Structural BIM Processes for Modular Multi-story Buildings in Design and Construction

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ABSTRACT:

Modular construction and prefabrication is a growing trend in the Architecture, Engineering, and Construction (AEC) Industry based on a series of technological developments and its historical exposure to design and construction practitioners. Some of these technological developments come from a computing side such as Building Information Modeling and advanced parametric studies or in new methods of structural modularity in the systems. Modular systems are inherently different in structural behavior, construction, design, and modeling in relation to traditional stick-built structures. Methods to develop efficient solutions differ just as their other attributes do. Furthermore, the inclusion of modular and prefabrication design notions into the design process is often limited based on a lack of well thought out processes; the same can be said for the construction phase. Because of the need for better understanding of how modular systems function and interact with systems is limitedly known, defined processes in how to account for these behaviors can reduce the current high variability that relates to system effectiveness and project teams willing to implement it. This paper will focus on describing current design and construction processes and identify where modular aspects need to be considered at different lifecycle phases such as conceptualization design where the scale of modularity must be determined as an example. Beyond the current status of industry processes, recommendations will be made on where more effort needs to be placed on defining more detailed processes around new technologies like Building Information Modeling. Additionally, the ties between defined processes and how they help software developers will be discussed.

INTRODUCTION

Modular construction and prefabrication in the Architecture, Engineering, and Construction (AEC) Industry is a growing trend (Giles and Lara 2006). From a definitional standpoint, modular construction refers to one or more factory-built building units from the fabrication site then transported and assembled on-site (Pasquire 2002; Lu and Klorman 2010). Examples of the varying complexities of modules can be seen in Figure 1. The production of modular units are best suited in an industry that thrives from a supply chain process, which accounts in developing a few parts as possible to build the end project (Giles 2008). These systems have the ability to impact many sectors and building types such as residential, multi-family dwellings, educational, correctional and high-rise (Schoenborn 2012). With its unique requirements, modular construction is not feasible for all architectural styles and building classifications, particularly those with little repetition (based on current practices and technologies).

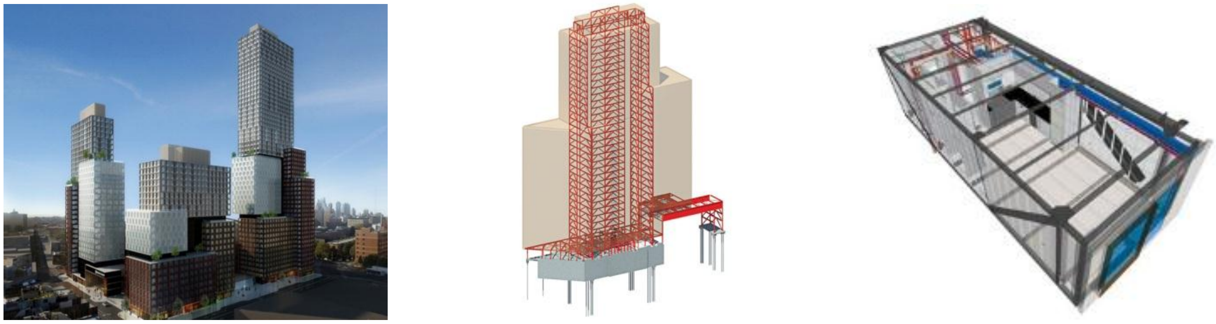
A primary motivation behind a shift towards manufacturing the building process is to reduce cost, time-to-build, and improve the quality of the project (Alwisy et al. 2012). A 2011 market report states that 37% of the AEC industry takes advantage of modular construction on a high volume (≥ 50%) of projects within their firms (McGraw-Hill 2011). It is projected by those same industry professionals to rise to 45% by the end of 2013. Schedule time saving of 35-66%, decrease in project overall budget by a min of 6% to 20%, improvement to off-site labor productivity by as much as 2.32%; these are the main driving factors (Eastman and Sacks 2008; McGraw-Hill 2011). Growing trends such as these, could be accounted for by present construction nearly always has an off-site component that plays a major role to some degree and to varying complexities of modularization (Nawari 2012).

a) Prefabricated Roof b) Water Closet Prefabrication c) Container Unit Decomposition

Figure 1: Examples of Physical and Virtual Modules

Other areas that promote modular construction that has advantages revolves around: reduction of need for workforce, the reduction of on-site carbon emissions, the improvement of construction schedule and product quality, economy of scale in manufacturing of multiple repeated units, speed of installation on-site, and improved quality and accuracy of the product (Lawson and Ogden 2008; Lu and Klorman 2010; Lawson et al. 2012)

Historic building construction typically factors in consideration by architects and engineers related to standard performance characters for the main disciplines on conditions related to the final build configuration. Off-site construction now requires not only consideration of the performance after construction but also consideration of production, transportation, and installation performance. This industrialization shift in the construction of the building requires special methods of production technology and particular design criteria to support these new processes, all of which now need to be accounted for in the design phase (Moghadam et al. 2012). An example of a high quality mid-rise to high-rise project in the U.S. depicted in Figure 2.



a) Architecture Rendering b) Structural Lateral System c) Modular Unit

Figure 2: $4.9 billion Atlantic Yards Project (Largest Modular Project in the US)

(Source: http://continuingeducation.construction.com/article.php?L=5&C=943)

Mass customization of modular units and the development of digital technology are the new emerging paradigms of the twenty-first century. Interrelationships between these two domains have already prompted a shift towards mass customization based on developments in the digital revolution (Huang and Krawczyk 2007). However, the modular industry today still faces challenges related to moving past traditional market social stigmas within the AEC industry (Jellen and Memari 2013). Major social, as well as technical, issues that inhibit adoption (based on a lack of understanding of the scope) encompass (Lu 2008):

- Understanding how to coordinate the system interactions
- Understand how modularization works;
- Not designing for modularization early enough
- The lack of knowledge about what is needed with complex modular construction

There is, however, a potential for closing this gap with another successful technology that is redefining processes through adoption in other areas of design and construction. This technology is Building Information Modeling (BIM). Relating BIM to modularization, McGraw-Hill Construction in conjunction to National Institute of Standards and Technology (NIST) listed the emergence of BIM technology as a major factor fueling the interest in modular construction and prefabrication (McGraw-Hill 2011).

Information driven technology, BIM being one of them, has the potential to continue advancing our understanding of how to perform design and construction on modular and prefabrication construction. Ikerd (2008) and Aldea et al. (2012) state that firms who use collaborative information technology can gain a significant competitive advantage by adopting new processes for the structural sector of the AEC Industry. As of now, current modeling techniques are limited especially for the relationships between the modular unit and any extra lateral system needed in taller structures. In essence, there is no special software for the design of modular buildings currently as compared to stick-built where there are a multitude of software and tools. However, such tools could be developed according to Ramaji and Memari (2013).

In looking towards tool development, an understanding of the process must be known or proper tools cannot be developed to meet the needs. The lack of understanding and having ill-defined processes that professionals can reference focusing on modular design and construction is still incomplete. However, BIM has started to change this through developing such processes. Defined processes can reduce the current variability that relates to system effectiveness and project teams willing to implement modularization on projects. This paper will layout and summarize process advancements where modular thinking needs to be conducted.

BIM IN MODULAR DESIGN AND CONSTRUCTION

Recently, new terminology and their meanings are becoming mainstream such as Building Information Modeling (BIM), Virtual Design and Construction (VDC) and Integrated Project Delivery (IPD). All of these are resulting in more and more engineering firms being asked to participate or are required to collaborate in model-based workflows (Rammant and Adriaenssens 2008). BIM can be thought of as a tool and as a process that generates, through multi-person and firm participants, the ability to convey design concepts and details in a clearer and more concise manner. Often this conveyance allows for earlier considerations of various topics. This “shift” proves essential in that design decisions cannot be afforded to be revisited later in a project, especially as projects become more complex as timelines are compressed (Middlebrooks and Hammond 2010). This has made numerous large-scale projects possible by breaking down communication barriers. In general, these types of tools and processes are in the process of transforming the way business is being conducted (Keil et al. 2001), particularly over the last several years in the building industry (Jacobi 2007) with unprecedented opportunities for expansion.

To support BIM adoption, Fallon and Palmer (2007) found that successful software adoption at the design stage can lead to a 10% cost savings on a project based on better: design efficiency, material selection, and coordination. Bayramoglu (2001) and Gallaher et al. (2004) additionally found through an extensive study on technology improvements, that there is a reduction in errors on the order of 20%, all possible through the use of enabling technologies that improved communication between all stakeholders. McGraw-Hill Construction's report (2012) expands this value to 37% across the lifecycle, which is a 10% increase from 2009 results. Furthermore, they concluded a 36% profit increase were found within firms that have adopted BIM, this is up 15% from 2009.

Relating BIM to the modular domain, Nawari (2012) identified countless advantages that can lead to significant impacts in off-site construction including: the support and increase in speed, sustainability, safety, constructability, quality and time of construction, and enhanced prefabrication yield. Additionally, Song and AbouRizk (2006) found that virtual systems can simulate the shop production environment at a realistic level. The associated realism with BIM can help simplify any simulation modeling misunderstandings and has the capability to help grasp complex systems' interactions more clearly. One of Lu and Korman's (2010) modular BIM case study projects showed that while it costs $44,000 to implement BIM technology into the firm, it saved a project $220,000 overall for a $44 million dollar project as compared to the same company who did not use BIM for modular.

In order to understand the technology and how it can play a role in the process, a discussion on the structural aspects of modular construction is needed. The section to follow provides a discussion of these highlights.

STRUCTURAL MODULARITY TO CONSIDER IN DESIGN

Based on the survey that Haas et al. (2000) conducted, the top building trades that are using prefabricated components most effectively involving structures are: structural assemblies (3rd), concrete (9th), and masonry (14th). These results are still valid in that McGraw-Hill (2011) found that in industry, mechanical systems are still the most prefabricated while architectural components and structural as a whole remains in send and third respectively. Structurally speaking, many items can be truly modular and/or simply just prefabricated based on current manufacturing methods (Badir et al. 2002; Hallowell and Toole 2009).

Modularized structural systems can come in different classes and it is necessary to know the types and configurations in order to make recommendations in the process. The main classes to differentiate items are 1) panelized systems and 2) 3D modular or volumetric systems (Jellen and Memari 2013). Panelized systems are flat assemblies that often focus on wall, roof, and floor systems, whereas 3D modular systems are volume spaces that are often made up of panels. A third system that can be considered prefabricated is structural elements/sub-assemblies. Ramaji and Memari (2013) categorize modular buildings in five typical configurations. Within each combination, however, there are unique attributes to each. Grouping prefabricated structural systems by type, Table 1 lists the most common as suggested by prominent literature.

Table 1: Types of Prefabrications

Elements	Panelized Systems	Typical Configurations
Concrete forms	Wall (bearing, lateral, infill curtain)	Stacking 3D modular system
Reinforcing cages	Roof	Hybrid Cored-Modular
Precast concrete	Floor	Hybrid Podium
Joists and trusses	Precast concrete	Framed Unit systems
Stairs		Open Building System

As Table 1 represents, many items we design for are in fact considered modular; it's just that the traditional engineer of record (EOR) does not account for the modular aspect in most cases. The more standardized, consistent and repetitious the dimensions are, the larger the number of components can be.

In order to design, engineers and other trades related to modular construction need common and specific/specialty knowledge about different criteria, behavior, modeling assumptions, decision factors and much more. This knowledge is particularly important when working with technology that needs this different information to function, thus the "I" (information) in BIM. Without it, then it's simply a 3D model for visual purposes only. Information needed in modular BIM is still unknown as it has limitedly been studied and deployed, particularly with no proven and efficient software to run simulations. Listed in Table 2 are key information classes that should be known to properly model behavior and to make decisions on modular designs. This listing is not comprehensive due to this domain being so new. As new technology is developed, this list will surely expand.

Table 2: Examples of Potential Information Knowledge Needed

Design and Performance Criteria	Behavior of the Structural Systems	Owner Criteria
• Safety • Redundancy • Robustness factors	• Individual module diaphragms • Whole building diaphragm • Continuity in vertical plane • Connection of units • Limit states	• Completion schedule • Cost • Material requirements • Aesthetic look
Modeling Considerations	**Manufacturing Domain**	**Optimization Studies**
• Load definitions • Module overlap • Element definition • Boundary conditions • Force-deformation relationships	• Factory space limitation • Available human resources • Factory working hours • Automation limitations • Available equipment	• Cost • Schedule • Benefits and challenges • Performance and function • Material Properties • Configurations

PROCESSES SUPPORTING MODULAR

The misunderstanding of current technology and lack of integrated and collaborative delivery methods is a concern. This is because they do not actively support efforts such as modular construction notions to make a real impact. Processes help all project team members to better understand other stakeholder's role(s). They also provide a foundation for defining workflows that support integrating computational modeling particularly between disciplines to convey and test design ideas (Lee et al. 2012).

Various efforts have been or are still being conducted to define proper processes. Current process models depict the big picture project workflows at different stages of the building lifecycle but at a low level of detail to define what could be modular. An example is with buildingSMART International's (Norway) examination of structural design of a system as a whole yet it focused on model generation in the design phase (buildingSMART International 2007). However, a few projects have placed more emphasis on identifying locations where technologies are needed. Lee et al. (2012) is developing an integrated model that describes the entire planning and design process for all major participants on energy efficient renovation projects. Additionally, Solnosky (2013) developed an Integrated Structural Process Model (ISPM) that identifies critical tasks at an integrated and structural level for structural planning, design, fabrication and construction of new projects implementing BIM and integrated concepts.

Efforts are now being centered in the research community improve to the process to support these new technologies including modular, prefabrication, and off-site construction. The following sub-sections look at the general structural processes based on Solnosky's (2013) Integrated Structural Process Model in relation to where prefabrication and modularization fits within the larger picture. The topic here is limited to concepts that could lead to heavily influencing modularization adoption.

Perhaps the two most prevalent and demanding design trades that modularity and prefabrication affect is the architectural and structural disciplines, a close third is MEP but there is more room later in the lifecycle for refinement. There is a close relationship between these two design processes due to architectural designs defining the geometry of the building elements where it then becomes a key input in structural designs (Porwal and Hewage 2011). An integrated interaction between various parties, particularly architectural and structural designers, in the early stages is beneficial as they then complement one another (Holzer et al. 2006). Looking at the relationships and functions of the architecture, the structure, and the true modular aspects, clear definitions emerge. Architecturally, spaces and layouts of components and modules are represented in three dimensions and must yield to city bylaws and national codes. Structurally, the modules and the supporting structure and lateral system requires that the designs meet building codes and meet performance requirements for smaller components such as walls, beams, and columns. Modular, in and of itself, takes these two notions and provides a set of rules needed for dividing the layout into units and specifies allowable module dimensions based on road regulations, acceptable dividing elements, and rules related to structural systems capabilities.

Planning and Early Design

Planning centers on the start of a project and looks at the owner's program and proceeds to define major requirements, which the design and construction team must meet. Following the program, major requirements and constraints that need to be met are then identified. Simultaneously, a project execution plan (PxP) needs to be decided upon. This leads to the development of initial requirements and their priorities from diverse perspectives such as spatial, functional and financial. Here is where the modular experience of the team needs to be evaluated to understand how to approach modular attributes. Additionally, the requirements and goals of the owner and teams need to be aligned and compared with what can be done from an off-site construction aspect. Next is the development of site, schedule, and cost constraints. The last section is the generation of the architectural vision that is developed while finalizing the building occupancy rating. Concurrently, project and modular risks to the goals need identified and proper planning needs to be undertaken.

Now that planning is essentially complete, next comes the early design or conceptualization design phase. No matter the name, the focus here is on selecting and testing schemes and ideas against early rules of thumb and best practice techniques to develop feasible alternatives. Early design transitions from planning with the determination of the design criteria for the different systems including modular at a large scale focus. Examples of these include: spatial impacts, performance, reliability and efficiency. Relationships between the systems need to be identified, including the modular characteristics and requirements. This task set looks to study modularization opportunities without going in-depth with calculations. Modular definitions and the creation of groups to facilitate sub-assemblies are identified. The key to prefabrication is to acquire feedback from specialty subcontractors. Feedback focuses on the ability to achieve tight tolerances, delivery times, availability of equipment to ship, the amount of repetition and uniqueness, and envelope sizing limitations.

The remaining portion of early design, essentially is to postulate and holistically evaluate alternative schemes for stick built and modular built aspects of the project, thus narrowing down to one solution. Possible material types and system configurations are identified and those not feasible are dropped. Major prefabrication details in terms of systems and sizes are isolated through early design routines and iterative parametric studies. The optimum implementation of modular units and assemblies can be achieved by designing one of two ways: 1) highly serviced and more expensive parts of the building and 2) more regular and repeating features. Both of these reinforce careful consideration to the architecture and spatial planning of the building. The studies on modules will be given to the owner to determine if they support these ideas and their associated details. A goal here could be to look for and try to include as many off-the-shelf components as possible. Design items to focus on at this point include:

- Access areas in the building design to maintain modules as needed
- Make the modules as complete as possible to speed construction and improve quality, safety, operations and maintenance
- Integration of air distribution systems as part of the structural system
- Exploit the high strength and stiffness to weight ratio
- Utilize wall and floor decking as an inherently stiff system to resist lateral loads
- Integrate slabs for better acoustic, fire and environmental performance between units

Once alternatives are chosen, constructability reviews, preliminary sequencing, and code reviews can be conducted to help select the best alternatives. These alternatives are then compared to the other systems to narrow down the ideas to the single best to be then fully designed. To conduct these concepts, Table 3 lists the major tasks and subtasks that impact modular ideas in planning and early design.

Later Design and Detailing

Having determined the type of structural system to be designed and the modular configurations in a larger scope, the design of these separate structural systems and their interactions can now be done. In traditional construction these phases are referred to as: Design Development (DD) and Construction Documentation (CD). An extension of these phases is detailing, which is really just a continuation of design but now at a smaller more detailed level. These phases can be looked at within two distinct view points, the module structure and the supporting secondary structure.

For the non-modular based structural systems, designing evolves the concept(s) from a holistic level into a single solution that is optimized at the member level. Systems' narrowing focuses around the configurations, orientations, and patterns within the lateral, foundation, and gravity systems. As this process refines the solution, the more detailed the checks and models become. Constructability, site logistics and planning for fabrication and construction can start to be formulated here to ensure the design meets the appropriate construction techniques. Major considerations regarding the site build portion of the structure that needs to be thoroughly looked at is listed as follows:

- Considerations for walls, enclosures, MEP penetrations, specialty equipment in the building, etc.
- Energy performance and, if appropriate, deconstruction and reuse of the pods
- Diaphragm action and redistribution of lateral loads
- The connectivity and adaptability to contain and support the modules
- Strength and serviceability needs to support modules without damage and to protect the structure against man-made and environmental conditions

- Coordination to ensure constructability, sustainability, and performance against building codes, standards and industry best practices are fulfilled

Table 3: Major Planning and Early Design Tasks that have Significant Modular Impact

Main Integrated Tasks	Subtasks with the Integrated	Modular Aspects of the Tasks
Develop the owner's program and objectives	Define the owner's needs and corresponding constraints	Owner recommendations on modular
Develop initial project requirements and their priorities	Consider priorities from diverse perspectives such as spatial, functional and financial	Align modular priorities between: • Owner, consultants, and trades Module size
Determine structural criteria requirements for the design: • Spatial impact • Performance • Reliability • Efficiency	In particular relating to the building code: • Systems requirements • When code provisions cannot be used	N/A (no specialty aspect)
Consider prefabrication of various component complexities	Acquire feedback from specialty subcontractors	Consider: • Delivery times and transportation • Specialty equipment
Conduct interactive rationalization between the systems	Layout the project massing based on different systems and how they dictate one another	Develop concepts around: • Overall layout arrangements • Building • Floor to floor dimensions • Column spacing • Symmetry effects • Module size and shipping
	Look at how the site and geographic conditions can drive a particular system selection	Consider selecting modular aspects: • Adjacent structures • Geotechnical findings • Geographic region • Architecture impact
	Consider the applicability for the structure to overcome special situations	• Concerns for isolation and damping • Special system needs • Multi-hazard resistance • Build-ability and load transfer
	Look at the parameters in determining what material is available and its associated limitations	Investigate the impact on the unit and supporting structure: • Material availability • Material resistance to load • Meeting project drivers • Limitations of the configurations and systems • Weight concerns
Conduct a constructability and project driver review		Module size Ability to control quality Off the shelf product used
Obtain input from a fabricator and determine if the ideas are feasible		Have vendor involvement

In the design of the modular units themselves, structurally there are two main ways of doing this. The first is through proprietary systems and the other is through customized systems. The first lends itself to more off-the-shelf products. As a result it can more quickly be built due to less fabrication and schedule constraints. Many of these are not done by the Engineer of Record (EOR) and instead are done by the specialty contractor (in this case the modular expert). The second way is through custom designed systems are unique to the project. These require a much deeper understanding of structural behaviors and limit states which results in the EOR producing these designs.

In either case, but more specifically the second, the goal is really generating a modular structure capable of resisting the loads acted on the module. These include site loading, long term sustained loads, fabrication loadings, and even transportation loading. The scale of the structure is considerably smaller at a unit level than at the supporting level with stick built. Because of the scale, the narrowing and refinement of the structure often is done more quickly as there is less per unit to determine and refine. The coordination here can be said to be even more serious than normal as tolerances and considerations on buildability in the factory with other systems is more constrained by the unit parameters. The design process is fairly standard with just different criteria and requirements. Typically it follows: analyze, design, coordinate, modify, and repeat till a final solution converges. Much of the design of the modules can actually be correlated to traditional design and construction in the detailing phase where the details are determined. Here with modular, detailing can be done on the module at the same time that the site built support structure is being done at a far less level of detail at the connections level. The main area to consider is coordinating the module interaction and the relationship to the supporting structure (if there is any).

Correlating the relationships between site built supporting structure and the modular units (structure included) there are many characteristics on how the two relate that need to be known. This area as a whole has been limitedly studied due to most historical modularization has had limited structural aspects to it or there was no need for supporting structures. The characteristics to consider all focus on the change in known behavior mechanism of the systems. This is a result in that they fundamentally behave and connect differently. The characteristics below focus on these relationships:

- Second-order effects due to sway stability of the group of modules
- Force transfer of horizontal loads to the stabilizing system
- Diaphragm action within the walls of the modules in how they relate to the building diaphragms
- Manufacturing tolerances and alignment of stick vs. modular components
- Robustness against accidental actions within the modular system during construction and during occupancy
- The influence of installation eccentricities on the additional forces and moments induced on the modules
- Modules corners in how they act together to transfer wind loads and to provide for alternative load paths

To summarize these two concurrent tracks, Table 4 lists the major tasks and subtasks that are in later design and detailing that focus on modular structures and supporting structure that have the most influence.

Table 4: Major Later Design and Detailing Tasks that have Significant Modular Impact

Main Integrated Tasks	Subtasks with the Integrated	Modular Aspects of the Tasks
Early and detailed site logistics		Consider: • Storage of modules • Location of cranes • Placement sequences
A quality control and assurance review	Perform on both the resultant designs and the models for accuracy	• Ensure modular model matches remaining site built structure
Coordination with other disciplines	• Areas heavily influence design decisions • Review for final errors • Conduct with the other disciplines	Coordinate how the modular system connects with other disciplines and fits together
A code and permit review is conducted to ensure designs meet expectations	Ensure: • Standard code provisions are met • Special provisions are met	Review any specialty areas related to modular philosophies
Determination of initial temporary supporting structure with construction methods	Determine: • What needs support • How to support • When to support	Determine: • If modules will need support during fabrication, transportation and during erection
Conduct a value analysis resulting in suggestions for value improvement	Fabricator input on component options	Input from the shop fabricators and foreman for best designs
Erection planning and engineering of the structure as a whole to ensure safe and stable construction	Ensure: • Pieces can safely be erected • Stability of the structure is maintained • Any special limitations are met	Consider: • Module weight, equipment capabilities, lifting points on module, erection loads and stress in the unit

Fabrication and Construction

The modular building lifecycle of the structure continues after detailing and begins with the assembly of the modules. There are really two types of assembly, preassembly (off-site fabrication) and on-site assembly (traditional site construction). These two can be thought of as merely an extension of one another. Off-site fabrication is often referred to in the industry as Modular Construction Manufacturing (MCM). Off-site fabrication is really where the benefit of modularization is at the forefront in promotions. Expanding fabrication’s definition, it is merely a transition phase from taking the developed system and component designs from the digital world to the physical world in a plant setting. While fabricated elements can be in several forms, only the engineered-to-order types are considered in this paper.

Fabrication inherently implies there is a manufacturing of components, elements, and assemblies to a certain level before they are shipped to the site for final assembly (construction). Within fabrication there are two primary core ideas, they are: planning the production in the factory and the other is the actual production of the modular unit. The production line for making the units can take three directions:

1) All hand assembly (human workforce)
2) Fully automated (machine workforce only)
3) A hybrid of 1 and 2.

Depending on the modular units and available automated machinery, the third option is most likely. Here smaller components are machine automated then hand assembled into larger units. The production line for modular units (in particular full units) can be divided into a number of substations for different activities and different systems. The framing structure, enclosure, MEP, and finishes are the most popular unit substations. Specific sets of shop drawings and/or 3D BIM models are required for each phase and station for accurate and efficient assembly.

Once the modular unit or assembly is finished within the factory, then the construction phase starts. A major advantage with modular construction is that it takes most of the production and time away from the construction site which is often the slow unproductive activities on a daily basis. On-site placement of modules reduces the high variability in how different structural types could be constructed. Construction starts with an adjustment to the structural schedule for any delays or conditions that appear onsite or issues that occurred at the factory and were not previously accounted for.

The first actual construction task is the erection of any supporting structure that will be used to support the module(s). Often times, these are lateral systems and possibly even floor/diaphragm systems. Also, foundations need to be constructed. Once constructed, the modular units can be set into place and attached/connected to other building support systems. Any temporary structure(s) may be used during this process depending on the project and the modular conditions. With any on-site tasks there is always the inspection process and potentially requests for information (RFI) conduction occurring. Now though, the RFIs are more on how modules interact with site built portions. After module(s) are set for a particular sequence, a critical process gateway will ask if all sequences are complete. If not complete, then a cyclic loop triggered where more modules or even back to fabrication is done depending on how large the project is. The process repeats until the entire structure is constructed as planned. Achieving this, the remaining tasks that follow generate and deliver the record (as-built) model to the owner for any future use they may want including operations and maintenance. Further detail in key tasks during fabrication and construction are listed in Table 5 in relation to modularization.

With hardware and software becoming more user friendly, BIM is moving into the field permitting direct usage of the models at the site. During this entire process, BIM and other advanced technologies can be implemented to speed and refine the process. Models can be used within construction to perform the following:

1) Performing infield clash detection in regards to alternatives being erected and ensuring modules are going to fit
2) Managing the construction process of what gets done each day and track progress
3) Perform structural simulations such as settlement or movement of the modules once set
4) Coordination between the trades
5) Layout the locations for modules with GPS and surveying equipment via model referencing.

Table 5: Major Fabrication and Construction Tasks that have Significant Modular Impacts

Main Integrated Tasks	Subtasks with the Integrated	Modular Aspects of the Tasks
Determine plant production schedule and method to conform with the construction schedule	Determination optimal shipments of materials to the plant and site	Module weight Module size DOT limitations
Finalize material and resource allocation for fabrication	Allow for time to be optimized while waste is minimized based on: • Materials, layouts, and finishes Input from the erection team on: • The fabrication of elements, components, and assemblies	N/A (no specialty aspect)
Fabrication of the individual elements and components	separated by: • hand (human) and automated machine	Determine sizes of elements capable of being hand manufactured
Construction of assemblies and complex components	How sub components are assembled into the larger units	Ensure proper trade coordination when multiple systems are assembled
Recording and shipping of pieces and assemblies to the field	Track: • Elements, components, assemblies, and modules	Module weight Module size DOT limitations
In-field clash detection	Account for onsite conditions as well as for conflicts with design intent	Focus area on: • System connectivity • Modular to site built items
Manage the construction process		N/A (no specialty aspect)
Layout of the structure	Each section can be laid out with: • Appropriate tools, equipment and models	Items to layout and coordinate: • Penetrations • Connections to utilities • Connections to other systems • Corner points • Heights
The erection of any temporary supports, the structure and modules	Layout in the proper sequence the: • Structural elements • Components • Assemblies	N/A (no specialty aspect)
Inspection for errors	Appropriate tools, equipment and models	N/A (no specialty aspect)
Generation of the as-built documents	Ensure actual built conditions are modeled properly	Account for all modular components and if / how they can be serviced

MOVING FORWARD WITH PROCESSES AND SOFTWARE

The processes discussed herein support open unbounded integration between the trades such that the structural system can be as efficient as possible. Throughout this process, modular highlights and traditional methods of modular design and construction were integrated in. While the process supports modularization, detailed modular processes on the design is conducted and how technology is used is still limited. Moving forward, more detailed studies are needed to improve the processes such that it will promote and clarify modular procedures.

Support for Further Studies

New detailed processes would need to be constructed as they are critical to understanding what the proper techniques and methodologies are that directly relate to developing new modular software. Further, more detailed maps with corresponding information exchanges, model uses, and discipline interaction identification are needed at the critical phases where the software could be employed. These areas need looked at, at different project phases as a process often changes as the design becomes clearer and more evolved. Such processes with information exchanges identified are part of a study by the authors with the goal to develop a modular BIM platform. Additional support the processes may give are in helping to understand how users may interact with the software, when they would use it, and what they need to conduct work in the software. Additionally, early in the process, designs are more approximate, as such less information is attainable. This infers that the software may take different forms or menus for different stages of design.

To properly make BIM software capable of supporting designers and constructors, knowledge of information usage is needed. Modular information was touched on earlier yet these identified instances are merely a few of what the program needs to know for the different stages of the lifecycle. Information that is used, stored, and generated has to be defined to ensure the software generates it, accepts it, and can store it. This could relate to an extended creation of a Level of Development (LOD) requirements defined by the NBIMS for modularization. The current LOD standard being researched, with intent to be in the next NBIMS, does not look at modular construction as they are focusing on conventional systems.

SUMMARY AND CONCLUDING REMARKS

The process to plan, design and construct a building is a complex endeavor that takes many skilled participants. Structurally speaking, the process has a natural evolution in the design but there remain barriers to adopt integrated practices and larger scale modularization concepts. Described in this paper is an integrated process that deploys BIM based technology to support collaboration. Locations where modularization should be considered and how it fits within an integrated process were identified. Modular concepts and schemes must be considered early before the form of the building is finalized or else the opportunities quickly become limited. From here, close collaboration is needed between the structural systems within the module and those secondary supporting systems to ensure stability, integrity, and functionality of the structural system is upheld. With the size and function between the two being different often the module design progresses faster and detailing of members and connections can be done earlier. Fabrication and construction are similar to current practices but now more work is shifted to a factory that can be automated and/or manned by human workforce.

A BIM based process for modular design has more advantages than simply guiding a firm or project team. When properly constructed, it allows programmers to follow the process to develop interoperable software capable of linking software together. This is critical for modular construction as no good mainstream tools exist currently and is the direction of a current study by the authors.

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