BIM Software Framework for Prefabricated Construction: Case Study Demonstrating BIM Implementation on a Modular House

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Abstract: Building information modeling and prefabrication are concepts that are undergoing intense study in the construction industry. As the technology to implement BIM is commercially available, many industries have started to use BIM in construction related projects. However, BIM implementation can vary significantly according to the nature of the project. Therefore, development of a BIM software framework for a particular industry to meet its requirements is the most efficient way to use Building Information Modeling. This paper will present a BIM software framework developed for prefabricated construction industry and will demonstrate the use of the framework during the design stage of a modular pre-fab house.

Keywords: Building Information Modeling, Prefabrication, BIM Software Framework, Construction

1. Introduction

Prefabricated construction can be considered as an efficient solution to reduce the environmental impact of construction. Building information Modeling (BIM) is an important member of the Prefabrication industry due to its ability to provide an accurate virtual prototype of physical components of the building prior to manufacture at factory. Apart from the design and manufacturing process of building components, BIM will also play an important role during construction and operational stages of a building.

As the technology to implement BIM is readily available with the introduction of 3D building modelling software by industry leaders such as Autodesk, adoption of BIM has increased around the world in the past few years. However, Implementation of BIM varies according to the requirements of a project. Therefore, it is important to use the correct combination of software to create the BIM model for a particular type of construction. BIM software framework demonstrated in this paper will mainly focus on the prefabricated construction industry.

What is Prefab?

Prefabricated construction is defined in this paper as manufacture of complete modular houses, or manufacture of main components in a building in an offsite factory, prior to installation on site.

Prefabrication can be dated back to nineteenth century where it was used by British as a practical strategy to provide shelter to soldiers who were deployed in other countries. It was used as a

There is a significant growth in the prefabricated industry due to the manufacture of prefabricated modular housing. In Australia, with the population growth in 2013/14, 152,000 additional houses were required to be built. However, it has been estimated that there is a short fall of 40,000+ houses compared to the demand (HIA, 2014). In order to cater for the high housing demand, prefabricated housing can be considered as the perfect solution due to its significant improvement in construction time. Prefabricated construction time is 50-60% less than conventional Construction (Rogan, et al., 2013). This time period can be reduced even more by improving the construction sequence in the factory.

Prefabricated construction can vary from complete modular construction to construction of individual building components such as walls, floors, roof trusses etc. The term prefabrication mainly refers to off-site construction, where, factory made components are transported to the building site and assembled to build the complete building. Generally there are three types of prefabricated construction; Modular system, Component system and Hybrid pod system.

Hybrid pod system is where different spaces of the building are manufactured separately in an off-site

factory and then transported to the building site for assembly. These pods can be bathroom units, bedrooms, Kitchen and other spaces of the building. This system is mainly used in buildings with many repetitive spaces (i.e.: Apartment Buildings, Office buildings, Hospitals)

Component system is where, different components of the building (i.e.: walls, floors and roof, Duct systems, Piping systems) is manufactured in an off-site factory which can be quickly and efficiently assembled on-site. This system is mainly used in building with less repetitive spaces. Modular system is where, the complete unit is manufacture at an off-site factory and transported to the site. This system is mainly adopted in prefab housing industry.

According to a study conducted by Queensland University of Technology on 'Profiling the Nature and context of the Australian prefabricated housing industry', the level of prefabrication of complete modular houses is high compared to the level of component based prefabrication (see table I, Steinhardt, et. al., 2013). However, modular prefabrication is not an effective strategy in commercial buildings due to its size limitations. Complete Modular construction is generally limited to the size of a 40-foot shipping container due to transportation difficulties. Therefore, in many cases a combination of modular and component prefabrication strategies are used to overcome the challenges faced during transportation.

What is BIM?

Building information modeling (BIM) can be used as a method of generating and managing information about the building during various stages of its lifecycle (Lee et al., 2006). It can be used as a platform to integrate all key stakeholders during design, construction and operational stages of a project. Although Building information modeling is a concept undergoing intense study at the present time in the AEC (Architectural, Engineering and Construction) industry, it can be dated back nearly thirty years (Laiserin, in Eastman et al., 2011). The concept of BIM is described by Charles M. Eastman in 'The Use of Computers Instead of Drawings in Building Design' published in the AIA journal in 1975.

There are many fields that interact with BIM in a project. They fall under three main categories as Technology, Process and Policy. This concept was originally proposed by (Succar, B 2009) and is presented in figure 1.
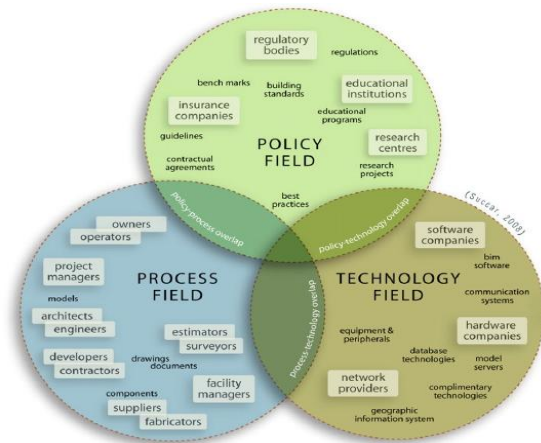

Figure 1: Three interlocking fields of BIM activity . (Source: Succar, B. 2009)

All the categories have inputs and output to BIM in a project. There are also interactions within and between the categories mentioned in figure 1.

BIM discussed in this paper will be mainly focused on the process - technology overlap shown in figure 1. In other words it will provide a framework of integrating the process and technology fields. Policy category is not in the scope of this paper but will be discussed in the future research.

The visualisation aspect of BIM is mainly considered as a medium of communication between the different fields involved in a particular project and providing logical solutions for problems that might occur during design, construction and maintenance stages of the project. Having a visual model of the finished product will help resolve the problems at early stages of the project. However, BIM is not limited to visualising purposes. BIM can be used to conducted analysis in different disciplines and it can also be used as a construction management tool.

Importance of BIM and Prefabrication for AEC industry

Traditional construction approach often leads to many conflicts between different disciplines during construction stages. This is mainly due to the lack of coordination between these disciplines. In Traditional construction, building services designers, facility management teams and energy consultants are not involved at the initial stages of the project (Mawdesley & Long., 2002).

Generally MEP consultants are introduced to the project when the structure of the building approaches its completion. This results in a very

complicated building services design and installation process as engineers will have to use the space provided to install the MEP services. Designers will have to overcome many clashes with the structural design and also with other MEP disciplines. Since the structure of the building is already completed, building services engineers will have to avoid any changes to the structure of the building. However, in many cases where there is no alternative option, changes are made to the structure of the building in order to accommodate the MEP installations. This process can be very costly and time consuming depending on the extent of structural changes required. Construction quality of services is poor in many buildings due to the unplanned installation and space restrictions. Since all disciplines are cramped in one area and are being installed simultaneously by many workers, it will result in poor workmanship and high risk involvement at site.

Poor representation of analysis is also another main drawback of traditional construction. Most of the calculations such as heating and cooling loads, electrical loads and other analysis are done in Microsoft excel or as written calculations. These calculations are not highly accurate and reliable as there can be many human errors. These analysis are not properly documented and due to the complexity of the calculations, they cannot be easily referred to by clients and other building users. Therefore, in many cases these calculations are not used after the completion of the project. Energy analysis, indoor air quality and fire analysis are either ignored or done by separate parties after the construction of the building. In traditional construction, the building is designed to meet the requirements in the standards related to each discipline. This limits the designer's ability to come up with a unique design as often they do not comply with the requirements in relevant standards.

Building Information Modelling (BIM) and prefabricated construction has changed the construction industry from a costly, time consuming and a tedious process to a dynamic, professional, cost and time saving process that is more focused on design and construction of sustainable buildings. There are many benefits for the building services industry from using BIM. Involvement of building services designers from the initial stages of a project is every important in BIM. This will help to develop computation 3 dimensional models that will be used for virtual representations, information storage and analyses in a project. All the information about every element of the model and analyses conducted on the model will be stored in a central location where it can be used for future reference. Significant time and cost savings can be achieved as clash detection can be conducted prior to construction. Integration of all disciplines at the design stage of the project creates the opportunity for prefabricated construction. Many major services such as plant room, chilled water pipes, bathrooms, etc. can be prefabricated at an off-site factory and brought to site for installation. This will reduce the construction time, as most of the testing such as pressure tests and air tightness tests can be done at the factory prior to transportation. Pre-planning of services will result in excellent quality finishes as clashes and other challenges are identified prior to construction stage. Prefabrication of MEP services will reduce the risk of high workforce on site as all discipline will coordinate and produce service modules at the factory and transport it to the construction site.

BIM will create an opportunity for designers to carry out analyses related to building services prior to construction stage in order to get an understanding on how the building will operate after construction. The model can also be used to carry out energy analysis prior to construction, so that energy saving technologies can be introduced during the design stage of the project. This will also help the clients to get an idea on the operational cost of the building. 4D construction simulations can be achieved using software such as Autodesk Navisworks, which will help the project management team as a time line and it will help the health and safety engineers to get a better insight into health and safety challenges that can occur during different stages of construction. Building heating and cooling loads can be calculated using the model rather than using Microsoft excel spread sheets and hand calculations. HVAC duct sizing and pipe sizing can be calculated using the model. Separate reports can be generated for all computational analyses carried out using the model.

Section 2 of the paper will discuss the development of a BIM framework using the software available in the industry and section 3 will demonstrate the use of the BIM framework to create a BIM model of a modular prefabricated house.

2. BIM Software Framework

Due to the wide range of BIM implementation techniques, it is important to develop a BIM software framework based on the requirements of a particular project. However, the framework presented in figure 2 provides a general software framework that can be used in both commercial

and residential prefabricated construction projects. All the software used in the framework is commercially available and the interoperability of software was taken into consideration when developing the framework. The software that are not directly compatible with Central BIM model were used as supplementary software to gain the information that can be in the BIM model.

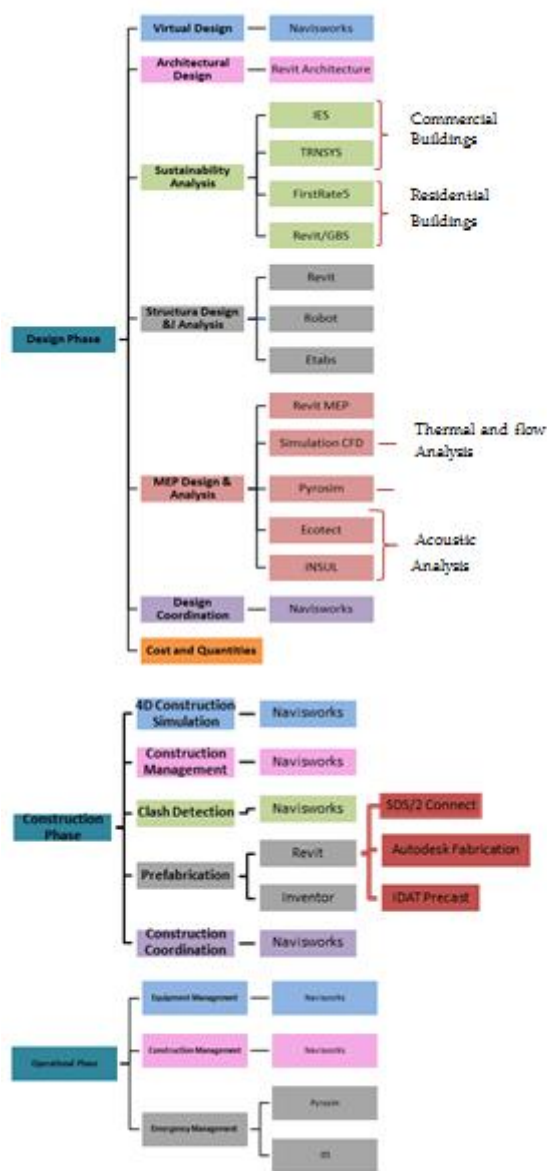**Software used for analyses and development of BIM framework**

Figure 2: BIM Framework for Prefabricated

Construction

Framework for the design stage shown in figure 2 can be used for both conventional construction and

phase, SDS/2, IDAT Precast and Autodesk Fabrication will be an important software addition, which will act as supporting tools to generate precise Structural and MEP 3D models for prefabrication at factory.

Case study in section 3 will demonstrate the use of software framework during the design stage of the project.

3. Case-Study (BIM demonstration on Modular House)

The case study project consists of a modular house with two bedrooms, kitchen, Laundry, bathroom, spacious living and dining area. The building is designed to meet the BCA and other relevant standards. It is designed to transport easily and install in a very short period of time. The modular house is designed to be flexible to change in layout. The house is prefabricated as two modules in an off-site factory and is installed on site as one complete modular house. This case study will illustrate the use of different software to conduct analysis and create a complete BIM model that can be used at design, construction and operational stages of the building.

Architectural Design

Three dimensional architectural model was created using Autodesk Revit Architecture. Building materials were assigned as mentioned in table 1. The house was divided into two separate modules for ease of transportation. Main MEP installations were designed to be located on one module to reduce the complications that can arise during the manufacturing and installation of the modules.

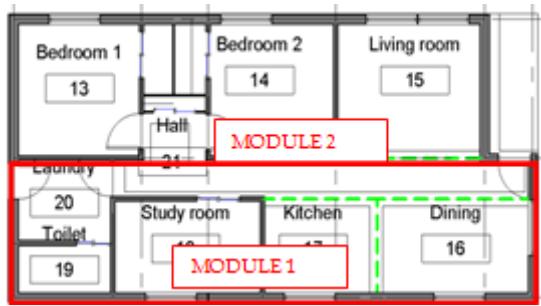Figure 3: Autodesk Revit Architectural model

Figure 4: Internal Space separation

Structure and materials

Table 1: Construction Materials

Component	Structure/ Materials
External wall & roof finish	1.6mm PPG Corten steel pre-painted panel, engineered steel structure conforming to ISO/ASTM
Internal wall & ceiling finish	10mm Plasterboard/ Villa Board
Floor finish	15mm FC sheet with vinyl finish
External doors	Sliding aluminium frame external doors
Internal doors	Hollow core timber internal doors
Windows	Aluminium windows with safety glass
Joinery	Laminate MDF cabinets and tops
Plumbing	Copper piping with mains outlet. UPVC sanitary plumbing to outlets
Electrical	All wiring within conduit system Electrical fittings include: Television, phone, data points, light fitting and GPO's

Building Services Design

Building services is a combination of many disciplines that are required to operate the building after construction. Mechanical, Electrical, Fire engineering, Sustainability and Hydraulics can be considered as main areas of building services. Revit MEP was used with a combination of other software to develop an MEP BIM model for the project. MEP model was linked to the architectural and structural models to create a complete BIM model.

- *HVAC design*

Two air-conditioning options were modelled on Revit. Option one (Figure 5) is a basic air-conditioning design with a multi-split unit consist of individual indoor units for each air-conditioned area. Option two (Figure 6) is a duct system which serves the air conditioned areas of the house. Duct system is designed with a central duct that runs along the hall area of the house and flexible ducts connecting the inlets to each room. Use of flexible ducts allows the users to change the air-conditioning system if the locations of the rooms need to be changed. Option 2 can be considered as a more architecturally appealing design as there are no indoor units fixed to the walls of the air-conditioned spaces.
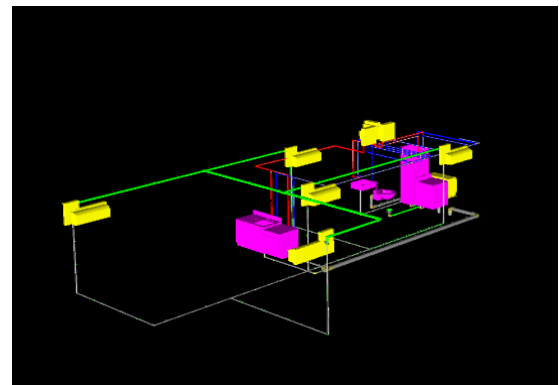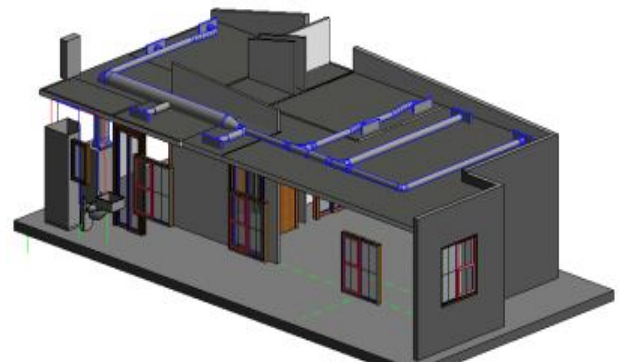

Figure 5: HVAC Option 1

Figure 6: HVAC Option 2

Cooling and Heating load analysis was conducted using IES VE, Revit and FirstRate5 software. Generally for a basic house, a FirstRate5 analysis or a Revit cooling and heating load analysis is sufficient to get an idea of the cooling and heating requirement. However, for a commercial project, it is recommended to use IES VE for load and Energy analysis.
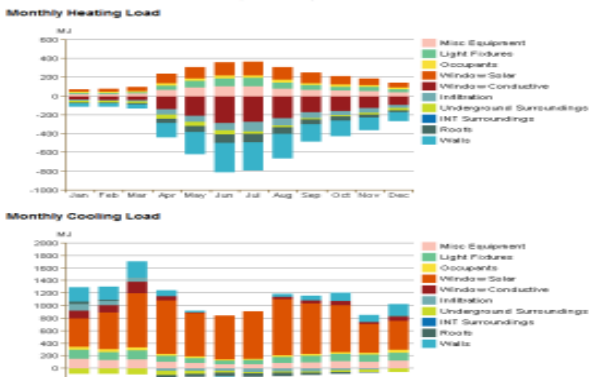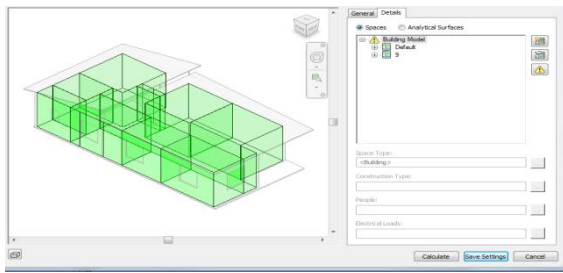
Figure 7: Heating and cooling load on Revit

- *Thermal Analysis*

Building thermal analysis was conducted using IES VE software. The model created on Revit was imported to IES in order to carryout thermal and energy analysis. Internal room temperature of every room was compared with the outdoor dry bulb temperature in order to get a clear understanding of the thermal performance of the building envelope. Improvements were made to the building envelope in order to achieve an internal air temperature of $18-24^0$C. The same model was used to gain an understanding of the occupant comfort levels.
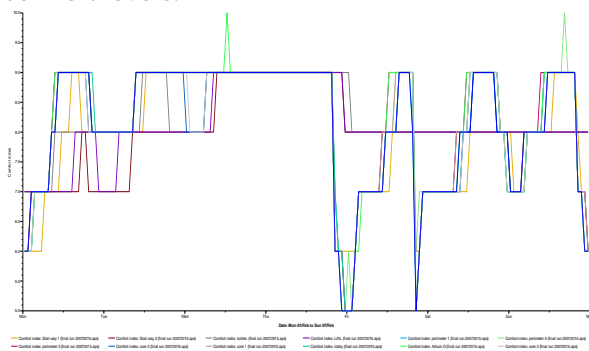
Figure 8: Occupant comfort Index (IES VE)
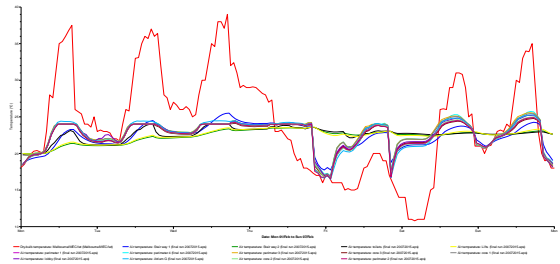
Figure 9: Internal Temperature Analysis (IES VE)

- *Plumbing Design*

Plumbing design was completed using Autodesk Revit. Three separate plumbing systems were generated for sanitary plumbing, Hot water and cold water in the building. The system was designed in such a way that if required, modular prefabrication can be done separately for the bathroom area. Therefore, Bathroom and other areas have separate plumbing systems for sanitary, hot water and cold water. All piping systems were directed towards the rear of the building for mains utility connections. Pipe pressure loss report can be generated for each system used in the building using Revit.
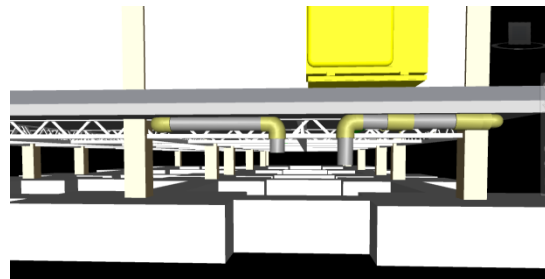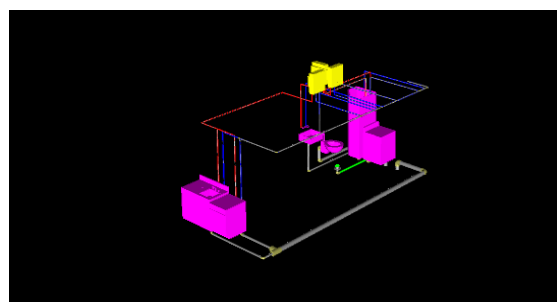

Figure 10: Integrated pluming design (Navisworks)

Figure 11: Integrated Bathroom Module (Navisworks)

- *Electrical Design*

Electrical design was completed using Autodesk Revit. Electrical devices and equipment such as, power outlets, lighting fixtures and panel boards were included in the model. Generally for conventional buildings, wires aren't actually routed in the model and it is left to the contractor

on site. However, in prefabricated construction it is important to model the actual conduits and wiring route in the model as the construction process is mostly automated. Electrical load calculations, power and other important details of the electrical system is available on revit and can be genrated as a report.
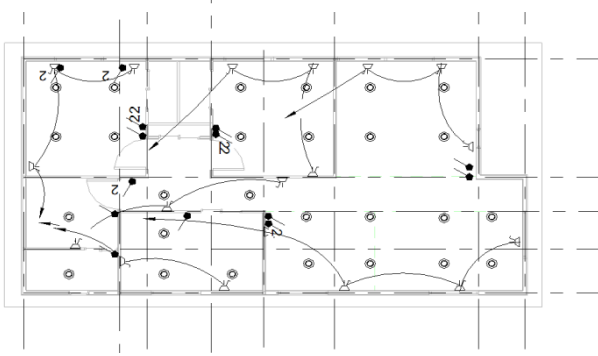

Figure 12: Electrical Circuit Diagram (Revit)

- *Building Energy Analysis*

Building energy analysis was conducted using Firstrate5, Autodesk Revit (GBS) and IES VE software. Fistrate5 was used as a rating tool to achieve the Australian star energy rating requirements. Generally for a residential project, firstRate5 and Revit (GBS) is sufficient to conduct the required energy analysis. For commercial projects, BIM framework outlined in section 3 of this paper suggest the use of IES VE software. However, in this case study, all three software were used in order to demonstrate the capabilities of each. It was clear from the results that, IES VE provided a more detailed analysis report which can be used to get a clear understanding on the energy usage, thermal comfort, Indoor air quality and daylighting analysis. FirstRate5 and Revit were useful to get a clear star rating for the building.
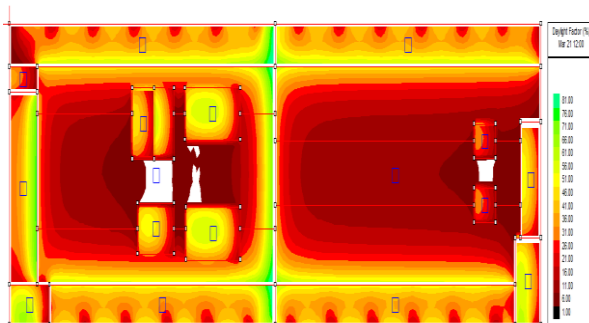
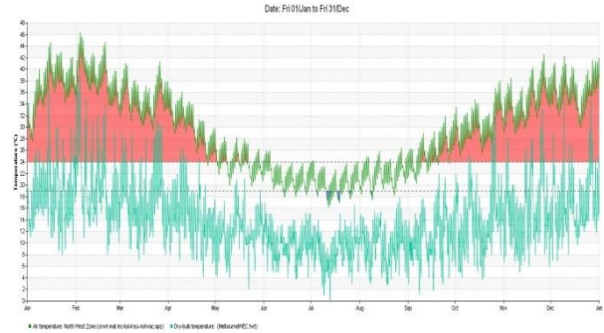

Figure 13: Daylighting analysis (IES VE)

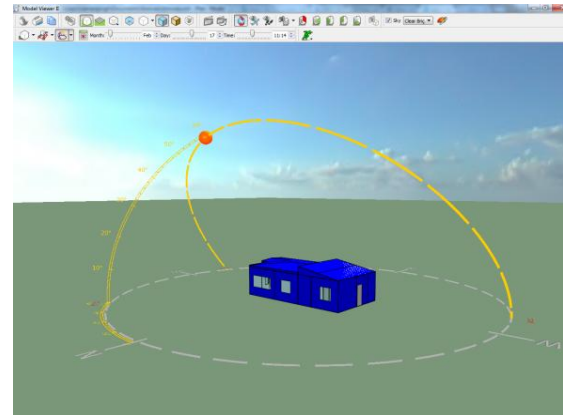Figure 14: Internal Temperature Analysis (IES VE)

Figure 15: Sun-Path on IESVE

Structural Design
Structural design and analysis was conducted using Autodesk Revit and Autodesk Robot software.
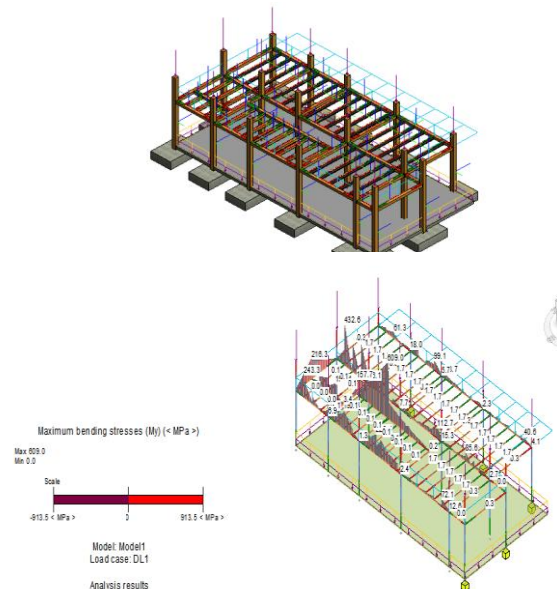

Figure 16: Structural Model developed using Autodesk Revit and Robot

Acoustic analysis

Building acoustic analysis was constructed using INSUL. The software was used to examine the acoustic performance of each building component (i.e. wall panels, floor and ceiling). The software can be used to predict transmission loss, impact sound and rain noise. Trial version of the software was used for demonstration purposes.

Figure 17: Acoustic report generated on INSU

Model integration to create BIM

All Designs developed on Autodesk Revit were exported to Autodesk Navisworks to create the integrated BIM model. All analysis conducted on different software can be linked to Autodesk Navisworks to create a central BIM model that can be used for clash/interference detection between the disciplines, Quantity surveying, Cost calculations, 4D construction simulations. The model created on Navisworks can be used as a communicational tool within the project during the construction stage.

Figure 18: Integrated model on Navisworks

Figure 19: Integrating MEP Models on Navisworks

4D construction simulations and Quantities
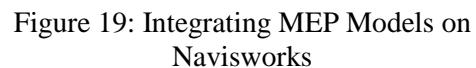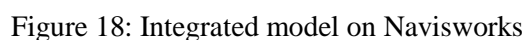
Complete integrated BIM model can be used on Navisworks to create 4D construction simulations. Autodesk Navisworks, allows the user to integrate the construction time-lines developed on Microsoft project or Excel to be integrated with the complete 3D models to create a 4D construction simulation. Construction simulation can also include the temporary site constructions and site preparations. This model can be then used to calculate the quantities and costs of the project.

Figure 20: 4D construction simulation on Navisworks

Clash detection and drawing Review
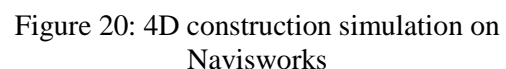
Integrated models can be used to check for clashes in Autodesk Navisworks. Individual fields can be examined to detect clashes with another discipline. Separate view ports can be created for different clashes and comments can be made in the model itself. Navisworks also can generate a complete clash detection report where different parties responsible for providing solutions can be assigned to the task.
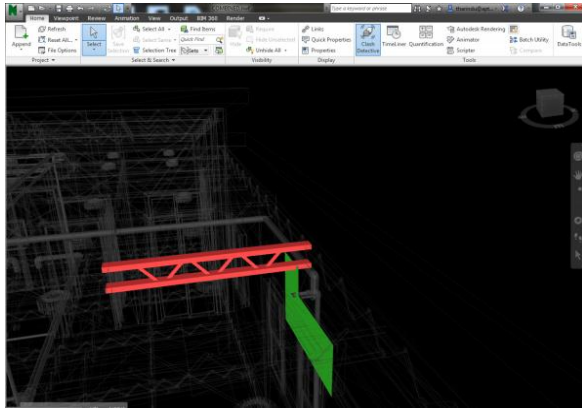
Figure 21: Clash Detection run on

4. Conclusion

BIM framework was developed using the software available in the industry and the case study project was used to demonstrate the use of the BIM framework during the design phase of a prefabricated housing project. Most of the analysis related to residential buildings were demonstrated using the software mentioned in section 3. Fire and evacuation modeling is not demonstrated in the case-study as it is generally conducted for commercial buildings. However, main areas such as, integration of different disciplines, clash detection, 4D construction sequence, thermal and energy analysis were demonstrated using the case study model.

Most of the analysis demonstrated in section 3 of the paper can be implemented on complete module, component basis or hybrid prefab construction. Integration of different disciplines, clash detection and construction sequence can be considered as critical areas in a prefabricated construction project. Software use during the construction phase of the project is not demonstrated in the case study as it will be demonstrated by using a different case study project in the future literature. However, development of a BIM model using the frame work in section 2 can be used in prefab, conventional and hybrid construction approaches to achieve many benefits during the construction life cycle of a building.

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