BIM AND MODULAR MEP SYSTEMS FOR SUPER-TALL AND MEGA-TALL BUILDINGS

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Abstract: Mechanical, Electrical and Plumbing (MEP) work in high-rise construction can be very challenging due to the different crews involved during installation. Conflicts between the crews generally cause delays in project schedule and result in additional cost due to rework. This study will identify the MEP conflicts in high-rise construction through observations made by the author during the time spent in case study projects. This study focuses on the use of Modular MEP systems in high-rise construction to eliminate the current conflicts. Traditional MEP construction process was reviewed to identify changes to the process when using modular MEP systems. Challenges in implementing modular MEP in high-rise construction is discussed and an implementation strategy is proposed. Role of Building Information Modelling (BIM) in modular MEP construction is highlighted in the study and its involvement during different stages of the modularisation process is discussed.

Keywords: MEP; High-rise; Modular; Prefabricated; BIM

1. Introduction

Mechanical, Electrical and Plumbing (MEP) also known in the industry as Building Services are the active systems in a building that make the buildings liveable by providing electricity, communication, heating/cooling and ventilation, supply and disposal of water (Barton, Fryer, & Highfield, 1983). Scope of Building services engineering has increased significantly with the introduction of modern sophisticated high-rise developments. ASHRAE defines a Tall-building as one whose height is more than 91m and recently introduced two new building classes as super-tall (taller than 300m) and mega-tall (taller than 600m) (Simmonds, 2015). Service design for these buildings can be very challenging due to the height of the building and the capacity of equipment. Introduction of intermediate service floors and decentralised services are preferred over centralised services for these types of buildings due to the height and multi-occupancy arrangements.

Most of the services for tall buildings are located in the central core of the building and service shafts are shared by different electrical and mechanical services, making coordination during design and installation a risky and time-consuming task. Rework can occur due to conflicts between different service crews and poor installation inside crowded MEP shafts. Building Information Modelling (BIM) and Modular MEP can be considered as solutions for the above problems. There are however, limitations in modular construction that need to be identified before implementing modular MEP services for tall buildings. There is a notable gap in the industry for a methodology for identification of optimum modules and module division points in MEP. The study is focussed on introducing a modularisation methodology that will be integrated with BIM that can be practically implemented in the construction industry.

1.1 Modularisation and Standardisation of MEP

Modularisation and standardisation are two terms that are well known in the prefabrication and product development industry. Although, these two words are used together in many cases, there is a distinct difference between them when applied to product development. (Börjesson, 2012) has described some of the main differences of the two concepts when applied to product development.

Misjudgement of these concepts is one of the reasons for lack of prefabrication in Mechanical, Electrical and Plumbing (MEP)
systems. Both these concepts can be applied to MEP systems, however, there is a strong dependency on the building functionality. For example, standardisation can be applied to data centres, where the cooling load of the building depends greatly on the data centre size. There are standard sizes for data centres and therefore, the cooling system can also be standardised to meet the cooling requirement. This is a concept of providing a standard, scalable product to function another range of standard products. A set of battery-operated toys can be taken as an example. They all have the same type and size of battery; however, the number of batteries depends on the size of the toy and the operation.

In commercial buildings such as, hotels, offices and shopping malls, variation in heating and cooling load due to architectural and functional aspects makes it impossible to achieve standardisation in HVAC systems. In other words, it is very difficult to provide a standardised product to function within an irregular product range. Another dominant factor that limits standardisation are the onsite limitations during construction. Due to the late installation of MEP systems, there are number of limitations on site. Tall buildings in urban areas have MEP systems located in the basement level of the building and when transporting equipment onsite, limitations caused by the existing building structure should be taken into consideration. These structural and architectural limitations vary significantly from project to project. The variation in design restricts the use of standardised MEP systems.

Limitations during construction and variations in design makes modularisation the perfect solution for MEP systems in commercial buildings. In the construction industry (especially in the case of MEP systems), unlike in product modularisation, a constraint-based approach should be considered from the initial stages of the modularisation process. This gives the MEP designer the freedom to design the optimum system for each building and the modularisation process will mainly consider the limitations during construction and easy maintenance during operations.

1.2 Conflicts between MEP Systems in the Field

When compared to the uniform and predictable progress of the structural work in building construction, MEP work is considered to generate the most waste due to its uncertainty and instability. A significant amount of time is wasted in construction projects, in doing rework due to design changes and conflicts between MEP crews. Mechanical, electrical and plumbing (MEP) systems contribute to 40-60% of the total construction cost of commercial buildings (Khanzode, 2010). Court et al., (2009) identified health and safety, congestion on site, crew relationships that creates conflicts and delays, productivity, worker availability and skills as the primary issues in MEP construction that generate waste and delays the completion of the project.

Labour efficiencies in the mechanical aspects of a project drop significantly due to the late owner initiated design changes (Hanna et al., 1999). One such change can affect all the inter-connected services in the building. For example, changing the operation of a space in the building will require ventilation system to be changed and therefore, will affect duct sizes and at the same time will affect other services such as plumbing that shares the same service shaft. This will result in a significant amount of rework, which would lead to delays and additional costs.

1.3 Traditional and Prefabricated MEP Construction Process

It is important to understand the current coordination process in a traditional construction system, to identify the differences to the prefabricated system. In the traditional construction process, the scope of the design engineer in design-built projects does not include coordination. Once the contract is awarded, a speciality contractor on site is responsible for development of shop-drawings, which identifies the interferences between the systems. Once all the interferences are
resolved, a coordinated shop drawing is submitted to the engineer for approval. This coordination process can be time-consuming and can fall on the critical path for system installation (Tatum & Korman, 1999).

The initial cost of the design can increase significantly if the coordinated design varies a lot from the initial design submitted by the engineer. It is important to consider both the construction and operational stages during the coordination process to confirm the ease of construction and maintenance. In prefabricated construction, design engineers and speciality contractors have to maintain a strong communication from the initial stages of the design process. Unlike in traditional construction, almost all MEP systems are fabricated at a single offsite facility prior to installation on site. This results in significant changes to the project master program.

In conventional construction, MEP installations during construction can be divided into three main stages as initial stage, installation stages & testing and commissioning stage. Although, MEP engineers get involved from design stage (at least for larger commercial projects), involvement during construction happens rather at a later stage where the building structure is complete or near completion. MEP engineers are however, on site from beginning of construction to verify that the opening/penetrations, building earthing and conduit laying is provided prior to concreting some areas during the initial stages.

The main MEP installation takes place when the project approaches its completion date.

According to the Construction Managers, this late kick-off of MEP installations comes down to insurance issues, equipment warranty issues, security issues and requirement of storage to maintain the original condition of the equipment prior to commissioning. Therefore, in many cases construction managers prefer to start MEP installations closer to project completion. Especially in Sri Lanka, due to the humid conditions and the fact that the country is surrounded by the ocean, equipment and pipe corrosion is a major issue.

However, from the design engineers point of view, late kick-off for installation is also due to the tendency of architects and clients making minor changes to the building while on-going construction. These changes to the function of different spaces in the building can have significant effects on the MEP installations. To address these changes, MEP designers tend to consider a 20-25% design safety factor in HVAC systems. However, in cases where building original design remains unchanged, HVAC system are over-sized resulting in poor energy efficiency.

This tentative design approach practiced in the industry is a major barrier for MEP prefabrication. In modular prefabricated construction, all MEP designs shall be finalised at the initial design stage prior to construction onsite. This allows the concurrent manufacture of building services modules while structural & civil work being done onsite.
Introduction of modularisation to MEP systems should take place during the preliminary concept design stage. However, major changes shall be made to the conventional design process if modularisation is to be practiced in the MEP industry. Figure (1) illustrates the conventional design process and the prefab design process. In conventional design, the performance of the system is mostly considered during design stage. Once the design is complete, it is pushed into procurement stage where items in the design are purchased. Items are then delivered to site and pushed into fabrication. Once the main equipment and elements are fabricated, it is then pushed for assembly. Testing and commissioning is done once the assembly process is complete. This can be considered as a push process. This process is reversed (pull) when applied to prefabricated construction. Engineers should design and procure a system that is commissionable and buildable. This concept is similar to Design for Manufacture and Assembly (DFMA) in the product development industry. DFMA is based on parts reduction, which is the reduction of number of part per components and reduce the type of components (Barbosa & Carvalho, 2013). When there are other challenges that should be considered during design stage such as transportation in the case of prefabrication, DFMA concept changes to DFX (Design for Excellence) (Bralla, 1996).

Construction managers and MEP site managers should have much greater influence on MEP design from the preliminary stages, where, site constraints shall be discussed with the MEP designers during the concept design stage prior to preliminary designs. These site constraints shall be considered during the design stage to identify the limitations in module size, weight and assembly methods. Authors involvement in case study projects and the time spent during visits was used to identify the typical onsite constraints that will have a major influence on modular MEP constructions. Constraint details and the inputs required from onsite staff will be discussed in the next section. Involvement of facility/maintenance managers is important to identify the requirements during maintenance. Clustering of certain elements in the system to form a single module can have adverse effects during maintenance. For example, equipment replacement can be difficult if it is permanently connected to many other elements that do not require replacement. When system modularisation is based on ease of operation, replaceability of components should be studied to cluster components with similar replaceability rates (Isaac et al., 2016).

There are different forms of prefabrication in the MEP industry. Fully modular, components and elements (parts) are the main three forms of prefabrication.

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**Figure 2: Prefab Construction System Model for MEP**
It is most likely to see all three forms of MEP products coming to the same construction site. Plantroom modules, riser modules, distribution modules and corridor modules can be considered as fully-modular products. Indoor HVAC equipment, valves and pipes can be considered as components and nuts, bolts, threaded bars, GI-sheets can be considered as elements.

In prefabricated construction these three product types come straight to site and might also have an interaction amongst them before arriving on site. For example, components and elements are required to fabricate a fully-modular product. Figure 2 illustrates construction system model for prefabricated MEP.

2. Challenges for Modular MEP Construction

Challenges for modular MEP implementation can be categorised into technical challenges (challenges that directly affect the installation) and design challenges (challenges that affect the design). Technical challenges include the on-site limitations, skilled level of labour force, transportation and availability of a fabrication facility. Design challenges include poor communication, availability of fabrication function in BIM software, Inter-operability of BIM software etc. Samarasinghe et al. (2015) identified the inter-operability issues in BIM software, proposed a BIM software framework and the required Level of Development (LOD) for prefabrication. In this study, authors will only concentrate on the technical challenges in modular MEP construction.

Module transportation, onsite handling and assembly are the key factors that govern the modularisation of MEP systems. The weight and the size of the module is decided considering the module transportation options and onsite module handling options. This study considers only the modularisation of MEP systems and therefore, it is assumed that the structure of the building is done conventionally. This makes the onsite handling of MEP modules very challenging. In many cases the plant rooms and other service areas are located in the basement level or at the roof top of the building. Therefore, when determining the size of the modules, the dimensions of the corridors and the entrance opening to the plant room should be taken into consideration. Another challenge in supertall and mega-tall buildings is the intermediate service floors. Crane operation and forklift operation are almost impossible in these situations due to the height of the building. Therefore, innovative methods of on-site delivery and installation shall be considered.

Maximum weight of a module is decided considering the onsite handling equipment. This varies from cranes for heavy object lifting, handcarts and folk-lifts for transportation of modules within the building. This should be discussed with the construction management team before the modularisation process begins.

Weight of a complete module can be considered as some of the element weights and this should not exceed 80% of the handling equipment capacity. This leaves a 20% safety factor to address the possible weight distributions during onsite transportation.

Other than the module size and the weight, assembly of modules/components onsite can be considered as the third challenge in modular MEP installations. The goal of prefabrication is to reduce the number of onsite assemblies and avoid having to employ a skilled labour force. Therefore, it is ideal to have as many components as possible within a single module that is constructed offsite. However, due to the limitations in module size and weight, this ideal situation is not achieved in many cases. Provision for maintenance and replacements should be considered from the design stages of the system. This should not affect the operation of the building. Onsite constraints mentioned above may change during operational stages. Crane and forklift operation may not be available for onsite transportation. Ideal modularisation should address the dismantling of the system as well.
2.1 Modularisation Methodology for MEP

Module identification in the current prefabricated MEP industry is a time consuming manual process where engineers mostly use the grid system to divide modules. The cost and the difficulty of onsite assembly are not taken into consideration. Researchers in other industries have adopted matrix clustering for identification of optimum modules. In the product development industry, interactions between product, process and consumer is mapped using Design Structure Matrix (DSM) to identify possible clusters (Browning, 2001). Pimmler & Eppinger (1994) used matrix-clustering for identification of modules for a climate control system in cars and trucks of Ford Motor Company.

Absence of a practical methodology for division of modules in MEP industry, leads to many modular designs not achieving the optimum modularisation that considers the ease of assembly on site and the module size limitations. There are many types of assemblies associated with mechanical and electrical installations. Authors have taken HVAC chilled water plant rooms as an example. Weld connections, flange connections, coupling and flexible connections are some of main assembly types in chilled water plant rooms (refer to figure (5)).

<table>
<thead>
<tr>
<th>Type of Truck or Cart</th>
<th>Maximum Load</th>
<th>Maximum Transport Distance</th>
<th>Minimum Axle Width</th>
<th>Type of Transfer to and from Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-wheeled hand cart</td>
<td>227 kg</td>
<td>33 m</td>
<td>1.3 m</td>
<td>Ma. P.</td>
</tr>
<tr>
<td>Hand-carry lift truck</td>
<td>602 kg</td>
<td>33 m</td>
<td>1.3 m</td>
<td>Ma. UL</td>
</tr>
<tr>
<td>Electric pallet truck</td>
<td>2373 kg</td>
<td>82 m</td>
<td>1.3 m</td>
<td>Ma. UL</td>
</tr>
<tr>
<td>Electric hand-jack lift truck</td>
<td>2273 kg</td>
<td>33 m</td>
<td>1.3 m</td>
<td>Ma. UL</td>
</tr>
<tr>
<td>Power low lift truck</td>
<td>2273 kg</td>
<td>326 m</td>
<td>2 m</td>
<td>Ma. P. UL</td>
</tr>
<tr>
<td>Electric hoist and crane truck</td>
<td>682 kg</td>
<td>82 m</td>
<td>1.3 m</td>
<td>Ma. UL</td>
</tr>
<tr>
<td>Power fork truck</td>
<td>2273 kg</td>
<td>164 m</td>
<td>2 m</td>
<td>Ma. UL</td>
</tr>
</tbody>
</table>

In order to identify the optimum division points for module identification, it is important to consider which assemblies require high skilled labour force, installation time and safety during installation. Components that required the above should then be clustered for offsite manufacture. For example, quality of a weld connection can be improved significantly if done offsite and it improves the safety as well. Coupling is a difficult task, especially between two heavy modules. Whereas, flange and flexible connections are ideal for onsite assemblies.

The modularisation process developed by the authors is divided into three main stages as pre-processor stage, configuration generator stage and optimizer stage. A significant amount of information is required to identify the module division process. This data can be extracted from the BIM model during the pre-processor stage, prior to modularisation. Site constraints can be introduced to the modularisation process as a set of rules that governs the division of modules. The configuration generator stage will use a clustering algorithm to identify possible clusters of components. Bond Energy Algorithm (BEA) will be used to
perform the clustering of components depending on the assembly type. Elements extracted from the BIM model are mapped on a design structure matrix and interactions between elements are identified. Each interaction (assembly) is given a cost penalty depending on the safety, difficulty and the quality of the assembly when done on site. Each element is then multiplied by the elements surrounding it to achieve the Bond Energy value. Elements with the highest Bond energies (high cost penalties) are clustered together and are identified as modules for offsite fabrication.

Once the module configurations are derived, modules will be assessed for onsite handling and installation where, heavy and larger modules will have to go through the configuration generator for further division. In cases where there is a possibility of more than one module arrangement, optimizer stage will introduce a cost penalty method for choosing the optimum configuration which achieves the minimum cost of assembly, handling and installation. The optimum modularity index (OMI) is based on assembly cost (ACP) and handling cost (HCP) and can be calculated using equation 1. Cost penalty and matrix clustering was initially used by (Lapp & Golay, 1997) for modularisation of nuclear power plants.

\[
OMI = ACP + HCP
\]

In the case of HVAC chilled water plant room modularisation, flange and flexible connection points are considered as optimum division points. However, these different arrangements can mean that the assembly cost changes as the number of modules varies and the handling cost varies with the module weight. Assembly cost penalty (ACP) and handling cost penalty (HCP) for each arrangement can be determined from equations 2 and 3.

\[
ACP = \sum_{i} n_i \times CP_i
\]

Where,

\( \text{n}_i \) = Number of assemblies of type \( i \)

\( CP_i \) = Cost Penalty for assembly type \( i \)

\[
HCP = \sum_{l} m_l \times RC_l
\]

Where,

\( m_l \) = Number of modules in the weight category \( l \)

\( RC_l \) = Equipment renting cost for weight category \( l \)

Figure 2: (a) Flange Connection (b) Flexible Connection (C) Welding

Figure 3: MEP Modularisation Methodology
3. BIM in Modular Construction

Multi-trade prefabrication requires a significant amount of pre-planning and design coordination. Building Information Modelling (BIM) is ideal for design coordination, construction planning, on-site delivery planning, clash detection and fabrication planning in Modular construction. Design, Construction and Operation and maintenance are the three main aspects that are considered during MEP coordination (Korman et al., 2010). This requires the involvement of many specialists from different stages of the project. In modular construction, onsite delivery and installation specialist, Construction managers, fabrication plant specialist, design engineers and facility managers are involved during the project preliminary/concept design stages.

Clear communication between these individuals is very important to avoid additional work onsite and problems during transportation and installation. BIM improves the communication between the different stakeholders in the project and helps to get the designers, construction teams and the maintenance team involved from the initial stages of the project. Prefabrication industry is moving towards the use of advanced robotic manufacturing equipment. This creates a new requirement for BIM software to transfer fabrication models directly to manufacturing machines such as CNC, 3D printers etc. Machines can have different inputs and models should be adjusted to meet the requirement. This can be very challenging and is one of the reasons for lack of fabrication functions in BIM software. Prefabrication as an industry is still at its early stages and it is likely to see improvements to the BIM software once the fabrication process is more standardised.

While improving the communication between the stakeholders, a more technical use of BIM in modularisation is to obtain the necessary information from the BIM model for module identification and optimisation for job site delivery. Modularisation methodology presented in section 3.1 requires information about the type of assemblies, site limitations and element details at the pre-processor stage. All this can be obtained from the BIM model and can be automatically extracted in different file formats. Proposed BIM based methodology for module identification and optimisation uses an open source platform (Dynamo) which allows data transfer from different file types to develop a virtual code for modularisation. Python based nodes are developed to perform the different operations (extract data, element interaction matrix, BEA, etc.) and identify the element arrangement and the OMI of a given MEP design. BIM based methodology for modularisation is illustrated in figure (7). The final aim of the study is to develop an API for optimum modularisation of a given design.

Figure 4: BIM Based Modularisation Process
4. Conclusion

This paper clearly identifies the challenges in Modular MEP construction and explains how they can be used as constraints in the proposed modularisation methodology. Onsite challenges such as assembly and handling were identified as the main constraints of the modularisation methodology, and a cost penalty approach was introduced to identify the optimum module division for a given design. MEP challenges in conventional high-rise construction is discussed with authors experience in the industry and changes to the conventional construction process when implementing modular is illustrated in section 1.3. Application of a BIM based modularisation process during the design stage was proposed in the study.

The proposed methodology for modularisation only considers the onsite lifting limitations and assembly difficulty. This concept will be improved in the future to include constraints such as module height, width and length and to consider the replaceability rate of components during the clustering process. The BIM based process will be further developed to a user-friendly platform that can be used in the industry.

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