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APPLICATIONS OF DESIGN FOR EXCELLENCE IN PREFABRICATED BUILDING SERVICES SYSTEMS

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Abstract: Prefabrication is a sought after area in the AEC industry for manufacture of building components in an off-site controlled environment. Although, most of the structural element such as panels and modules are efficiently prefabricated and assembled onsite, prefabrication of complete mechanical, electrical and plumbing (MEP) systems is not achieved in many cases. This is mainly due to the limitations during assembly of different systems, poor implementation of building information modelling (BIM) and lack of standards for offsite manufacturing. The research will introduce the concept of Design for Excellence (DFX) which is currently used efficiently in the automotive, aerospace and shipbuilding industries. Applications of the DFX concept for building services in residential buildings were studied. This paper presents the overall concept of holistic approach to arrive at an optimum solution for design integrated building services systems for prefabricated buildings.

Keywords Integrated Building Services; BIM, DFX;

1. Introduction

Construction industry when compared to other industries such as aerospace, ship building and automotive is struggling to acclimate to new technology. Requirement for standardization and mass production are the key dynamics that impedes the use of prefabrication in construction projects. However, (Gardiner 2016), research on the use of prefabrication in other industries shows that even in aerospace there are areas of standardisation and also requirement of customized design. Where most of the aircrafts manufactured will have standard components and special cases such as rockets and satellites will have customized components. This same concept can be used efficiently in prefabricated building industry for fabrication of building services systems. In many buildings, although the building geometry is different, MEP backbone of the building such as plant rooms and HVAC systems tend to repeat. Design of MEP systems depends greatly on the type of facility and the usage.

Lack of technological development in the building services industry for integrated design is yet another factor that limits the adoption of prefabrication in MEP projects. Use of Building Information Modeling (BIM) is compulsory in the prefabrication industry to develop an integrated design to assembly process. Although ample amount of research has been done on implementing BIM during design and construction stages of traditional construction projects for MEP coordination and analysis, there is a critical research gap for BIM integrated design process for MEP prefabrication. Level of development (LOD) required for different stages of the MEP prefabrication process is yet to be identified. LOD requirement for prefabrication depend greatly on the fabrication process of the manufacture.

The concept of design for excellence (DFX) was applied to the MEP prefabrication industry and a BIM based framework was developed to meet the requirements for each stage of the process. The essence of the DFX process and the applications to MEP prefabrication industry will be discussed in section 3. This paper will review the integrated building services systems used in the prefabricated building industry and explore the applications of DFX in integrated building services design. A practical framework was developed for BIM based

MEP design and fabrication. The framework was divided into four main areas as BIM based Design, Costing, Fabrication and Installation. The paper will also present the ongoing collaboration work with the industry partner (Amoveo), where DFX and BIM was implemented in a case study project during design and manufacturing stages. Assembly and operation of the proposed systems are not in the scope of this paper, however, will be discussed in future literature. The structure of this paper involves three parts:

- Industry review on integrated building services systems
- Application of DFX and BIM in integrated building services design
- Evaluation of design to assembly process through case-study

2. Industry Review

2.1 Building Services and Prefabrication

Building services is a major component of a construction project. Although, it is referred to as a sole section, it is a combination of different fields such as, HVAC, plumbing, power, lighting, Energy, Fire and Acoustics, which falls under three main categories namely, Mechanical, Electrical and Plumbing, therefore, it is also commonly referred as MEP in the AEC industry. It accounts for a significant portion of the total construction cost and unlike other fields in the AEC industry; Building services are involved in all stages of a buildings life cycle. It is important to develop a system that connects the operational stages to initial building design stages. Therefore, building can be designed from the initial stages to match the sustainable goals that need to be achieved during the operational stages of the building.

Building Information Modelling (BIM) is one of the tools that help to create the strong link between all stages of a construction project. It creates the opportunity to design building services for prefabrication, which improve the efficiency of the project during the construction stages. Prefabrication of building services can be defined as the manufacture of complete building services systems or manufacture of main components of a system in an offsite factory prior to installation on site.

Prefabrication when compared to traditional onsite construction has many benefits for all stakeholders in a project. It reduces the waste and complications that can rise during installation of building services systems. When compared to other fields in the AEC industry, building services benefits in many ways by using prefabrication, especially due to the coordination difficulties during installation of separate services in limited spaces inside the building. Services are generally located in confined spaces in the ceiling, floor or narrow risers, where, room for installation is limited.

This is a common issue in high-rise construction where, labourers will be at risk at all times when installing services on MEP shafts in the core of the building. These installation difficulties leads on to poor workmanship and therefore results in inefficient building services systems. Prefabrication in building services systems is not a new concept as component prefabrication has been implemented by many contractors and engineers around the world. However, it is very rare to see complete prefabrication of building services systems and use of advance modelling techniques in the industry to optimize the services systems.

2.2 Integrated building services systems commonly used in the industry

Integrated MEP systems currently used in the building services industry fall into two main categories;

- Service to service integration (packaged units)
- Service to non-service integration (integrated wall panels)

Service to service integration is where two or more building services systems such as; fire protection, HVAC, electrical and hydraulics are integrated to form a single unit. These units are also known as packaged units in the industry. Packaged units are generally found in large commercial and high-density residential buildings. Modular plant rooms, MEP vertical shafts and multi-services racks are some of the common packaged systems available in the industry. Although, these systems are very popular in the prefabrication industry, complete offsite fabrication is not achieved in many cases. This is mainly due to the difficulties faced during transportation and assembly on site. Module weight and complex service connections are some of the main obstacles faced in the industry during assembly of prefabricated modules.

MEP prefabrication has been used effectively in Australia by A.G Coombs Pty Ltd, where they have implemented prefabricated riser system in the 43 story tower at Barangaroo South development in Sydney (McGar 2014). They claim to have eliminated 4000 hours of site installation and pressure testing duct work and pipe work off-site has led to minimum connections to be tested on site.

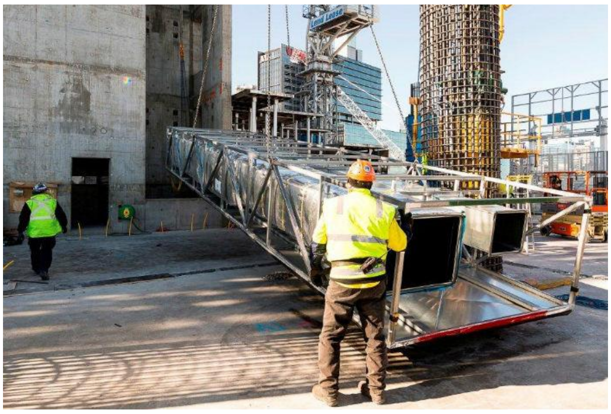
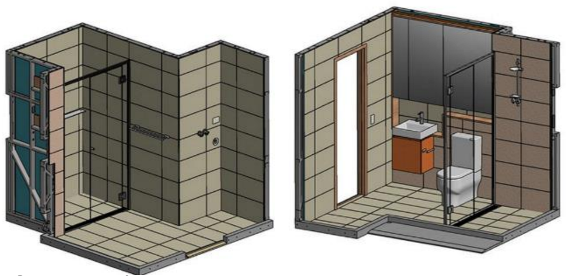


Figure 1: Prefabricated MEP riser at Barangaroo south development (Source: McGar 2014)

Service to non-service integration is when MEP services are integrated with structural or architectural elements. Prefabricated walls, ceilings, floor panels and bathroom pods are the most common components used in the current prefabrication industry. One of the best examples of efficient use of Pod system in prefabricated project is Hickory's 69 level tower in Melbourne CBD. It is one of the first Hickory construction projects to use 794 'Sync' bathroom pod units and claimed to have reduced the fit out cycle by 20% and significant reduction of waste (Hickory 2013b). Laing O'Rourke's service integrated bench at Leadenhall building in London is yet another example of innovative design using DFMA. Prefabricated steel table was fitted with MEP components and a precast slab (figure 3).



I y 2013b)

Entire 47 stories of the north core were completed using 141 integrated benches. This technology has reduced the work force required by 40% compared to traditional build (Young et al. 2013). Services integrated hospital bedhead is another popular prefabricated product currently used in medical facility construction.

Figure 3: North core and Service integrated bench at The Leadenhall Building (Source: Davies 2013)

In standard practice due to the high repeatability in building services systems, engineers often use previous design solutions and adopt them to suit new problems in new projects. Therefore, there is a great opportunity to standardize building services systems, so that mass manufacturing off-site becomes a feasible option to many contractors. Integration issues in building services design can be between service elements and non-service elements. For example, there are more integration issues between services elements in plant rooms whereas, in vertical and horizontal shafts there are integration issues with non-services elements such as structural and architectural.

2.3 Proposed concepts

There are some developments in the research industry for innovative techniques to ingrate façade elements with building services systems. Coydon et al. (2013) describes a concept of integrating external wall insulation systems (EPSW) with HVAC systems to achieve an integrated prefabricated panel for building renovations. The concept describes five integration options and has categorized them into two main categories as centralized systems and decentralized systems.

Ebbert et al. (2015), describes two concepts of decentralized HVAC integrated façade systems called "TEMotion" and "Capricon". Authors have mentioned the benefits of the system related to high efficiency from short duct lengths, however, have mentioned that integrating with a window panel and also maintenance as two major drawbacks of the system.

Ebbert et al. 2007 describe innovative options for refurbishment of office building using façade integrated building services systems. Interesting study has been undertaken to identify the potential to integrate building services systems to different façade types. Three main principals of facades renovation (single skin, double skin exterior and interior) with different combination (with window, box type etc.) has been analysed and double skin facades with decentralized HVAC integrated renovation was found to be the most flexible solution.

Ochs et al. (2015) is an EU sponsored research project which introduces micro heat pump and mechanical ventilation with heat recovery integrated to a timber frame façade system. The system is designed for very energy efficient buildings with a specific heating load around 10W/m2.

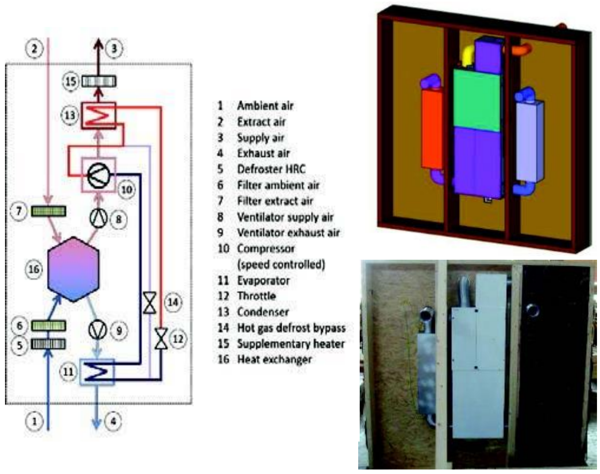


Figure 4: Integrated HVAC Panel (Source: Ochs et al. 2015)

2.4 Challenges when integrating building services systems

Discipline integration for prefabrication can be challenging due to different aspects that need to be considered to meet the requirements for safe working environment. These challenges can be categorized into following areas;

- Structural aspect
- Building physics (u value, thermal bridging, condensation, acoustics)
- Fire regulations
- Operation and energy performance
- Maintenance and replicability

Structural aspects of the integrated systems can be very challenging in modular shaft design. The structural frame of the module shall be designed to withstand the additional stress acts on it during transportation and lifting. In many cases prefabrication of MEP systems is limited to low and mid-rise construction projects due limitations in lifting and transportation. Vibrations during transportation and poor design of the structural frame can cause defects in the integrated MEP systems.

Connection of branches to main runs in pipe and duct work can be considered as a distinct challenge in integrated modular building services. For simple assembly and transportation, it is important to use light-weight material in modules. Onsite welding and soldering of steel and copper pipes is a major challenge in service connect in modules due to the sheer weight.

3. Applications of BIM and DFX

3.1 Need for integrated process and DFX

In traditional construction, Architectural and structural designs are given priority over MEP systems. In many cases the optimum building services design is not achieved due to the space limitations and clashes with other disciplines. Introducing modular MEP system to the traditional construction process can be risky as integrated design and installation planning is not practiced prior to assembly on site. In order to achieve complete prefabrication, integrated design and construction should be implemented in all disciplines involved with the project from planning stages. The concept of integrated design is practiced very efficiently in the automotive, aerospace and shipbuilding industries. The concept is commonly known in these industries as design for manufacture and assembly (DFMA), where, integrated components are designed for efficient manufacture and ease of assembly.

DFMA is based on parts reduction, which is the reduction of number of part per components and reduce the type of components (Barbosa et al. 2013). However, in the context of building services, implementing DFMA can be challenging due to extensive factors that need to be considered. Main challenges can be categorized into following areas; design complexity, discipline coordination, sustainable design, manufacturing, commissioning and transportation. The DFMA concept has been modified by different industries and researchers to address the other challenges faced that are relevant to a particular industry. This modified concept is commonly known as Design for Excellence or DFX. Where, 'X' refers to other challenges faced in the optimization process (Bralla 1996).

In traditional building services design, engineers start by calculating the required load, selection equipment, layout planning followed by connection method governed by objective requirements such as minimum pipe length, minimum fittings, etc. In DFX these factors are considered as set of constraints from the initial stages of the design process. Where, functionality, performance, manufacture, assembly and operation of the integrated building services systems are analysed prior to manufacture and installation.

Functional aspects such as modularity and flexibility are very important in prefabrication industry as product feasibility is achieved through mass manufacture of repeatable designs. Performance measures of the integrated systems such as effects to building physics, cost and energy consumption are also important aspects of the DFX process. Manufacture and assembly are key components of the process where defect reduction, material use are important measure during offsite manufacture. Limiting complex assemblies to factory environment and planning for standard minimum assemblies on site are the strategies that should be used when design for efficient assembly. Complete life cycle assessment of the integrated systems is achieved through designing to meet the-maintenance, replacement and refurbishment requirements during operational stages of the building.

A product that undergoes this development process will go through complete DFX optimization to suit the final requirement of the user. Figure 3 illustrates the DFX optimisation process.

3.2 Plug and Play Concept

The plug and play concept is used efficiently in the furniture industry where DIY products can be purchased off the shelf and installed with ease. This concept can be implemented in building services system up to a certain extent for residential buildings. System connections and testing and commissioning of the integrated systems are the greatest challenges faced in implementing this concept.

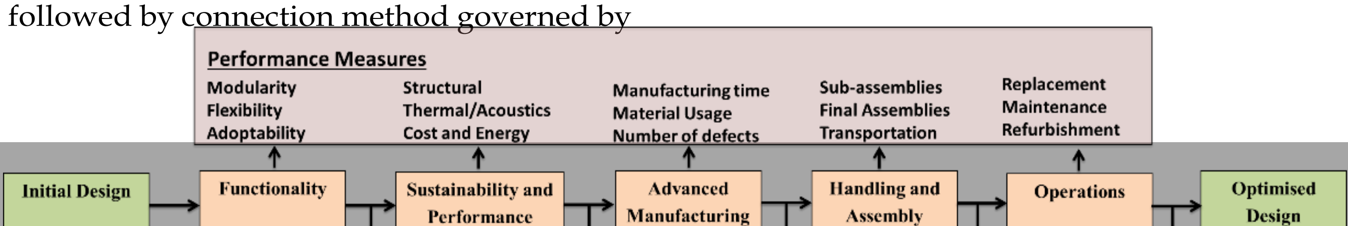


Figure 5: Proposed DFX Process

Generally, in many construction projects, a certified professional will conduct the testing and commissioning for individual system (plumbing, electrical and HVAC) once the installation on site is complete. This process can be done offsite if standardisation is achieved in the integrated building services systems. It is important to identify the complex assemblies in the systems and limit all the complex assemblies to the factory and final assemblies on site shall be designed for easy installation by minimum work force.

3.3 BIM for DFX

In order to implement DFX in a project, communication and collaboration between different disciplines is very important. Building Information Modeling (BIM) can be considered as the latest technology in the construction industry to improve collaboration between different disciplines to achieve integrated design. 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 BIM is a concept undergoing intense study at the present time in the AEC 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.Having a visual model of the finished product will help to identify problems at early stages of the project. However, BIM is not limited to visualising purposes. BIM can be used to conduct analysis in different disciplines and it can also be used as a construction management tool.

It is important to identify the exact application of BIM in the industry. Use of BIM varies from project to project and industry to industry. There are many benefits of using BIM in the building services system manufacturing process. When designing for excellence (DFX), BIM is involved from design to manufacture and assembly. Where factors such as sustainability, performance, collaboration, manufacture and assembly planning can be efficiently accessed using BIM during system development.

Designing building services for prefabrication has many differences to traditional building services designing. There are many factors that engineers and designers need to consider when designing for prefabrication.

It is important consider the manufacturing techniques in the factories prior to designing building services systems for manufacture. Manufacturing process at the factory can be simulated using software to make sure the products can be manufactured using the machines available in the industry.

It is also important to consider the ease of assembly on site as many services are installed in confined spaces in the building. Efficient use of BIM in the HVAC manufacturing process is described in Conway (2014), where application of BIM has resulted in elimination of waste, improved performance through monitoring and reductions in manufacturing time.

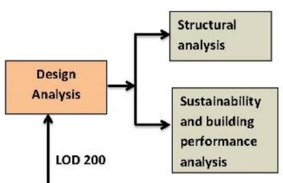


Figure 6: Framework for MEP prefabrication

Identifying the correct level of development required in a BIM Model at different stages of a project is one of the greatest challenges faced by the professionals in the industry. Level of development (LOD) was first defined by the American Institute of Architects in 2008 (AIA E202TM 2008). This document was constructed mainly to standardise the BIM development during design and construction stages of a project. . In order to further standardise the LOD specifications defined by the AIA, BIMForum appointed a working group in 2011 (BIMForum2015). This specification provided by AIA and AGC LOD working group contains both contents of the models elements and the degree of precision (Bedrick 2013).

However, in the context of offsite fabrication, LOD depends on the level of information required at the factory and the level prefabrication in the project. The fabrication process (automated or manual) and use of different machinery governs the required level of development of the fabrication model.

4. Working with the Industry

Amoveo Pty Ltd., principal industry partner of the Centre for Advanced Manufacturing of Prefabricated Housing (CAMPH) at University of Melbourne worked closely with the authors to develop a plug and play concept Nano-House that can be installed as an extension to an existing house. System integration, Design for efficient manufacture, Design for ease of assembly and transportation and energy efficiency were key considerations during the design process.

This case study was used to study the current prefabrication process practiced in the industry and practical difficulties faced during manufacture, transportation and assembly. Proposed framework for DFX and BIM were implemented during design stage of the project. Collaboration with manufacturing facilities in China aided to identify the LOD of BIM required for each stage of the framework.

System architecture

A hybrid prefabrication approach was taken when designing the Nano-house for offsite-fabrication. Where, modular prefabrication concept was used for services areas (kitchen, toilets, etc.) and panelised prefabrication system was used for living areas (living, dinning and bedrooms). Figure 9 illustrates the initial plan division. Service module width was limited to 1200mm, so that 2 modules will be equivalent to the width of a standard shipping container.

Integrated systems

MEP systems in the house are grouped in such a way that it reduced the number of complex final assemblies. Mechanical and plumbing systems such as ducted HVAC and hot and cold water piping are located in one module and all complex assemblies are designed to be done off-site and only the connection to utility mains are to be done on site. Electrical design has connections between the service module and the flat pack section. Main electrical switchboards and connection to the grid was located in the service module. Standard electrical and plumbing panels were developed so that it can be used in future projects and also for replacement if needed at any point during the lifecycle of the building.

Figure 7: Amoveo Nano-House

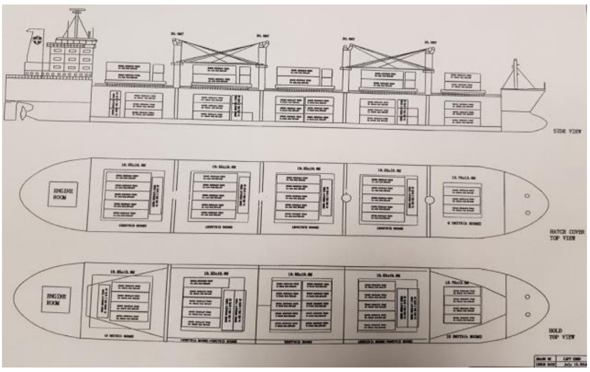


Figure 8: Design for Shipping

Figure 9: Initial Plan Division

Figure 10: Service Module

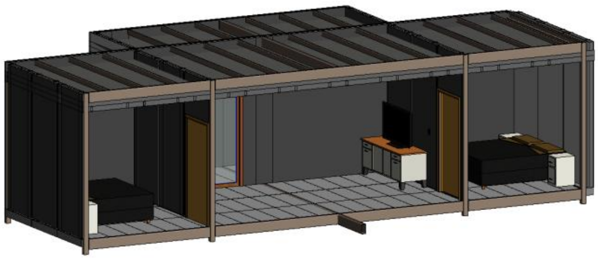


Figure 11: Flat-pack section

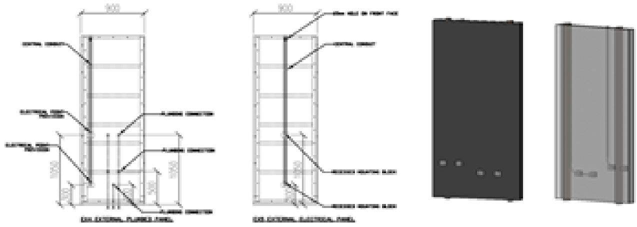


Figure 12: Integrated MEP panels

After the implementation of the proposed DFX process during the design stage of the project, following results were achieved:

- Development of single service module with integrated systems.
- Identification of complex assemblies for off-site construction.
- Reduce cost of transportation using the hybrid prefabrication system.
- Reduction of final on-site assemblies and therefore, number of people required on site.
- Achieving customisation through interchangeable integrated products.
- Easiness for maintenance activities.

- Improved system performance to meet the occupant comfort level.

Use of BIM in during design stages helped to reduce the time taken to convert architectural drawings into fabrication drawings and also improved the coordination between design office and the offsite fabrication facilities.

5. Conclusion and future work

This paper presented the applications of design for excellence in integrated building services design for prefabricated buildings. Framework was proposed for design optimisation through DFX and was implemented during the design stage of the Amoveo Nano-house.

Currently the project is in the manufacturing stage and will be monitored during the assembly and operational stages. Data collected will be compared with the traditional construction projects and practical difficulties faced during transport, assembly and operation will be studied further to improve the integrated services systems for future projects. Lessons learned from the case study project will be used to apply DFX concept for complex MEP systems such as modular MEP plant rooms in the future.

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