Workflow for Modeling Prefabricated Building Assemblies in Autodesk Revit

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In 2008, by request of the National Institute of Standards and Technology (NIST), the National Research Council (NRC) put together a committee of experts to advise a plan that would advance the "competitiveness and productivity of U.S. construction industry in the next 20 years." Two of those recommendations included the widespread deployment of building information modeling (BIM) and greater use of prefabrication, preassembly, modularization, and off-site fabrication techniques. Case studies on the subject overwhelmingly report faster project delivery, improved quality, and safer working conditions. However, current data indicates that labor productivity has still been significantly lacking, perhaps showing that investment and research in this area have been slow to develop. Barriers include lack of cooperation among teams, late design changes, and other coordination issues. This project addresses these barriers as a practical problem presented by two case studies and provides a flexible solution to both design issues with a plugin to the collaboration tool, Autodesk Revit©. The result is a software tool that alleviates feasibility issues, including pre-construction time, construction tolerances, design complexity, and flexibility, when implementing modular prefabrication on construction projects for integrated project delivery and design bid build.

Keywords: Modular Construction, Revit, BIM, Prefabrication

Introduction

The industrialization of the construction industry has been underway since the early 1900s, making headway in Europe and Japan before reaching the United States. At the time, prefabrication of construction elements had been explored as a strategy for increasing productivity and the speed of delivery, based on cues taken from previous developments in manufacturing. However, the adoption of these new processes into existing building paradigms has developed quite slowly and research into the merits of modular prefabrication specifically, however positive, have been sparse. The knowledge that has been acquired widely suggest that economic conditions have made it necessary for builders and designers to innovate how buildings are produced if the AEC industry as a whole is going to sustain viable levels of productivity and competitiveness.

Background

In 2008, by request of the National Institute of Standards and Technology (NIST), the National Research Council (NRC) put together a committee of experts to advise a plan that would advance the "competitiveness and productivity of U.S. construction industry in the next 20 years" (Smith, 2010). This was a move happening in due time as Smith also reports that the years leading up to the committee formation saw a construction industry operating with woefully low returns on investment despite being a significant portion of U.S. expenditure at $1.3 trillion, more than double the next developed country, Japan. While some studies disagree on whether the causal factor trends up (Sveikauskas, Rowe, Mildenberger, Price, & Young, 2016) or down (Teicholz, 2013) year over year, stagnant growth in labor productivity is cited as accounting for these small margins relative to other industries that have doubled in growth over the past half-century. The NRC committee came up with five recommendations to address this issue:

1. Widespread deployment and use of interoperable technology applications, also called building information modeling (BIM),

2. Improved jobsite efficiency through more effective interfacing of people, processes, materials, equipment, and information (lean construction and integrated practice),
3. Greater use of prefabrication, preassembly, modularization, and off-site fabrication techniques and processes,
4. Innovative, widespread use of demonstration installations, and
5. Effective performance measurement to drive efficiency and support innovation. (Smith, 2010)

It should be noted that these strategies will likely go hand in hand on the way to achieving higher rates of productivity. The real utility of BIM tools is being able to visualize the building at different levels of detail or stages in interoperable model space for all relevant stakeholders to glean information. This encourages input from owners, architects, engineers, and contractors early and throughout the design process. More collaborative project organizations, such as those with integrated project delivery (IPD), provide the contractual framework for this proposed method. And adopting an integrated approach to projects makes innovative construction processes more feasible, including prefabrication, modularization, and mass customization.

It should also be noted that the NRC committee recommendations have come years before more current data, mentioned above, indicating that labor productivity has still been significantly lacking, perhaps showing that investment and research into these strategies have been slow to come to fruition. Among 10 top tier construction related journals, there were 12,653 articles published between 2000 and 2013, only 100 of which addressed issues related to prefabrication (Li, Shen, and Xue, 2014). Of the 100 articles, research of prefabrication in the private sector and on residential buildings, which makes up a sizeable portion of projects, is particularly lacking. This suggests there are still significant barriers to implementing prefabrication processes, especially modularization. Based on industry surveys of individuals from a dozen or so companies, current challenges to modular prefabrication specifically include a lack of cooperation as most cited (47%) and transportation and logistical issues with special concern for the proximity of the manufacturing facility (41%); additionally, lack of knowledge on modular prefabrication processes among building officials, late design changes, and adversarial relationships between designers and contractors pose potential obstacles for implementing modular prefabrication (Lee and Kim, 2018).

For the purpose and scope of this paper, two recommendations will be addressed in more detail: building information modeling and prefabrication. Academics from Poznan University of Technology define BIM "as the process to generate and manage the digital representations of physical and functional characteristics of places. Building information models are files… which can be extracted, exchanged or networked to support decision-making with regard to a building or other built asset" (Bonenberg, Wei, & Zhou, 2018). They go on to define prefabrication as the process of manufacturing building components into assemblies or sub-assemblies at an off-site factory or other industrial facility, and then transporting the complete components to the construction site to be installed. In an industry environment poised to benefit from new delivery methods and processes, prefabrication provides a promising area to increase productivity while BIM provides the tools facilitating the collaboration necessary to successfully execute this goal. Some professionals posit that the industry eventually needs to move beyond the mentality of mass production of standardized assembly line projects based on economies of means and move toward a mentality of mass customization, enabled by the use of "digital information to automate machines for infinitely diverse outputs" (Smith, 2010). The merits of modular prefabrication present a compelling area of development to answer this call.

Modular Prefabrication

Modular prefabrication distinguishes itself from conventional prefabrication practices as it involves manufacturing virtually finished volumes of the building off-site (versus solely single-system or trade specific assemblies) to be slotted into place on the project site. As they are traditionally delivered, projects often contain about 10% prefabricated or modulated building components, whereas a modular procurement approach calls for over 80% of the project to be modulated. This includes "modular roof trusses, precast concrete floor slabs and walls, composite claddings, premanufactured linear or planar structural systems, fully panelized structural systems, volumetric modular stairs, and units and pods" (Sharafi, et al., 2018). Overwhelmingly, much of the literature we have on

modular prefabrication from studies in the US, England, Australia, Canada, and Hong Kong cite decreased schedule durations, lead times, project costs, risk, site traffic, construction waste, and increased quality and safety as benefits to implementing modular construction, albeit in case dependent situations (Said, Ali, & Alshehri, 2014). The best opportunities to implement modular prefabrication is early in the project design phase and with an integrated approach, ideally supplemented by BIM tools that can resolve the complex nature of modern construction. In this way, project teams can avoid some of the conditions that can make modular prefabrication unfeasible, such as frequent and/or late design changes.

Based on multicriteria decision analysis performed at Western Sydney University, industry respondents notably preferred modular prefabrication over conventional construction methods in situations where quality, safety, construction completion time, vulnerability to weather, waste generation, disturbance on the job site, and sustainability are principal concerns as mentioned previously (Sharafi, et al., 2018). Additionally, level of MEP coordination, repetitive/standardized components, ease of implementation of planning and engineering details, reusability of materials and components, design predictability, and ease of fabrication are all criteria where modular prefabrication is deemed superior to conventional methods. However, several other factors still make implementing modulation difficult compared to conventional construction, including controllable construction tolerances as the most notable, availability of standard system processes, the role of structural performance in system, pre-construction time, complexity of design, low design flexibility, ease of delivery/supply on site, and job site maneuverability. In summary, modular prefabrication is often superior to conventional methods when considering quality and safety, substantially superior when considering productivity and sustainability, but considerably hindered against constructability, logistics, and ease of design.

Methodology

This paper seeks a software-based solution to the practical problem constraints on construction tolerances, standard system processes, pre-construction time, and complexity of design present when implementing modular prefabrication on projects by analyzing two cases. In order to assess the utility and flexibility of the solution in differing procurement environments, the case studies are sampled at opposite ends of the collaborative spectrum: one traditionally bid, while the other took an integrated approach. The case studies also provide examples of how some project teams are addressing the challenge of implementing modular prefabrication. Using the decision making analysis criteria defined by Sharafi et al., the particular feasibility issues affecting each case study will be identified, and a software solution derived to augment the feasibility of using modular prefabrication. We will then analyze how the base software was used to natively address the feasibility issues. The utility of the Revit tool will be assessed by how thoroughly the constraints are potentially alleviated from its use.

Case 1

The first case details the Good Samaritan Regional Health Center in Mt. Vernon, IL, a full-service, state of the art healthcare facility. At 382,000-square feet on a 55-acre site, this project comes in at 131,306 man hours (Lightfoot, 2014). The general contractor attached to the project was McCarthy Building Companies, Inc as the CM at risk, and who was also responsible for pitching the adoption of modular prefabrication to the owner and subsequently leading the coordination once the owner was on board. Ultimately, the project team attributed the ~$350,000 cost savings, nine-week reduction in the schedule, and a 30% reduction in incident rates to the decision to modulate the project. Under a design-bid-build intended delivery, the design was finalized with the owner in 2006 without the initial intention to utilize modular prefabrication. This was cited as a challenge by the virtual design and construction (VDC) team. Because the design was already finalized there was a constraint by the owner not to have significant details of the design manipulated causing inflexibility in the design. This inflexibility also caused construction tolerance issues that limited the opportunities to modulate the project to the patient bathrooms and headwalls. Additionally, there wasn't a standard process adopted by the project team to address situations where they would need to adapt modular prefabrication on a rigid, existing design.

In order to address the challenges mentioned above, McCarthy implemented a 4 step process: "Assess the project for opportunities and enhancements; build the components as specified for efficient install; transport the units to the

jobsite; and install them." While this process did yield opportunities for modulation and ultimately improved schedule, cost, and safety outcomes, it fell short of significantly lessening the feasibility issues associated with its implementation. Having admitted that they would have seen more savings if they found more opportunities to modulate indicates a shortfall in developing mitigating design strategies, such as structural elements that would have alleviated the construction tolerances while not disturbing the integrity of the design. A more ideal solution to the process they implement needs to make scrutiny of existing repetitive elements more accessible.

Case 2

The second case involves the Stavanger University Hospital (SUS 2023) in Norway comprising 100,000 m^2 to be completed in 2023. This was an integrated project (IDP) employing two architecture firms (Nordic Office of Architecture and AART), two structural firms (COWI and Aas Jakobsen), and landscape architect (SLA) (White and Tungland, 2017). The collaboration began early in the design phase with ambitious intentions of implementing modular prefabrication using Revit as their collaborative BIM tool from inception. As the project is still in the beginnings of development, there aren't accessible quantitative metrics assessing the project's productivity as of yet but there are explanatory and qualitative details of the project that can be assessed.

As an overall improvement over Good Samaritan, the Scandinavian project team formulated a design strategy that could evolve in different stages of the design as stakeholders provided input, drastically improving the flexibility in their design. They used a "potentials map" design process where different elements in the design were populated and rated on their repetition and limitations (such as undesirable structural visibility, code requirements, and transportation restrictions). This not only allowed the team to modulate the bathrooms, but also penalize the patient rooms, portions of the facade, and various other interior elements. Once elements were selected for modularization the strategy shifted to industrializing the BIM model by taking advantage of duplication and aligning output with information demands.

Although there were significant improvements to the management of BIM information there are still limitations in the implementation strategy where feasibility issues persist. The way that their process is moving through the model space does not detail a specific structural system or lattice for connecting the modules and panels which will likely lead to the same construction tolerance issues that exist in the Good Samaritan project. This process has also inadvertently taken on new feasibility issues. The tools they use to 'instance' the modules into place rendered them strictly static, making manipulation or rotation difficult in the case of design changes. A more feasible alternative software solution would retain flexibility in the case of design changes and also be adaptable to additional systems that would support more options to modulate across the building schedule.

Solution

The software tool proposed by this paper aims to address the feasibility issues left in the processes of each case study by adding a function to Revit that can detect and quantify opportunities to modulate various building components, and then be able to copy instances of components throughout the model. Automating the detection of repetitive components enables project teams to study opportunities faster and have more readily available information on the constructability, as parameters relevant to mass producing modules will be more accessible (net weight, volume, etc.). McCarthy could have benefitted from this prescription for by being able to present to the owner savings across the entire project and not limited to the patient bathrooms and headwalls.

While the SUS 2023 project solved McCarthy's modular problem by pursuing IDP and requiring early input from relevant stakeholders, their decision to operate with referenced copies of the modules and not copies instanced natively within the model, caused design flexibility issues. A more flexible solution would require the option for modules to be detached from their instance and individually manipulated should conditions require it, including changes in the field, positioning of MEP elements, design changes, etc.
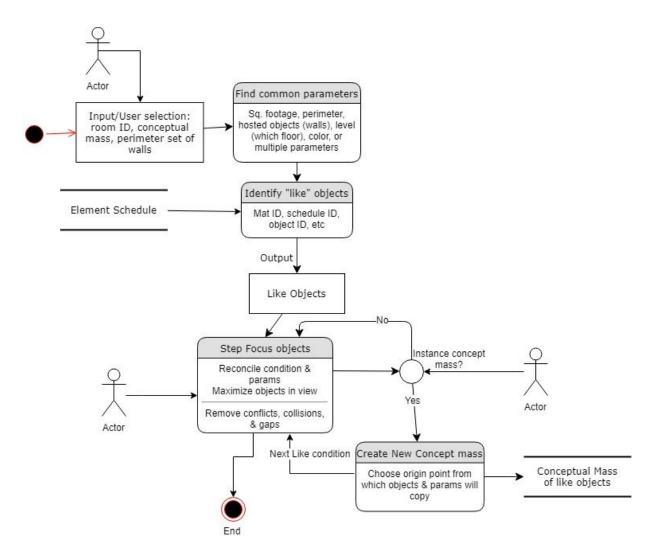
Figure 1: Code outline for instance copy tool.

Instance Copy Tool Description

The above software diagram presents a solution, in the form of a Revit collaboration tool plugin, that addresses the feasibility issues presented by Case studies 1 and 2. It does this by analyzing an element of the model selected by the user and comparing that selected element to the entire element schedule, looking for similarities in object characteristics. Of particular note is the tool's ability to target conceptual mass objects' commonalities so the tool can support several delivery methods.

The tools workflow consists of finding "like" objects based on user selection and object parameters, showing the user opportunities for modularization, and prompting the user to make a new conceptual mass instance out of similar objects. This process is encompassed in the contents of each box in Figure 1. The tool defines "like" objects as those objects whose parameters are within a user-configurable range. A user can choose which parameters to match on as well. Once these parameters are configured and an element is selected to be compared against, that element will be the basis for a new conceptual mass. The tool will then take the user through each element that has the potential for modularization. All elements selected for modularization will then have their parameters changed to match the conceptual mass. This will have several effects on the model. For instance, Walls that aren't room specific are going to be cut based on where edges of the mass hit walls. The tool also deletes all existing objects that collide with the

conceptual mass before copying objects in place. Lastly the tool will schedule the new module (hosted objects in dropdowns).

Conclusion and Discussion

Due to the lag the construction industry has experienced over the past decades in productivity growth compared to other industries, it's clear that effort and research need to be directed at developing new technologies and strategies for implementing them. Modular prefabrication offers an appealing step in the right direction as the potential for cost, schedule, quality, and safety savings and new efficiencies are clear. However, for many projects, feasibility issues still exist, often hindering its adoption in the delivery strategies of many decision makers. As representative examples, the Good Samaritan Hospital and SUS 2023 projects were still met with feasibility issues that hindered the implementation of modular prefabrication across the project. Like other firms engaging in this construction method, the project teams faced building tolerance constraints, constructability related problems, not having a standard process for implementing systems, design complexity, and design inflexibility.

To alleviate some of the feasibility issues experienced by the project teams, a potential software solution was sought to augment their processes as a compliment to an environment heavily relying on Revit to design their modules and arrive at their construction method. The new tool addresses their feasibility issues by automatically detecting opportunities for modulation based on the repetition of similarly represented objects and duplicating them across the model space. At the same time, the model retains flexibility by making each model interoperable rather than static to increase capabilities to collaborate.

While this tool is tailored more toward feasibility issues that have to do with representation and information sharing, there are still significant feasibility issues that cannot be readily alleviated with it. This includes the physical and logistical challenges involved with transportation constraints, the maneuverability of modules once on site and especially if the job site is limited on space, and the availability of skilled tradesmen able to perform the work. Additionally, the availability of structural prefabricated systems is limited as they often require new and costly permitting and approval from municipalities (Sharafi et al. 2018).

It should be reiterated that studies on the economic performance of modular prefabrication are limited and this would be an apt area of investment for the industry. Many companies already prefabricate some portion of the project, especially among trades. Modular prefabrication, especially if it can be directed to achieve mass customization would be the ideal next step forward. At the same time, more companies are going to have to place themselves at some risk in order to advance modular prefabrication. The present moment doesn't quite offer the same returns to projects like Good Samaritan as there may not be as much repetition in a lecture hall, museum, etc. There also needs to be more studies done on how modular prefabrication can be implemented on high-rises; residential buildings have an ample amount of repetition to theoretically make modular prefabrication feasible on such a project. Overall, we need more research and comparative studies on modular prefabrication.

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