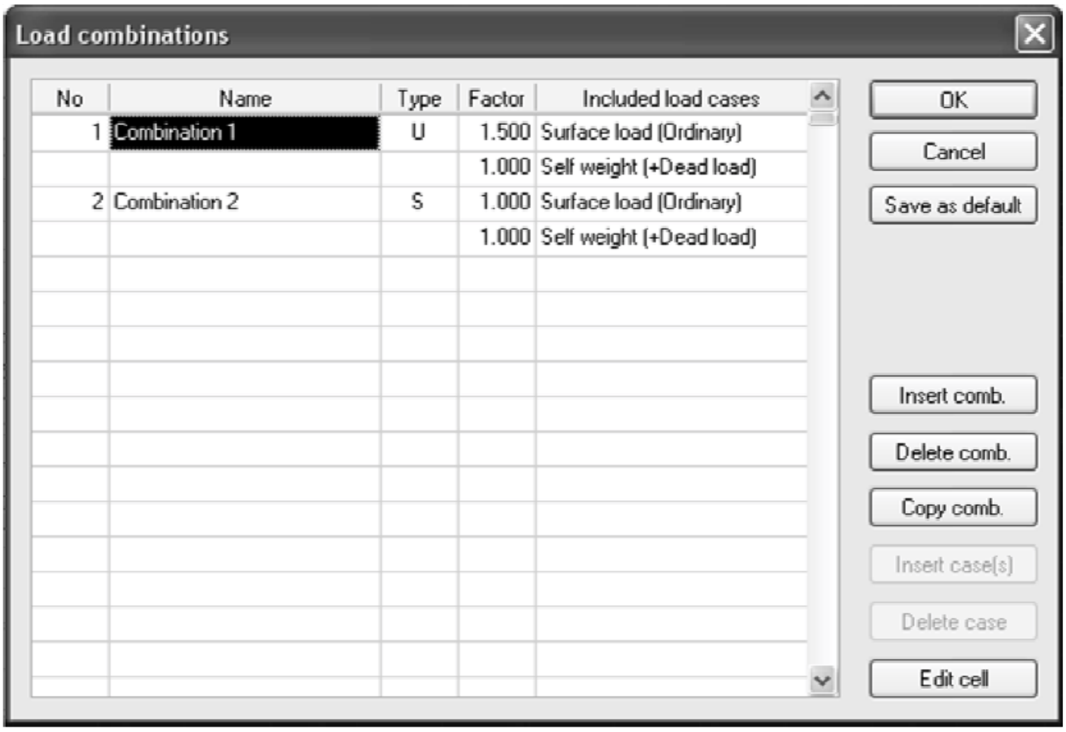

Figure A.12: Two load combinations made for testing the functionality of IFC the bridge structure transferred from Revit.

After having established a scenario for the calculations are the required results provides by FEM-design. Figure A.13 shows how displacements are shown in FEM-design.

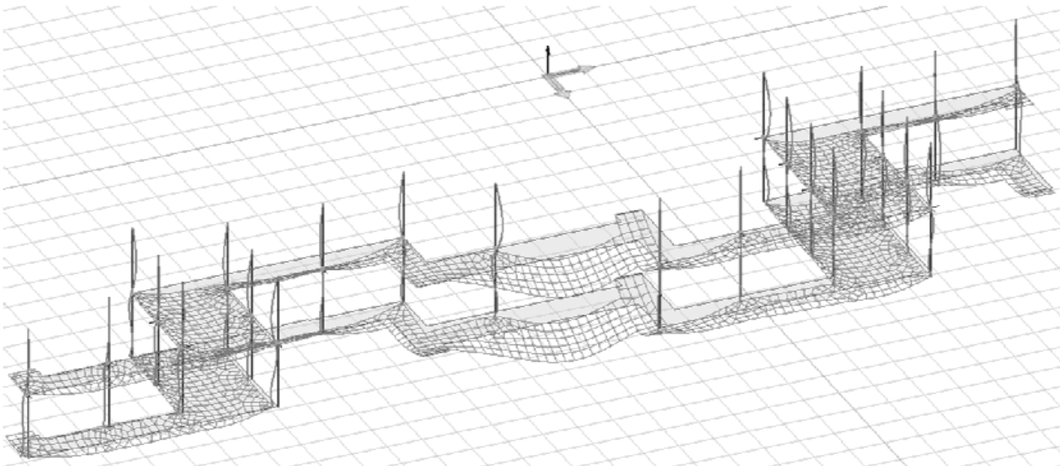

Figure A.13: Displacement figure from FEM-design based on the input from Revit and the applied information in FEM-design.

The displacement figure seems to correspond to the established scenario and the Revit components are thereby proven to be useable in FEM-design.

Appendix B

Working process for exchange scenario 2

This appendix describes the process in exchanging a model from Revit to FEM-design through a direct link. The description uses screen dumps for documentation, while the considered model files are enclosed in appendix H.

B.1 Process description

This exchange scenario investigates the capabilities of the direct link between Revit and FEM-design. The optimal solution is to exchange the analytical model since a representation of centerlines de-facilitates the use of one model for more purposes. Therefore the architectural model used for investigation of this exchange scenario is:

- REVIT2012_adjustedmodel_vers2.rvt

The 2012 version of Revit is used since this is the only version with the direct link available installed on student PCs in DTU.

B.1.1 Revit to FEM-design material and profile mapping

The first step in exchanging the model through the direct link is to use the material and profile mapping interface available in Revit as an add-in. Figure B.1 shows the interface where the profiles and materials are mapped.

All components are loaded from the Revit model and material parameters are translated to the parameters in FEM-design. No drop down menus or the like are available and FEM-design should be opened to see the exact translation of the considered materials. It is also necessary to look up profile names when these are mapped.

Figure B.1: Material and profile mapping interface from direct link add-in to Revit.

The screen dump presented in figure B.1 shows the mapping of the hangers. The hangers are made as a custom family in Revit and do not follow standard dimensions, at least not a dimension available in FEM-design. The mapping names are therefore corresponding to the FEM-design name which is automatically made when making the hanger in FEM-design.

Having mapped the materials and profiles the model is exchanged. The export results are shown in figure B.2.

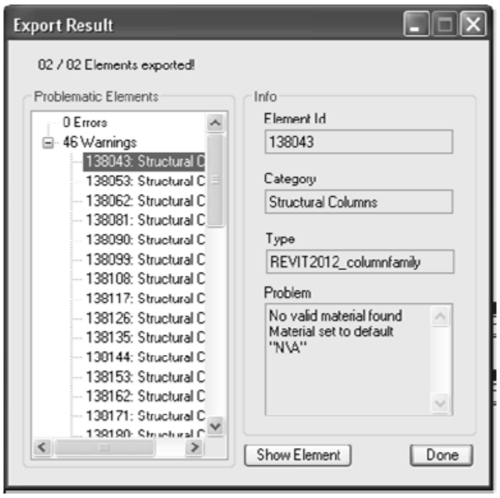

Figure B.2: Export result. It shows that the hangers have not been exchanged successfully since a valid material has not been found.

This export results show that the hangers are not exchanged successfully, but the exchange file has been created. The file is enclosed as:

- r2f_adjustedmodel_ver2.r2f

Since the exchange is not completely successful different elements are tried to investigate if only this element cannot be exchanged or if it is a general problem. Section B.1.2 describes the investigation of different profile types while B.1.3 considers the already created exchange file in FEM-design.

B.1.2 Test of different profile types for exchange through direct link to FEM-design

It has been tried to exchange the following component types since they are all included in the standard libraries for both Revit and FEM-design.

- HEA100 steel profile
- 300x450 mm concrete column

Are these component types successfully exchanged it will indicate that the exchange problems in the bridge model is caused by the fact that the hangers are custom components.

The two elements are modeled in Revit and mapped. The mapping interface is shown in figure B.3.

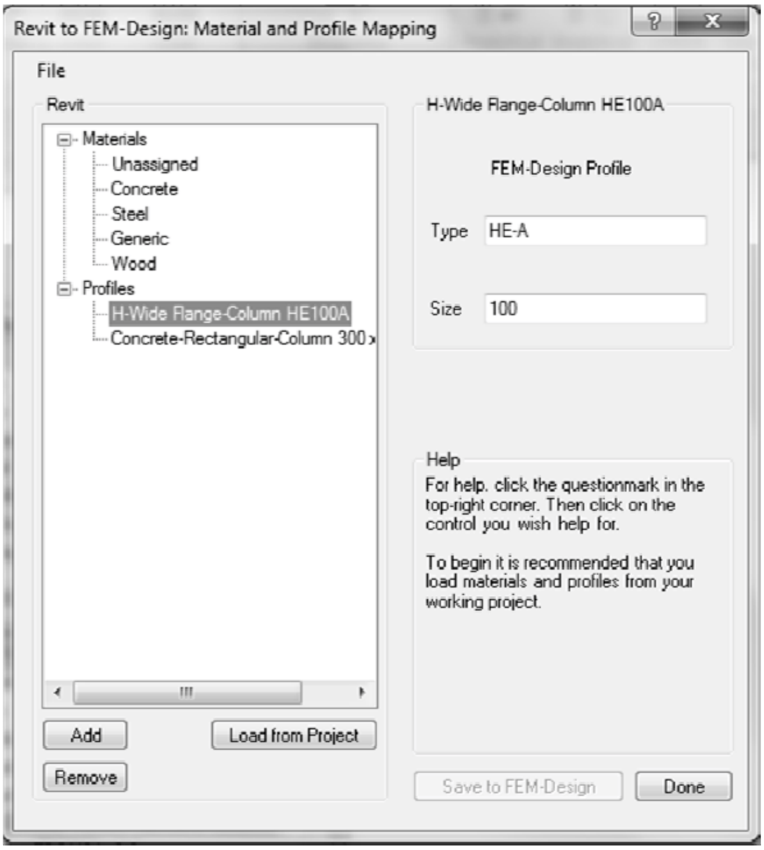

Figure B.3: Screen dump of material mapping in Revit Structure. Components that is available in both the Revit Structure and the FEM-design library is tested.

Having mapped the components a *.r2f file is made. The export result shows that there are no errors or warning when exporting the two components. In figure B.4 a screen dump of the export results is shown.

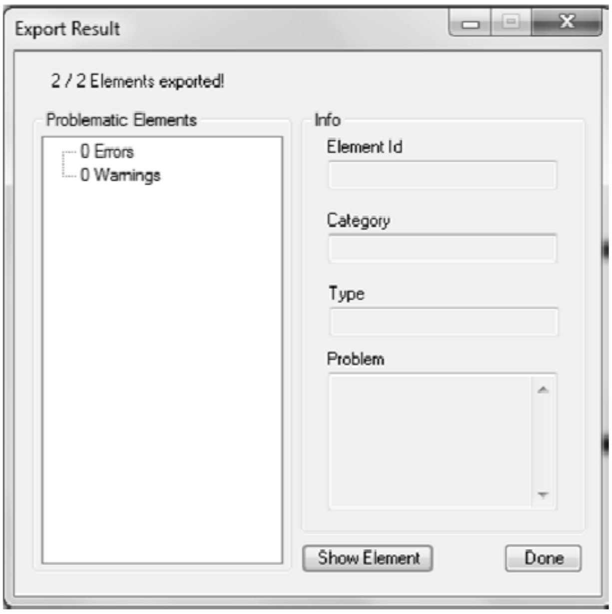

Figure B.4: Screen dump of export results from Revit. Both elements are successfully exported.

Since there are no errors or warnings it is expected that the components can be used in FEM-design without further modification. Figure B.5 shows the two components after opening the *.r2f file in FEM-design. As seen in the figure the geometry is present for each element.

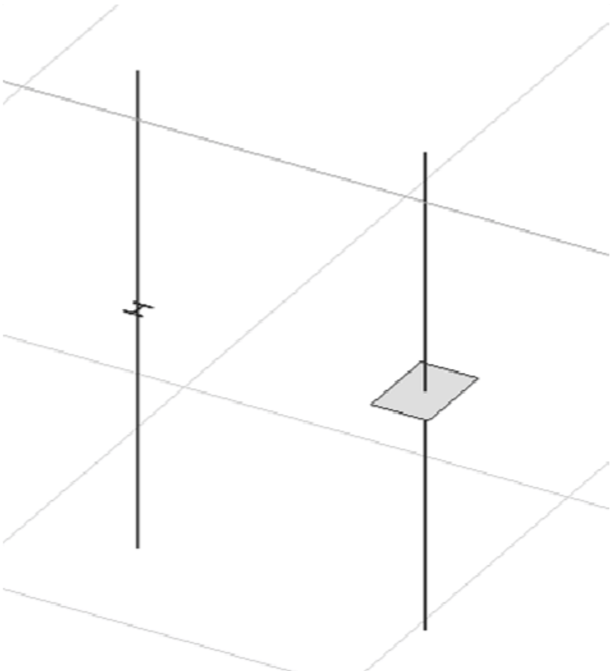

Figure B.5: Screen dump of components in FEM-design.

The hangers in the bridge model can easily be made in FEM-design as custom components, but the FEM-design custom components cannot be used in the direct link.

This investigation has shown that components that are available as standard components in both libraries can be fully exchanged through the direct link. A more thorough investigation should be made to prove if all custom components cannot be exchanged, as this investigation indicates is the case. The model files are enclosed in appendix H as:

- r2f_test-r2f
- REVIT2013_test.rvt

B.1.3 *.r2f file in FEM-design

The investigation of different elements have not shown useable results related to the profile type for the hangers. Therefore r2f_adjustedmodel_vers2.r2f is used for further investigation. The model is opened in FEM-design with the result shown in figure B.6.

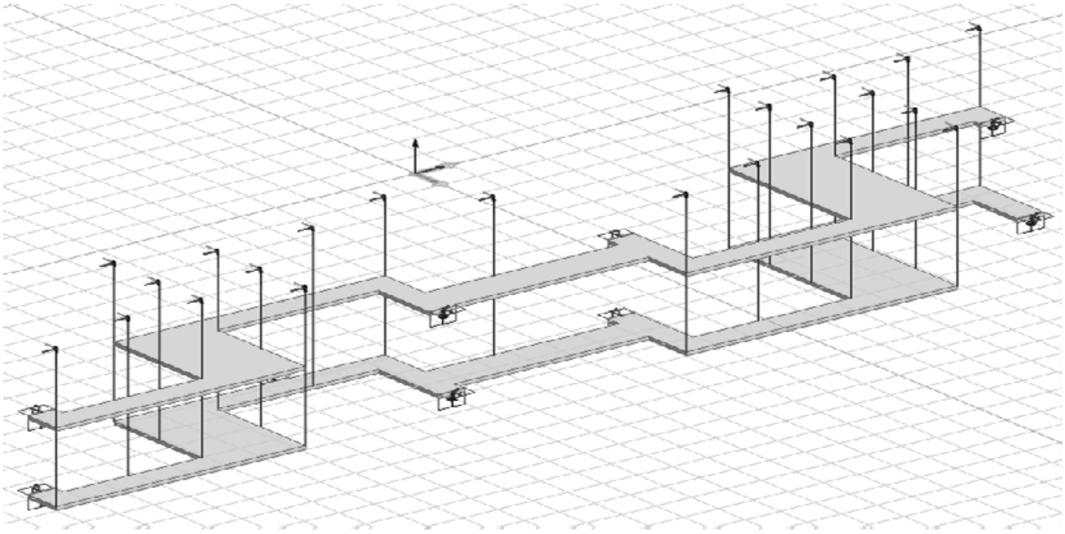

Figure B.6: Screen dump of r2f.adjustedmodel_vers2.r2f opened in FEM-design.

The figure shows the geometry which is modeled in Revit, but the hangers are only shown as lines. Further investigation of the hangers shows that no information is attached to the hangers. The lines, representing the hangers, are attached to the supports in the roof structure and the deck is also supported on the edges that were specified in Revit. All Boundary conditions have the same releases as in Revit and the exchange is successful at this point. The loads are not present in FEM-design.

In order to investigate the transferred components are the hangers remodeled to be identical with those in Revit. There are no problems in substituting the lines with FEM-design elements. The model with the adjusted hangers are saved and enclosed as:

- FEM9.0_scenario2_vers1.str

This model is used for structural analysis.

B.1.4 Analysis based on *.r2f file

To perform an analysis it is necessary to apply loads and load combinations to the FEM-design model. This procedure is the same as shown in chapter A.1.5, therefore it is not shown here, but stated that the same method is followed.

Figure B.7 shows a screen dump of the model after applying a surface load to the decks.

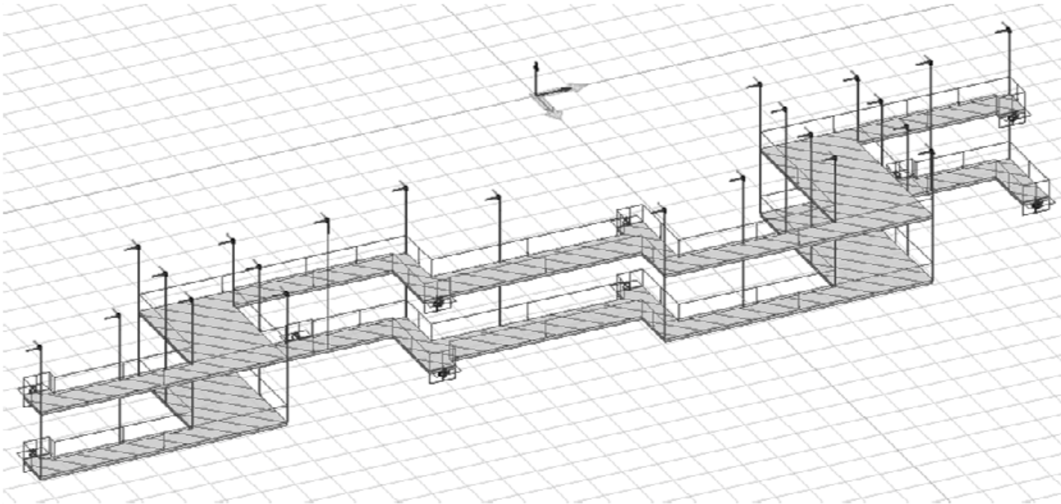

Figure B.7: Screen dump of bridge structure imported to FEM-design from Revit through the direct link. A surface load is applied to the decks and hangers are exchanged with FEM-design components where material information is present.

It is chosen to make an investigation of the displacement figure to see if it appears as in exchange scenario 1. Figure B.8 shows an identical figure as in exchange scenario 1 and the exchanged components are therefore considered to be exchanged successfully.

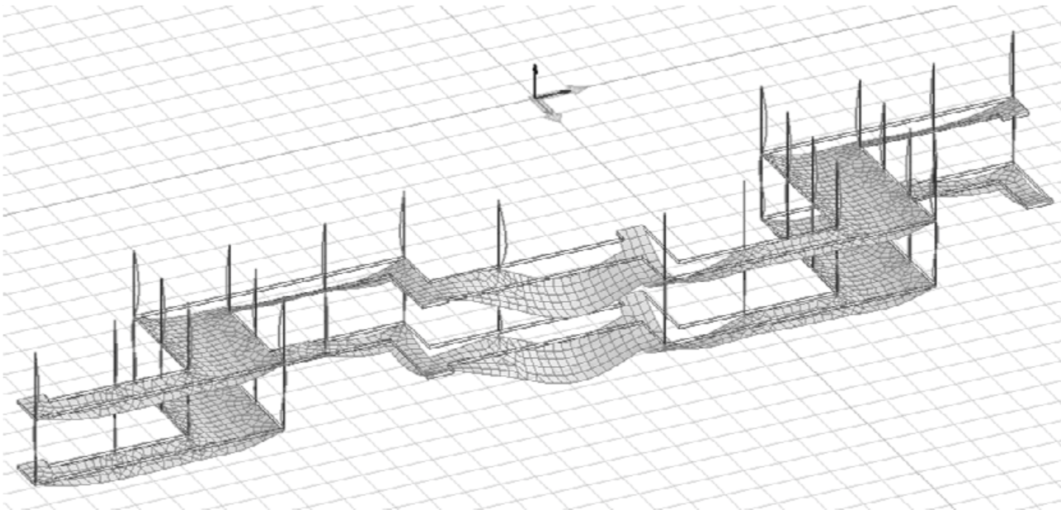

Figure B.8: Screen dump of displacement figure based on model exchange in scenario 2.

The model where all information and calculations are present is attached as:

- FEM9.0_scenario2_vers2.str

Appendix C

Working process for exchange scenario 3

This appendix describes the process in exchanging a model from Revit to RSA through IFC. The IFC file used for this data exchange is also used in exchange scenario 1 and part of the process will therefore be the same.
Documentation of the process is made in a description and with screen dumps from the considered software applications while the model files are attached in appendix H.

C.1 Process description

Exchange scenario 1 has shown that IFC uses the center lines for reference when making models. Since IFC is also used for this exchange scenario the same file can be used. The IFC file where all centerlines are connected is:

- SMV7.1_adjustedmodel_vers3.ifc

Investigation of the model has been made in exchange scenario 1 and further investigation of the content is therefore not made in this chapter, but in chapter A.1.3.

C.1.1 Import of IFC file in RSA

The first step is to open the IFC file in RSA. Figure C.1 shows the IFC model opened in RSA.

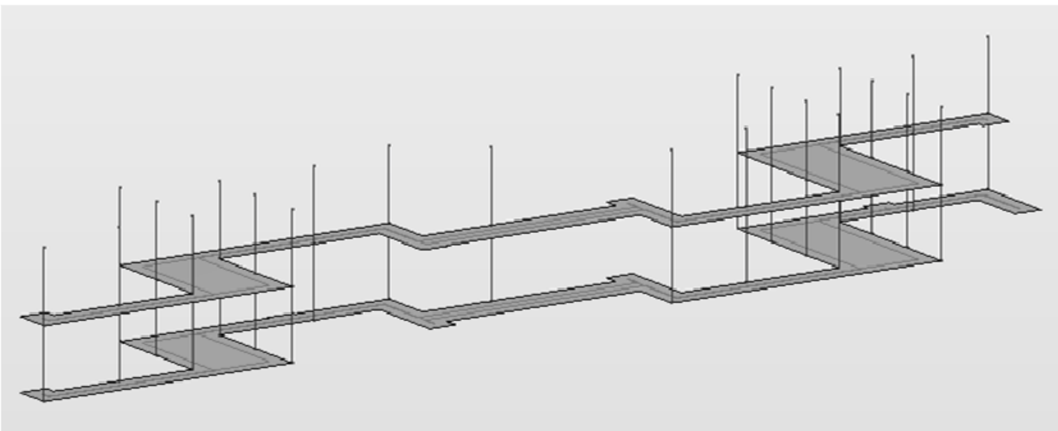

Figure C.1: IFC model opened in RSA.

The figure shows that the hangers and decks are present and nodes are created where the components are attached. Both hangers and decks are investigated to see the information attached to them.

No material properties were present in the IFC file and a mapping of the materials has not been made when opening the file in RSA, never the less materials are present and attached to the components. Figure C.2 shows screen dumps from the property lists for the hangers.

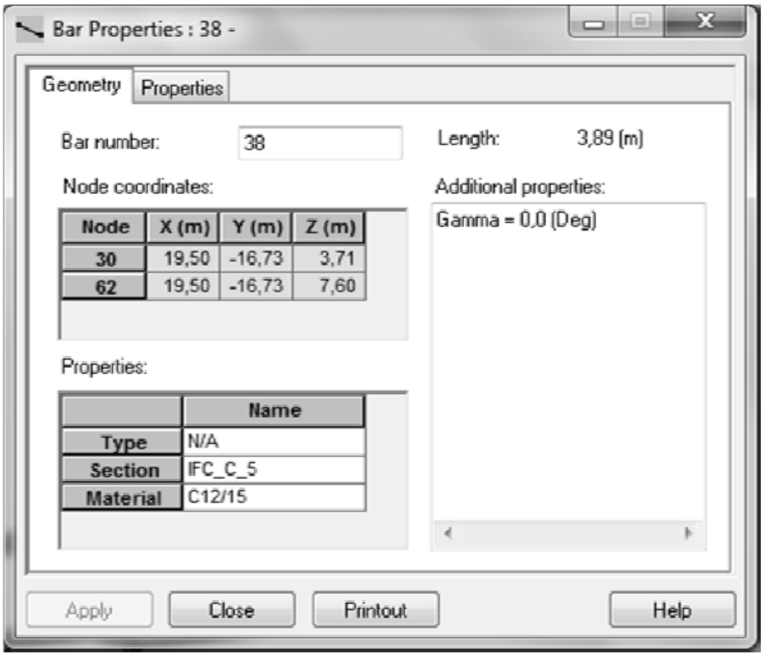

Figure C.2: Screen dumps of property lists for the hangers. The material is set to C12/45 which does not correspond to the value in Revit, while the section is the same as in Revit, but translated to IFC.

The material properties are available for both elements, but the types and strengths are not those given in Revit. The deck material is set to C12/15 as well as the hangers. All material properties should be changed before making a calculation based on the model.

Then boundary conditions are added. This is shown in figure C.3.

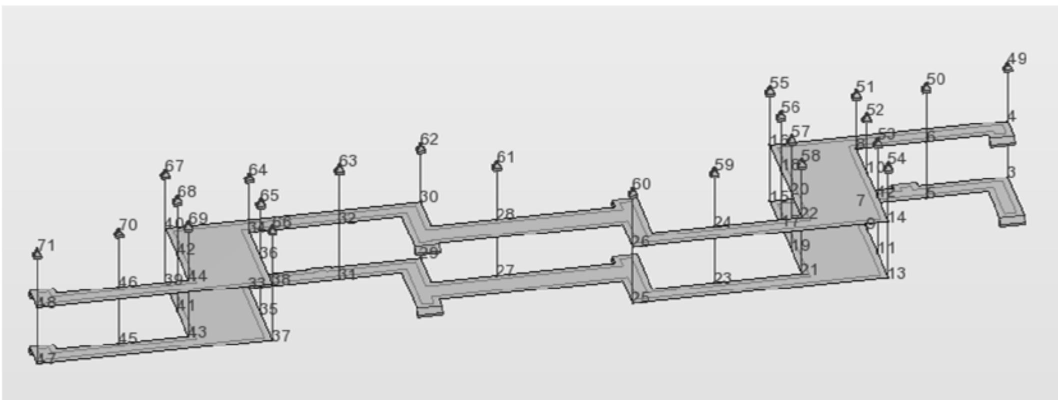

Figure C.3: Pinned supports added to the hangers and line supports added to deck edges.

Also loads are added to the structure and shown in figure C.4.

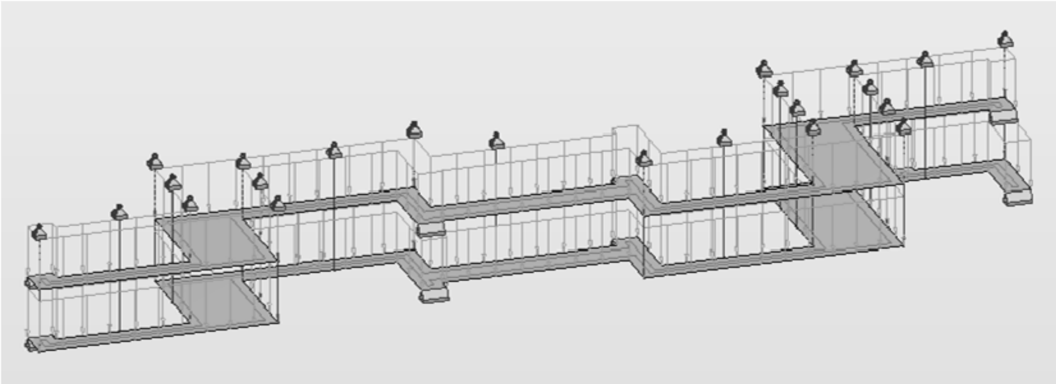

Figure C.4: Surface loads are added to the decks.

Having modeled the boundary conditions the model corresponds to what has been exchanged from Revit. A calculation of displacements is made to ensure that the elements can be used in RSA. The analytical model is enclosed as:

- RSA2013_adjustedmodel_vers3.rtd

C.1.2 Analysis in RSA

A displacement analysis is made based on the exchanged model. A screen dump of the displacement figure is shown in figure C.5.

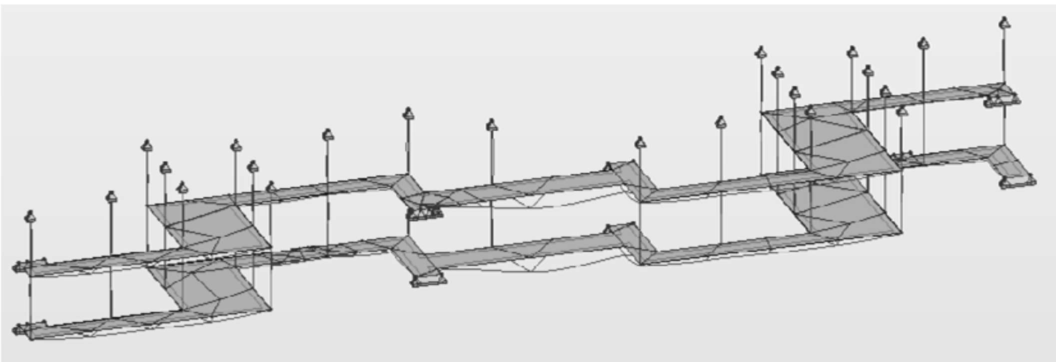

Figure C.5: Displacement figure calculated in RSA based on model exchanged through IFC from Revit.

The figure shows the finite element mesh used for the calculation. The size and type of the mesh has been automatically generated and it has not been investigated if it is sufficient. Never the less it is shown that the exchanged elements can be used for setting up a calculation in RSA.

Appendix D

Working process for exchange scenario 4

This appendix describes exchange scenario 4. The bridge model is exchanged from Revit to RSA through a direct link. This scenario differs from the other scenarios since both the architectural and structural software are is from the same vendor.

D.1 Process description

In this exchange scenario the analytical model in Revit is used for the exchange. The analytical model is from the Revit model:

- Revit 2013_adjustedmodel_vers2.rvt

The 2013 version is used since the exchange link is automatically integrated in the student version while it should be installed as an add-on in the 2012 version.

D.1.1 Export of Revit model

When exchanging the bridge model different exchange options are available. Figure D.1 shows the basic options where it is chosen which of the loads cases that contains self weight of the structure. It is also defined how the releases should be handled.

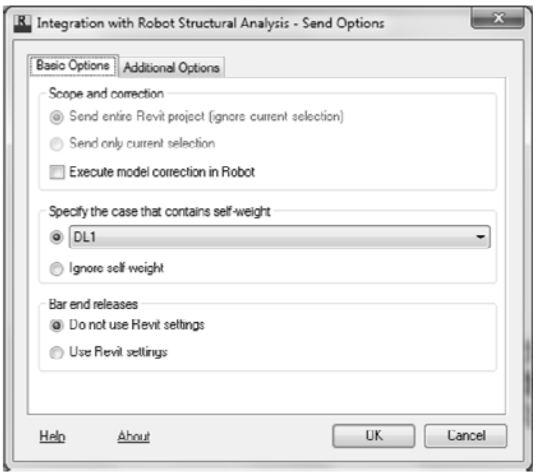

Figure D.1: Screen dump of basic exchange options in Revit link to RSA.

Also additional options can be set up before an exchange. The interface for the additional settings is shown in figure D.2.

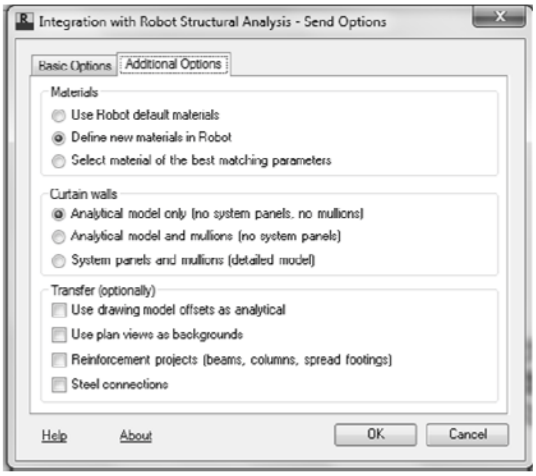

Figure D.2: Screen dump of additional exchange options in Revit link to RSA.

The figure shows which possibilities are chosen for this exchange. Especially the material settings are important in this investigation since the possibilities are to use RSA default materials, define new materials in RSA or use materials with the best matching properties.

It has been tried to use the different options, but it has not been possible to get the correct material properties after the exchange. Therefore, it has been chosen to define new materials in RSA to ensure that all properties correspond to the other exchange scenarios.

D.1.2 Investigation of exchanged model

The visual investigation of the model in RSA shows that both types of boundary conditions are exchanged successfully. A screen dump of the model is shown in figure D.3.

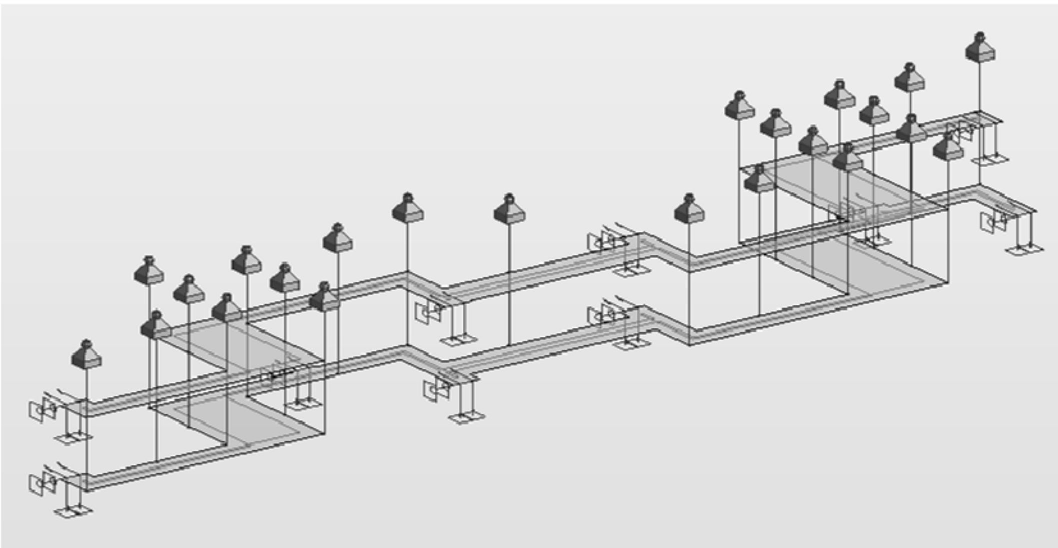

Figure D.3: Screen dump of bridge model exchanged through the direct link from Revit to RSA.

The loads are also investigated in the exchanged model. The load properties shows that the surface load added to the decks has the same magnitude as in the Revit model. Figure D.4 shows a screen dump of the load view in RSA.

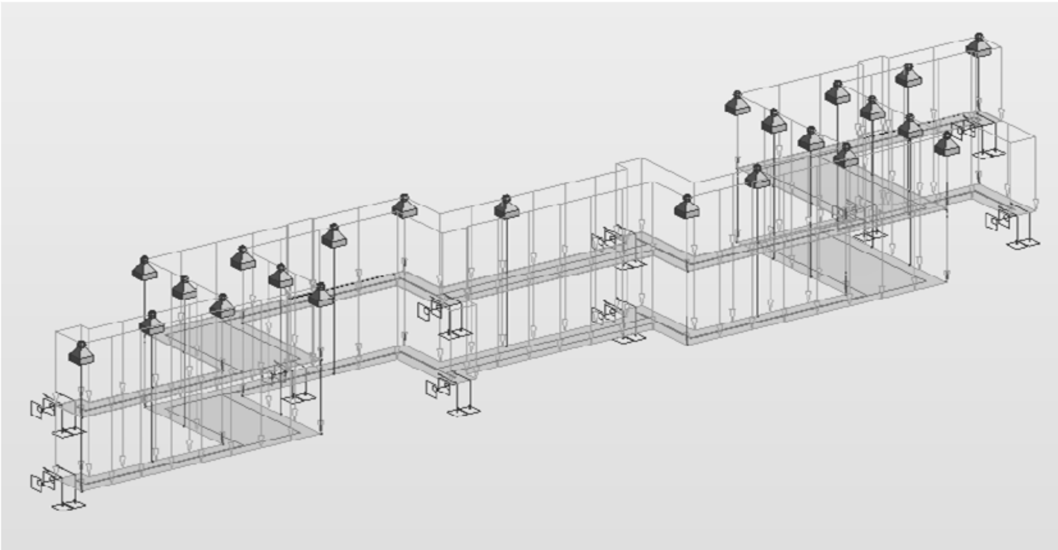

Figure D.4: Screen dump of load view in RSA. The figure shows that the direction of the surface load is downwards as in the native Revit model.

D.1.3 Analysis of RSA model

A calculation of the displacements is performed to ensure that all components can be used in RSA. Since all components have been exchanged through the direct link only the material properties needs to be adjusted before making the calculations. Having assured that all material information is present the calculation is made. The displacement figure is shown in figure D.5.

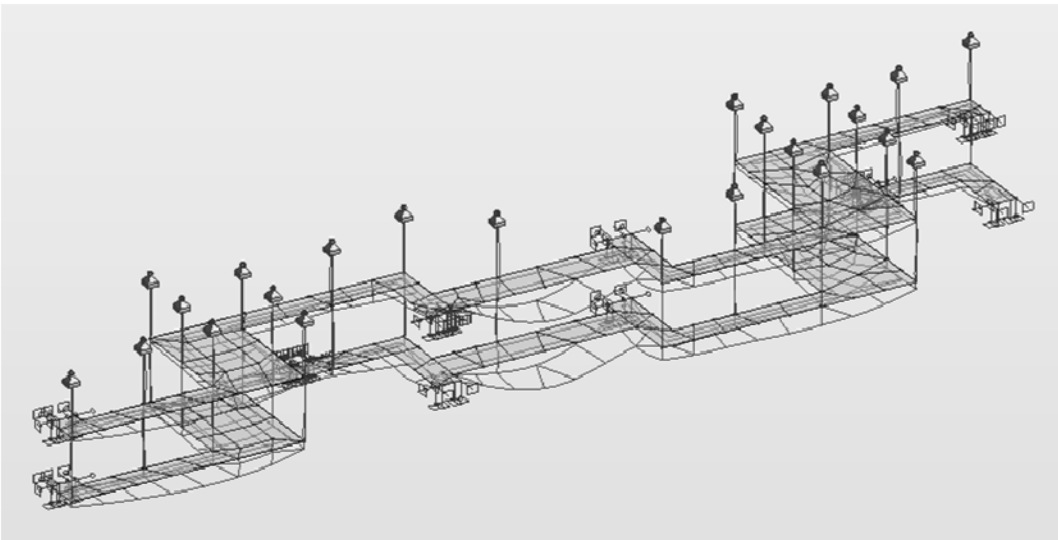

Figure D.5: Screen dump of displacement figure.

As seen in the figure a calculation is successfully made and the displacement figure corresponds to those found in the other exchange scenarios.

The model is enclosed in appendix H.

Appendix E

Working process for exchange scenario 5

This appendix gives the process in modeling the bridge model in ArchiCAD and prepares the IFC settings. The content of the IFC model is investigated in SMV.
The IFC model is finally used for a structural analysis in RSA. The displacements are investigated to be able to compare the displacement figure with the figures found in the other exchange scenarios.

E.1 Process description

The native bridge model is made in Revit. To ensure that all components are modeled with ArchiCAD properties the bridge structure is remodeled.

E.1.1 Remodeling of bridge structure in ArchiCAD

In ArchiCAD the Slab tool is used for the decks and the Column tool used for the hangers. In both cases it is defined that the components are structural to ensure that they can be included in the export of the model. Figure E.1 shows a screen dump of the model.

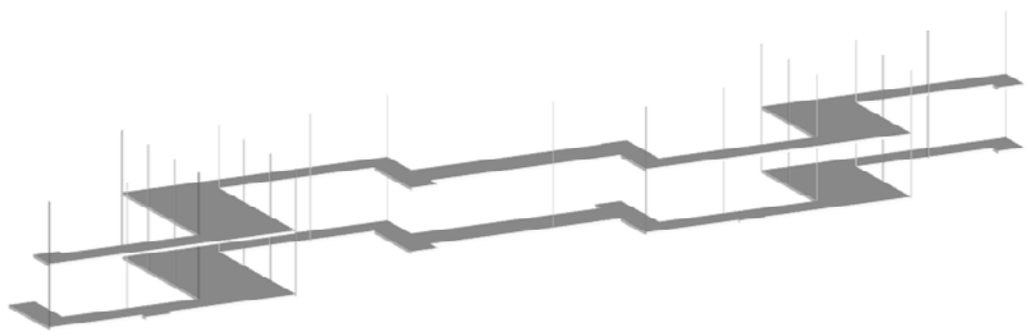

Figure E.1: Screen dump of bridge modeled in ArchiCAD.

In the IFC setup interface in ArchiCAD it is seen that the MVD “1.0 Coordination View” is used. Therefore it is expected that the model should be made in the same way as the third version of the Revit model. The hangers are attached at the edges of the decks and the centerlines are fitted to ensure that the architectural model corresponds to an analytical representation. The IFC setup interface is shown in figure E.1.

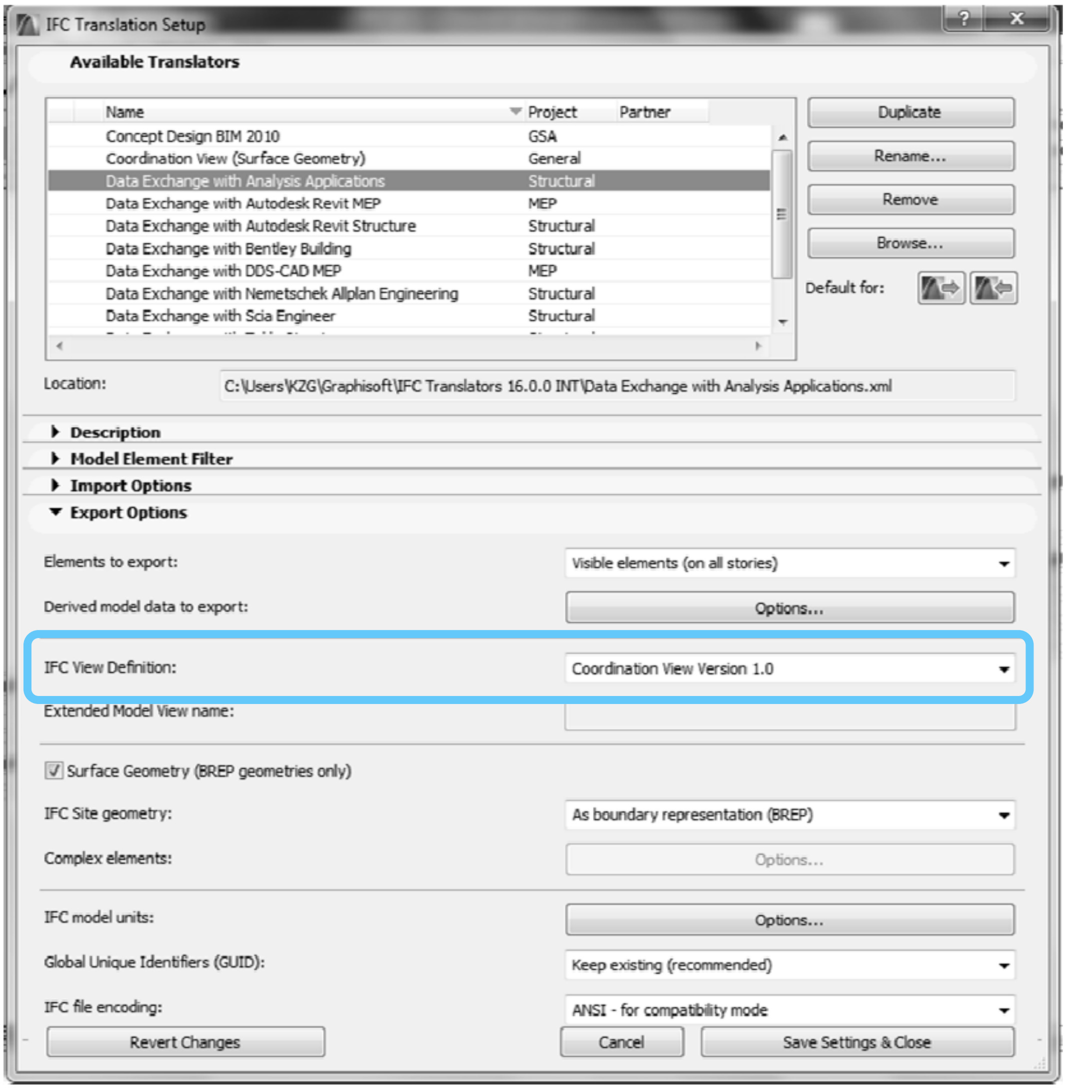

Figure E.2: Screen dump of the "IFC Translation Setup" interface in ArchiCAD. The MVD used for the exchange is given in the blue box.

Since ArchiCAD is an architectural modeling application it is not possible to add loads and boundary conditions as seen in Revit. The ArchiCAD model is enclosed in appendix H as:

- ACAD_scenario5-6.pln

The model presented in figure E.1 is exported as IFC. Figure E.2 shows that the model is saved as an IFC file. It is chosen to focus the IFC file towards analytical applications. In ArchiCAD this means that only the components that have been defined as structural when modeling the bridge structure.

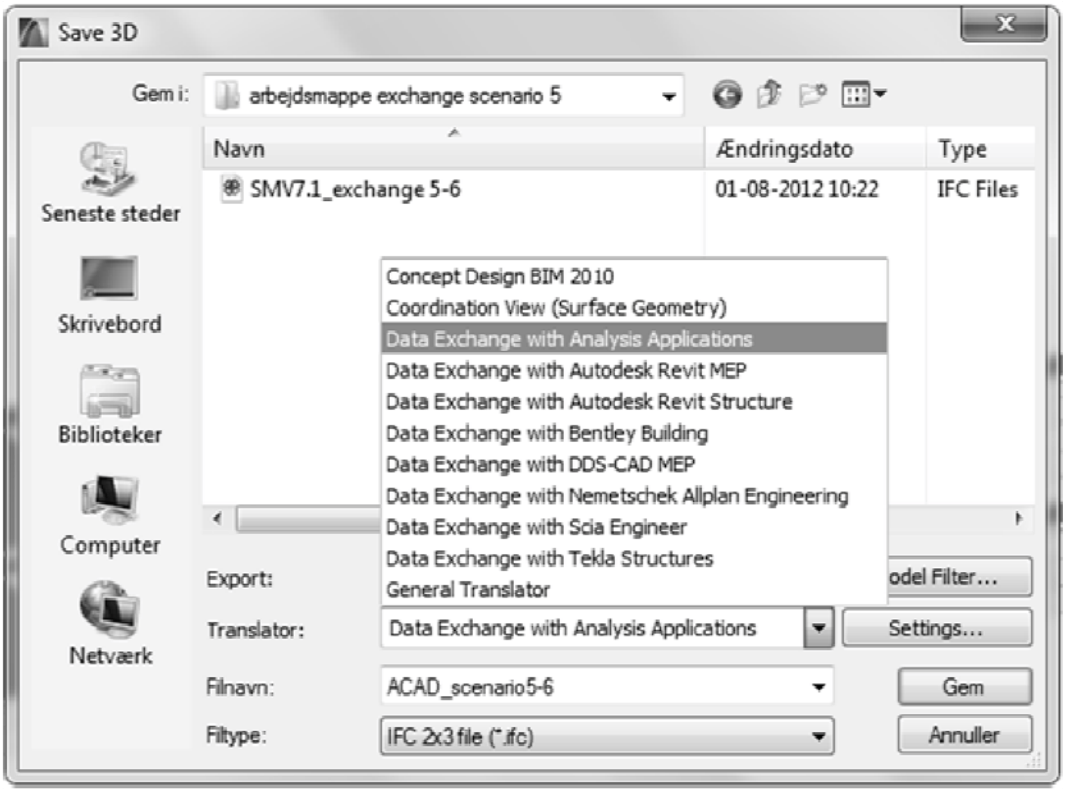

Figure E.3: Screen dump when making IFC file. The data exchange is focusing on analytical applications which is chosen in the drop down menu.

The next step in investigating this exchange scenario is to ensure that all content is included in the IFC file. The IFC file is enclosed in appendix H as:

- SMV7.1_scenario5-6.ifc

E.1.2 Investigation of IFC file in Solibri Model Viewer 7.1

The IFC file is opened in SMV to investigate the contents of the file. Figure E.4 shows a screen dump of the IFC model in SMV.

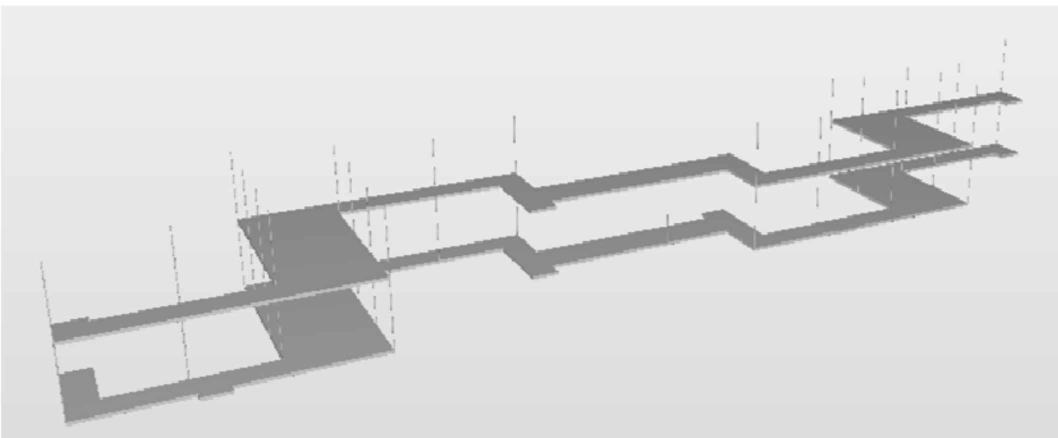

Figure E.4: Screen dump of bridge model in SMV. Both decks and hangers are visible when opening the IFC file.

The properties of the hangers and decks are investigated which is shown in figure E.5 and E.6.

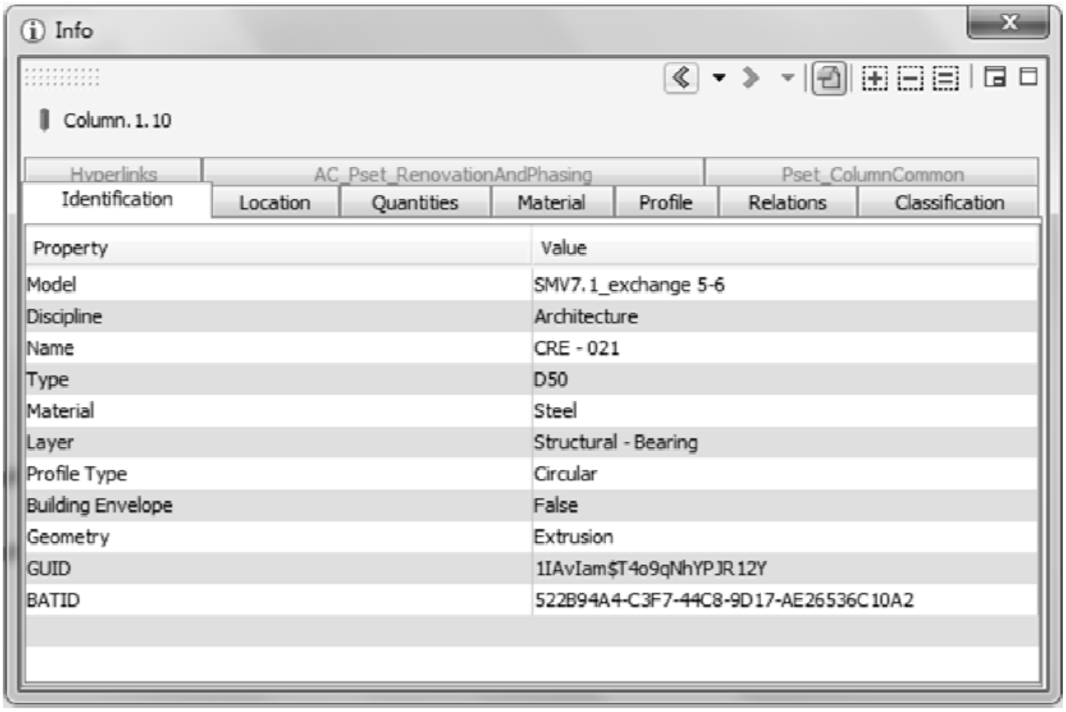

Figure E.5: Screen dump of the information attached to the hangers in the IFC model created in ArchiCAD.

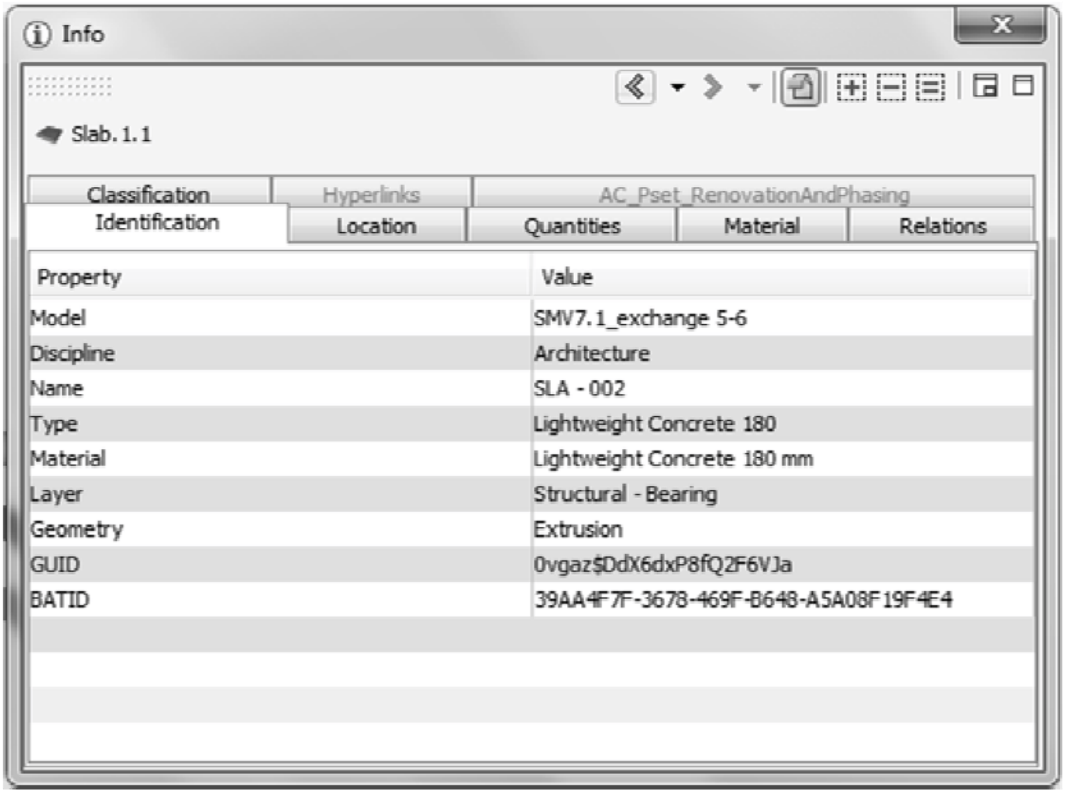

Figure E.6: Screen dump of the information attached to the hangers in the FIC model created in ArchiCAD.

The figures shows that the geometry is successfully transferred and that material properties are attached to the bridge components. Even though materials are given a value in the IFC file it should not be expected to use the material properties for structural analysis since the names corresponds to the names in the appearance settings in ArchiCAD.

E.1.3 Analysis in RSA

The IFC file does not contain information about loads and boundary conditions and these should therefore be added in RSA before a calculation is made.

Figure E.7 shows the model after attaching loads and boundary conditions.

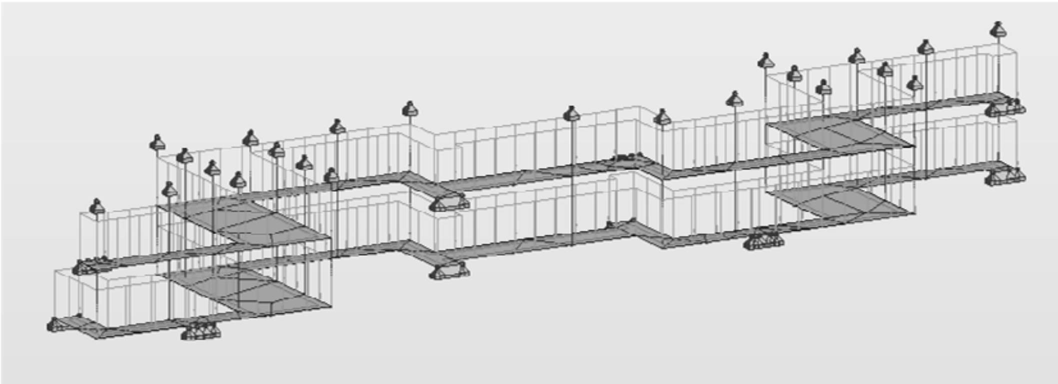

Figure E.7: Screen dump of bridge model after adding loads and boundary conditions in RSA.

Having attached the information a displacement analysis is made as for the other exchange scenarios. A screen dump is shown in figure E.8.

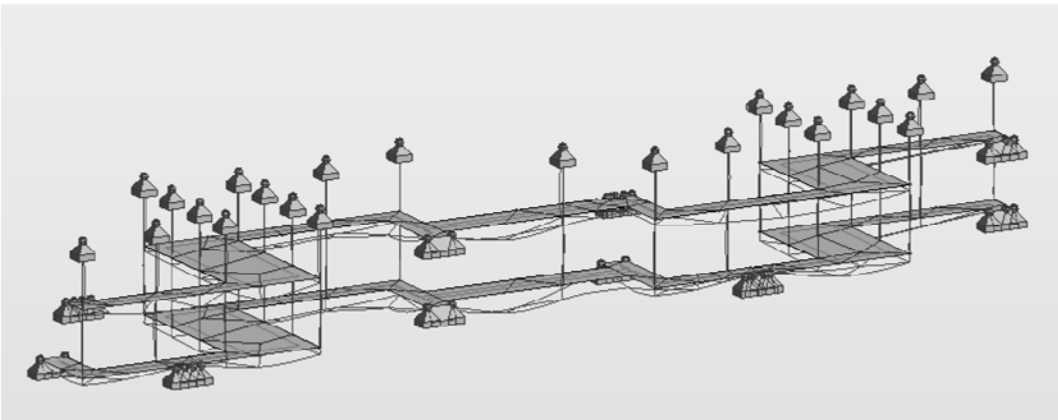

Figure E.8: Screen dump of displacement figure for bridge model modeled in ArchiCAD and imported in RSA through IFC.

The figure shows equal results as the other exchange scenarios and the displacements seems reasonable. This shows that the components are can be handled in RSA after an exchange through IFC.

The RSA model is enclosed in appendix H as:

- RSA2013_scenario5.rtd

Appendix F

Working process for exchange scenario 6

This appendix describes the process in exchanging the bridge model from ArchiCAD to FEM-design through IFC. The IFC file used in this exchange is the same file as in scenario 5.

F.1 Process description

This exchange scenario describes a data exchange from ArchiCAD to FEM-design through IFC. Since an IFC file from the ArchiCAD model has been made in scenario 5 it will be used here as well. The main goal of this exchange scenario is to investigate how the model can be handled in FEM-design and if the information from the IFC model is read in the same way as in RSA. If the model shows similar capabilities as in RSA it will be proven that the contents of the IFC file is determining for the exchange capabilities and not the analytical software that uses the information from the file.

Previous investigations have shown that the newest versions of FEM-design do not facilitate the use of IFC models. Therefore the FEM-design 9.0 is used for this investigation. When evaluating FEM-design it should therefore be taken into account that the IFC import capabilities does not function in the newest versions.

When opening the IFC file mapping of materials are made. Figure F.1 shows the mapping options.

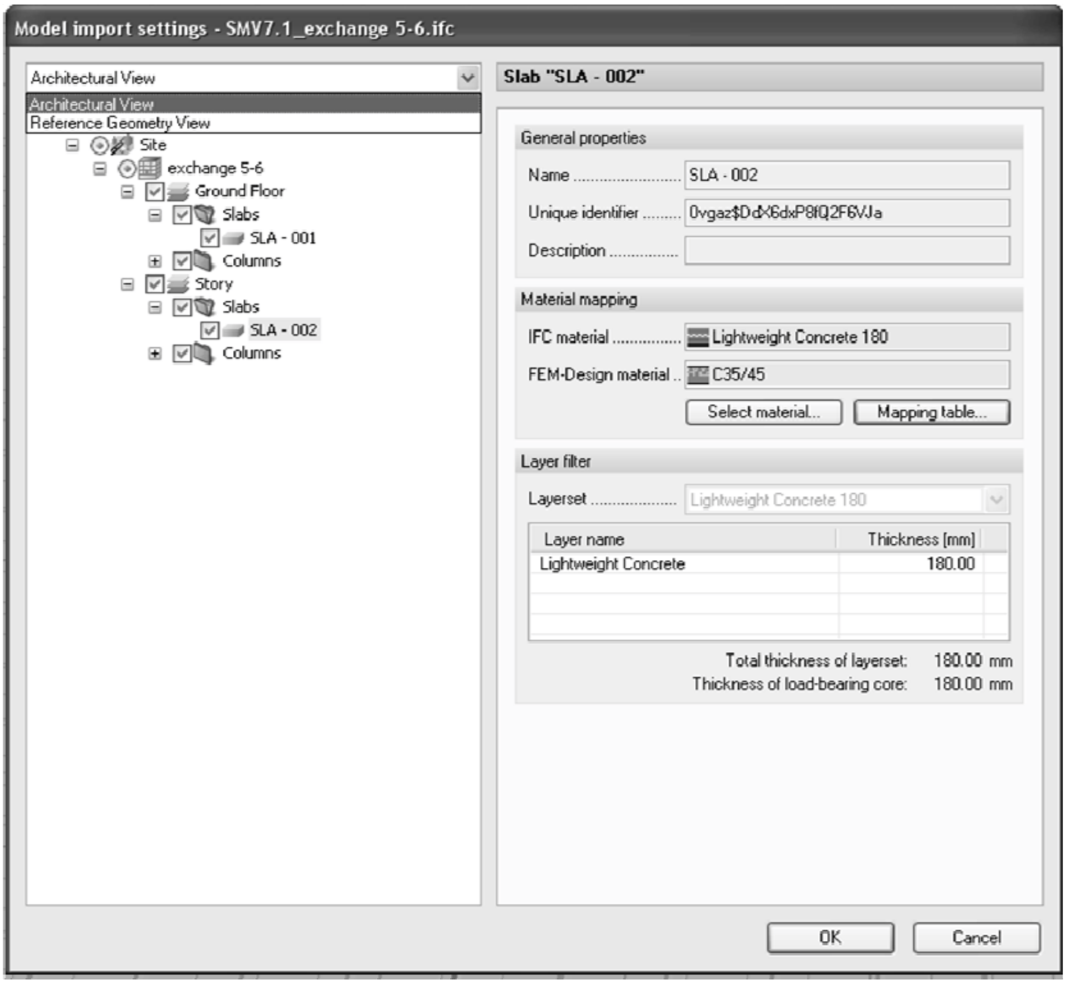

Figure F.1: Screen dump of model import options in FEM-design. The drop down menu in the top of the figure shows that the architectural view is chosen in order to include material information.

In the figure it is shows that the material name is “Lightweight Concrete” as in SMV. Having the name a FEM-design material can easily be assigned to the decks. Besides the information in the right hand side of the figure, the component placement can be seen in the left hand side. It shows that the components are still related to the floors that are made in the ArchiCAD model.

Having completed the material mapping the bridge model appears as shown in figure F.2.

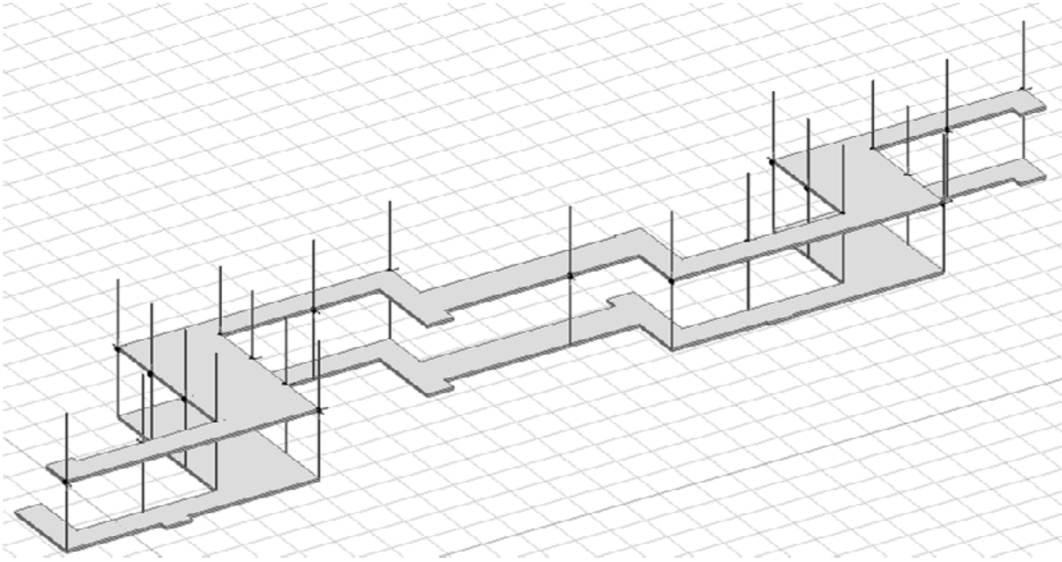

Figure F.2: Screen dump of bridge model after import in FEM-design.

The bridge model does not contain loads or boundary conditions since it was not possible to define these in ArchiCAD. Therefore these are applied to make an analysis possible. Figure F.3 and F.4 shows the bridge model after applying first boundary conditions and then loads.

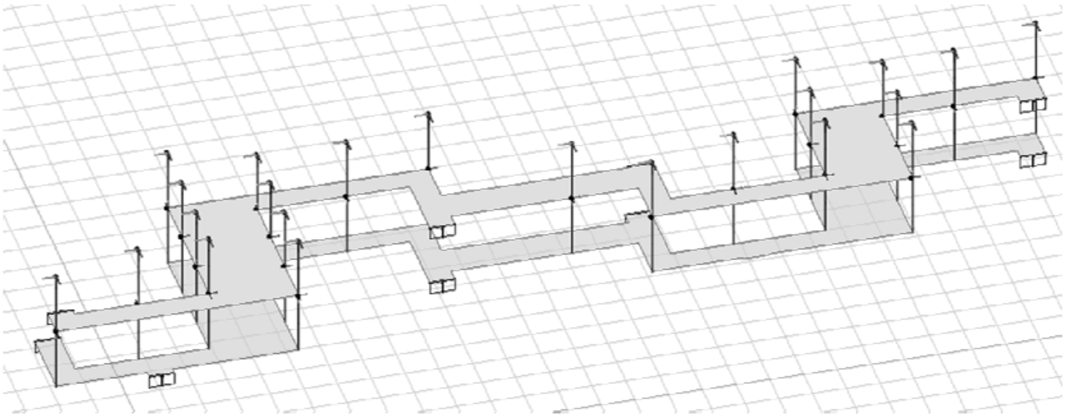

Figure F.3: Screen dump of bridge model after applying boundary conditions.

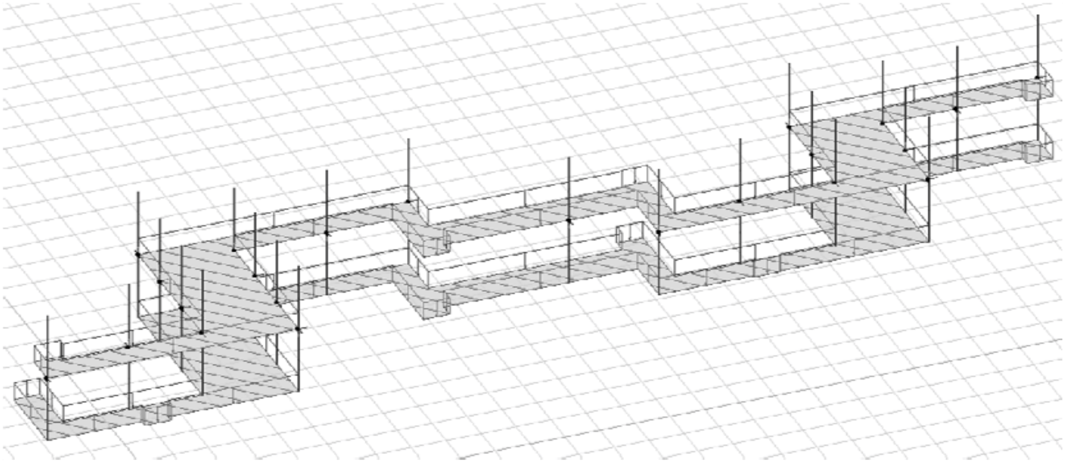

Figure F.4: Screen dump of bridge model after applying surface loads to the decks.

An analysis of displacements is then made to ensure that the exchanged components can be used in FEM-design. The displacement figure from the analysis is shown in figure F.5 while the FEM-design model is enclosed in appendix H as:

- FEM9.0_scenario6.str

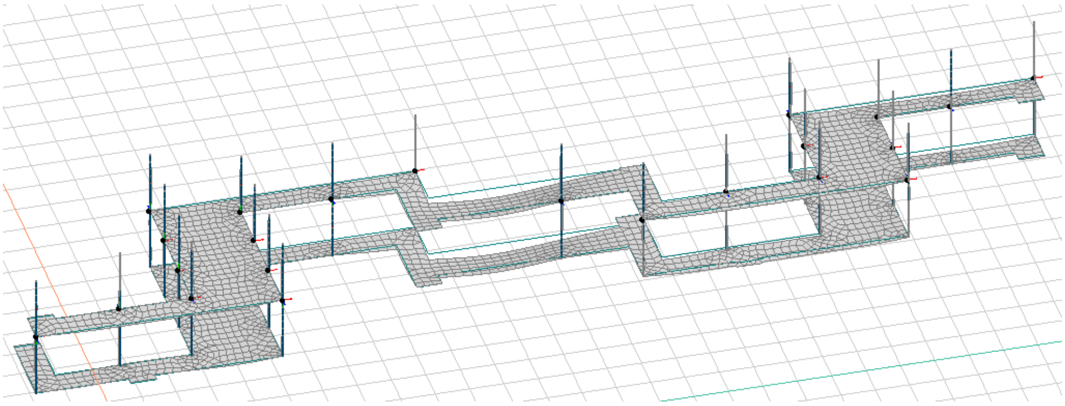

Figure F.5: Screen dump of displacement figure.

The displacement figure seems reasonable and the components do therefore seem useable in FEM-design.

Appendix G

E-mail correspondence with FEM-design support

This appendix shows an e-mail correspondence with FEM-design support where it is stated that there is a problem with the import of IFC in the newest versions of the software.

G.1 E-mail correspondence

Kenneth Gustavsen 30. apr.

til support

Hi Strusoft

I am working on a report that clarifies the advantages of working with IFC as data exchange format between architectural models and Finite Element models.

I have tried to import an IFC file into FEM-design 11.0, but there seems to be some problems in the import. The material mapping dialog box apperars and the mapping seems to function correct. After mapping the materials the problem occur, no elements are shown on the screen.

The IFC model has been checked in a model viewer and all information is there!

Does FEM-design 11.0 have problems with the import?

Hope you can help me to solve the problem.

Best regards

Kenneth Gustavsen

student M.sc. Technical University of Denmark
kenneth.zollfrank.gustavsen@gmail.com
+4540403953

Strusoft Support support@strusoft.com 30. apr.
til mig

engelsk > dansk Oversæt meddelelse Deaktiver for: engelsk

Hello Kenneth!

Do you have any possibility to atttach the IFC-file so that we can check the import-procedure with your file?

Best Regards
Fredrik Lagerström
M.Sc. Civil Engineering, FEM-Design - Support

Kenneth Gustavsen 1. maj
til support

Hi

I can't attach the file im working on, but the exact same problem appears when using the same procedure with a example file from Revit. I have made an IFC based on this revit file, it is attached

Strusoft Support support@strusoft.com 2. maj
til mig

engelsk > dansk Oversæt meddelelse Deaktiver for: engelsk

Hello Kenneth!

Yes, I have got a bit more information about your issue with the IFC-import. Our developers say that we have got an issue that makes the ifc-import very unstable. There has been a discussion to remove the ifc-support until we are able to fix it, but it still is in the program because it can work for some models.

Because of this bug, we recommend that IFC shouldn't be used as a transfer-format, but that you use direct connections from Revit Structure or Tekla to FEM-Design.

This is maybe not what you wanted to hear, but that is the current status on the FEM -Design-IFC-connection.

Best Regards
Fredrik Lagerström
M.Sc. Civil Engineering, FEM-Design - Support

Appendix H

Overview of model files

This appendix gives an overview of the files which have been investigated throughout the thesis. All file names are given and a short description of the contents is given. The files are enclosed on the CD-ROM.

H.1 Model files

Table H.1 shows the file names and the descriptions. The naming of the files is made so that the software applications in which they have been used are defined. The first part of the name defines the used software application, the second part gives a description and finally the file format is given.

	File content
Revit Structure files	
REVIT2012_originalmodel.rvt	Original bridge model without any modifications.
REVIT2012_adjustedmodel_vers1.rvt	Hangers are moved to the edges and the analytical lines are adjusted. Loads and boundary conditions are added.
REVIT2013_adjustedmodel_vers1.rvt	REVIT2012_adjustedmodel_vers1.rvt updated to Revit version 2013
REVIT2012_adjustedmodel_vers2.rvt	Hangers are replaced with new family since investigations show that the original hangers have different information attached.
REVIT2013_adjustedmodel_vers2.rvt	REVIT2012_adjustedmodel_vers2.rvt updated to Revit version 2013
REVIT2012_adjustedmodel_vers3.rvt	All centerlines are adjusted to meet where the nodes are in the corresponding analytical model.
REVIT2013_adjustedmodel_vers3.rvt	REVIT2012_adjustedmodel_vers3.rvt updated to Revit version 2013
REVIT2013_test.rvt	File for investigation of two standard components through direct link to FEM-design.

Revit Family	
REVIT2013_columnfamily.rfa	Hanger family where all information is correct. Used to replace the original hangers which have shown to have different information attached.
IFC models	
SMV7.1_adjustedmodel_vers1-1.ifc	IFC file based on REVIT2012_adjustedmodel_vers1.rvt
SMV7.1_adjustedmodel_vers1-2.ifc	IFC file based on REVIT2013_adjustedmodel_vers1.rvt
SMV7.1_adjustedmodel_vers2.ifc	IFC file based on REVIT2013_adjustedmodel_vers2.rvt
SMV7.1_adjustedmodel_vers3.ifc	IFC file based on REVIT2013_adjustedmodel_vers3.rvt
SMV7.1_scenario5-6.ifc	IFC file based on ACAD16_scenario5-6.pln
ArchiCAD model	
ACAD16_scenario5-6.pln	Bridge model in ArchiCAD with centerlines defining the components.
Robot Structural Analysis	
RSA2013_adjustedmodel_vers3.rtd	Analytical model of REVIT2013_adjustedmodel_vers3.rvt after exchange through IFC.
RSA2013_scenario5.rtd	Analytical model of ACAD16_scenario5-6.pln after exchange through IFC.
FEM-design	
FEM9.0_adjustedmodel_vers3.str	Analytical model of REVIT2013_adjustedmodel_vers3.rvt after exchange through IFC.
FEM9.0_scenario2_vers1.str	Analytical model of REVIT2012_adjustedmodel_vers2.rvt after exchange through the direct link.
FEM9.0_scenario2_vers2.str	Analytical model of REVIT2012_adjustedmodel_vers2.rvt after calculation of displacements.
FEM9.0_scenario6.str	Analytical model of ACAD16_scenario5-6.pln after exchange through IFC.
Direct link Revit to FEM-design	
r2f_adjustedmodel_vers2.r2f	File created in direct link interface based on REVIT2012_adjustedmodel_vers2.r2f
R2f_test.r2f	File created in direct link interface based on REVIT2013_test.rvt

Table H.1: Overview of files enclosed on CD-ROM.