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BIM AND LEAN IN THE DESIGN-PRODUCTION INTERFACE OF ETO COMPONENTS IN COMPLEX PROJECTS

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ABSTRACT

This paper presents a case study on a complex construction project that demanded a great level of prefabrication in order to meet a fast schedule and to overcome logistical challenges. The study was carried out with a mechanical contractor firm developing a series of Engineered-to-Order (ETO) components for the project. The objective of the research was to study the possibility of devising an integrated approach for production planning and control for this ETO environment. Two papers report on this research. The first one describes the methods used to plan in an integrated manner the prefabrication, delivery, and installation of ETO components at the job site. This second one discusses the use of BIM to support such integrated management and the challenges faced during its implementation. Finally, the paper describes how the team used lean construction principles to overcome some of these challenges. The contributions of this paper include, first, articulating challenges faced when using BIM on a complex project as a support to managerial practices and, second, illustrating the use of lean principles in the design-production interface as a means of leveraging BIM.

KEYWORDS

Building information modeling (BIM), complex projects, design-production interface, engineered to order (ETO), industrialization, production planning and control.

INTRODUCTION

Some construction projects present a high level of complexity as they are one-of-a kind products requiring multidisciplinary design and involvement of numerous parties in their supply chain. Demand for fast delivery and the logistical challenges associated with that demand contribute to increasingly larger proportions of

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building's components being fabricated and preassembled offsite (e.g., Eastman, et al., 2008). Often, these one-of-a-kind projects require customized design and fabrication of Engineered-to-Order (ETO) components. Unlike off-the-shelf parts being mass-produced, ETO components demand sophisticated engineering and careful collaboration between designers, fabricators, and installers. The design of such components also requires different disciplines to work together to ensure that the building systems are properly integrated and installed. The environment in which ETO components are produced comprises of a series of production units, i.e., design, fabrication, and installation. These different production units need to be integrated so that they will deliver the desired value while avoiding waste and rework: the right components need to engineered, fabricated, and available for installation at the time they are needed at the construction site. The importance of developing a so-integrated production planning and control system for ETO environments has been emphasized in previous research (Little, et al., 2000), however, the challenges encountered in this specific context are yet not fully understood (Viana, 2015).

The research presented here focuses on analysing the challenges of managing ETO components used in a complex and particularly fast-paced construction project. The study was conducted in partnership between the Project Production Systems Laboratory (P2SL) at UC Berkeley in the US, NORIE at the Federal University of Rio Grande do Sul in Brazil, and Superior Air Handling, a US mechanical contractor specialized in the market niche of complex construction projects. The objective of the research was to study the possibility of devising an integrated approach for production planning and control for the different ETO components under the mechanical contractor's scope. Two papers report on this research. The first paper (Viana, et al., 2015) describes the approach used to integrate the prefabrication, delivery, and installation of ETO components at the job site. This second paper discusses the challenges faced in the design-production interface and the role of the use of BIM combined with the adoption of lean principles to support that transition.

DESIGN-PRODUCTION INTERFACE OF ETO COMPONENTS

Bertrand and Muntslag (1993) describe the production environment of ETO components based on three aspects: dynamics, uncertainty and complexity. Although they adopt the perspective of companies that manufacture ETO components, past research in lean construction has used such framework to understand the challenges of managing ETO in the context of construction projects. Viana (2015) demonstrated that vast amounts of waste (i.e., waiting time and rework) get generated when fabrication and site installation are not managed using an integrated production planning and control system. Sacks, Akinci and Ergen (2003) emphasize the importance of exchanging real time information between installation and fabrication; furthermore Tommelein (1998) stresses the importance of establishing a pull system to control production. Within this context, the importance of managing the design phase of ETO is highlighted in the literature (Bertrand and Muntslag, 1993) especially because uncertainty inherent in the design phase hinders the ability to predict the overall lead times of these components.

Little empirical evidence was found to understand the challenges faced in this less tangible phase and what kind of managerial mechanisms can support the design-production interface of ETO components. Nevertheless, two potential managerial solutions were identified in the literature: BIM and the adoption of lean principles. Eastman, et al. (2008) advocate that BIM can help transition ETO components from design to production as it allows for rapidly verifying constructability and coordinating all building systems prior to producing each piece. The benefits of fabricators and subcontractors using BIM include, e.g., use of standard components and details; automated estimating; reduced cycle times for detailed design and production; elimination of design coordination errors; lower engineering and detailing costs; data to drive automated manufacturing technologies; and improved preassembly and prefabrication.

In addition, different authors stress the need to manage the design process in order to start the production phase successfully. Koskela, Ballard and Tanhuanpää (1997) argued that even when there is an optimal sequence of design tasks, internal and external uncertainties tend to push the design process away from that optimal sequence, leading to low productivity, prolonged duration and decreased value of design solution. They presented two methods to support design management, (1) the Design Structure Matrix (DSM) and (2) the Last Planner System (LPS), and they experimented with both in practice to support design management. However, regarding the combination of BIM with lean principles to manage design, we found evidence only about the use of some components of LPS and BIM in Khanzode, et al. (2006) and Khanzode (2010). Khanzode (2010) presented different case studies in which some components of the LPS were adopted to support BIM coordination with MEP subcontractors. Nonetheless, despite presenting empirical evidence, Khanzode mentions little about the complexity and uncertainty of the studied projects and no studies were found specifically about ETO environments.

EMPIRICAL STUDY

The analysed construction project is a large commercial building of approximately 300.000 m2 to be built in 3 years. Due to the fast pace of construction, the project demanded a high level of prefabrication. For the mechanical contractor, whose fabrication facility is located out-of-state, that meant establishing partnerships with local fabricators to meet the site demand. The responsibilities of the mechanical contractor included: review engineering drawings, submit equipment for approval, coordinate engineered components with other building systems, fabricate, manage the delivery and execute the installation. The first two authors’ role in the project was to support the mechanical contractor’s team with the implementation of the LPS to transition from the design revision phase to the fabrication- and installation phases. That effort started in March 2014, and in mid-August 2014 the joint effort involving the aforementioned research laboratories was initiated to investigate the opportunities of using an integrated management approach for the ETO components.

Data was collected over the course of 1 year to understand the activities and challenges related with the transitioning stage from design to production of ETO components. One important source of evidence was a series of interviews with team members and analysis of project documentation, especially related to the mechanisms used to support the transition from design to production, e.g., BIM and lean managerial techniques. Another important source of evidence was the participation of the researchers in meetings. Those meetings included: (a) project meetings, i.e., model coordination meetings, pull planning sessions, meetings to review issued design changes; (b) meetings with fabricators, i.e., co-design meetings, preparation for fabrication meetings, prototyping and testing; and (c) internal company meetings, i.e., production planning, LPS meetings and meetings to status internal progress.

CHALLENGES IDENTIFIED

The analyzed project presented a high level of dynamicity, uncertainty, and complexity, as defined in Bertrand and Muntslag (1993). The observed sources of dynamicity related mainly to a phased approach used by the owner to procure the project and the need for the mechanical contractor to cope with increased demand of additional scope if and when selected to build other project phases. The observed sources of complexity were myriad; however, the most evident was the involvement of an intricate supply chain to produce each ETO component. Such complexity can be exemplified, e.g., with the installation of control devices by another trade during the fabrication of the components, and with the combined electrical and mechanical racks that required close collaboration between these different subcontractors upfront to allow for their design and prefabrication. Finally, uncertainty was a major challenge to the successful installation of ETO components in the project. Two major sources of uncertainty were observed: (a) fragmentation in the procurement of design and installation; and (b) frequency and scope of design changes. The latter two sources are further discussed in the following paragraphs.

Figure 1 charts a timeline with design changes and the contractual situation of the mechanical contractor, reflecting the uncertainty during that period. The mechanical contractor held a design-assist type of contract as of April 2013. Around October 2014, the Guaranteed Maximum Price (GMP) for installation started to be negotiated. Some of the ETO items needed to be installed while the contract scope was still being negotiated and before the final contract was signed. The chart also shows an analysis of design changes that happened during that period. Data was collected until March 2015. Since the contract for pre-construction services was signed in April 2013 until March 2015 (last available data) 86 changes were issued to the bid set drawings, affecting the mechanical components. While some design changes were owner-driven changes in program and scope, others stemmed from to the need of further design clarification in a specific area, and were triggered by the General Contractor (GC), architects, engineers or subcontractors evaluating the constructability of the design bid set.

Uncertainty in design was also a consequence of different subcontractors joining the project in different times. Two problems were observed: (a) when the detailing team of a specific discipline was not yet in the project to participate in modelling coordination; (b) when the detailing team was in the project but no installation contractor was on board to verify if the design was constructible. As a result, placeholders with estimated dimensions were allocated in the model whenever detailing teams were not on board and detailed design would be verified only later by installers. This caused a delay in finalizing model coordination and resulted in a high level of rework. On a few occasions, problems were faced during field installation, when fabrication drawings were released early due to time compression without being fully coordinated and verified.

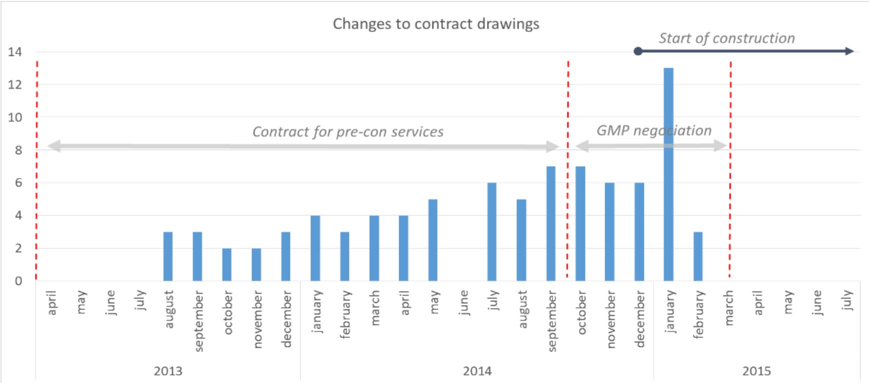

Figure 1: Design changes issued from bid set to GMP negotiation

For the mechanical contractor, uncertainty in the design phase related to scope changes resulted in an extended speculation period with fabricators, and delayed decisions on fabrication strategies. Staying too long in the speculation phase and accordingly pushing the firming-up of fabrication contracts (too) close to installation could also raise threats of increased costs for raw material and of challenges in qualifying the additional workforce needed to fabricate the components in a short lead time. Even when design changes did not cause scope changes, they represented a challenge for planning and producing ETO components. Figure 2 demonstrates that design changes may compress the time available to produce these components. The chart presents the total lead time to take one of the components from detailed design to installation. When the expected time for design completion gets delayed, it pushes forward all the predecessor activities preceding installation. If the installation date remains the same, that schedule compression can undermine important activities between these two phases, i.e., testing, prototyping, prefabrication, and constructability assessment.

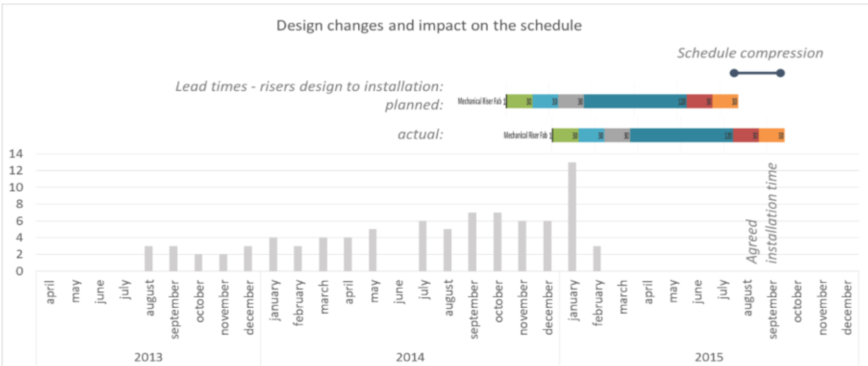

Figure 2: Design changes and impact on time to deliver ETO component

Figure 3 details the process taking issued design changes to the point of generating fabrication drawings. It was observed that not only activities have a long or unknown duration, but also they can be repeated several times. This makes it very difficult to predict when a design will be finished and fabrication drawings can be released. Especially when project participants are located in different parts of the world, the return time for answers and approvals can be even longer. In addition to that, owners' involvement in the selection and approval of material and equipment suppliers can also bring additional complexity. Every time a change is issued, the 3D model needs to be updated and re-checked against requirements, e.g., constructability, fabrication, aesthetics, functionality, and seismic requirements. This causes a series of iterative loops that makes it difficult to track design progress towards completion and brings the threat of having a complete design only after components have already been released to fabrication based on an outdated design and/or a mismatch between design and what was installed on site. Given the high level of uncertainty and its potential impact on the successful production and installation of ETO components, the importance of monitoring possible schedule compressions and managing the design-production interface became evident. The next session presents mechanisms that were used on the project for managing the design-production interface of ETO components.

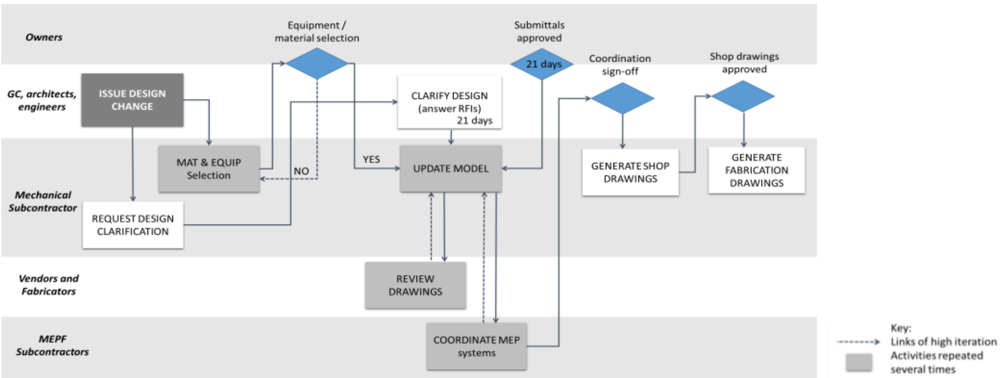

Figure 3: Process from design changes to fabrication drawings

BIM INITIATIVE

Use of the BIM model was key in supporting the transition from design to production of ETO components. BIM not only supported the team when confirming the constructability of the designed systems faster, but also refining the solutions with fabricators and storing important information that would later facilitate production planning and control.The design of ETO components required an intense iterative process of refining solutions based on ease of fabrication and degree of constructability in the field. Apart from the benefits of clash detection, the BIM model was extensively used to support production planning with other trades and the GC. The ETO components offered unique solutions developed particularly for this project and had never been installed on any project before. Being able to simulate their installation through BIM while verifying logistical challenges, interference with other building systems, available space for installation and preferred installation sequence in intricate spaces were some benefits of using BIM.

A key enabler of using the model for production planning was the familiarity of superintendents with the model, the level of detail in the model, and the availability of superintendents to participate not only in production planning meetings but also in BIM coordination meetings. BIM also enabled relevant information to be analyzed, i.e., linear meters and kilograms of sheet metal (feet and pounds) to serve the purpose of productivity tracking and cost estimating for raw materials, thereby facilitating production planning and control in the factory and during field installation. The model made it possible to extract layout points to be used in the field, automating and reducing errors in layout activities. This was possible due to the level of detail in the model, closely reflecting what was going to be built. A bar coding system was devised to track the ETO components from release to fabrication until their delivery and installation on site. This allows the mechanical contractor to track the different equipment and assemblies and it facilitates inspection for the GC.

However, we observed that not all the benefits expected from BIM could be realized, especially in regards to supporting production tracking and control. A challenge to using BIM in its fullest potential was the level of maturity of the BIM model when the team had to start fabrication. The high level of uncertainty observed in the design phase delayed the model's completion. The adoption of lean techniques supported the team to deal with this challenge, as discussed in the following section.

ADOPTION OF LEAN TECHNIQUES

Understanding the physical activities involved in the production system of ETO components was the starting point to support the management of the design-production interface. The Line Of Balance (LOB) helped to determine and visualize the pace of installation and fabrication of different components. Viana, et al. (2015) describe this topic in more detail. The calculation of lead times for producing ETO components started with understanding field demand, i.e., installation sequence and pace. Figure 4 shows the example of a specific ETO component. Each column represents a week and each line represents a different location. Installation occurs in 2 batches of 40 components, installed at a pace of 2 components per day. In order to meet that demand, prefabrication has to start 16 weeks prior to the start of installation and progress at a pace of 2 components per week.

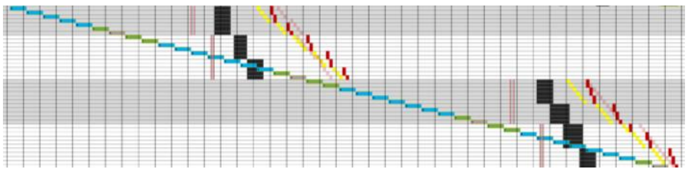

Figure 4: Visually analyzing fabrication and installation lead times

After analysing the pacing of installation and fabrication, we collected data about other activities that precede fabrication, e.g., material procurement, prototyping, and testing. The time that the factory needs to get all the raw material ordered and adjust their layout in order to meet the fabrication demand was estimated to be 6 weeks. This time includes prototyping and testing activities to identify any challenges related to logistics prior to entering full-scale production. The calculation of lead times was based on site demand, fabrication capacity, and storage availability and indicated the preferred scenario for ETO production from an economic perspective. The overall lead times for each ETO component (including fabrication, prototyping, and testing) were relayed to the GC, who incorporated this data into a tool created to support coordination efforts and identify priorities for model sign-off. Figure 5 depicts only the mechanical elements, although the tool contains information about the components from all different subcontractors.

The BIM model was composed of building geographies and those geographies in turn were divided into building blocks. The different ETO components displayed in Figure 5 were located in different blocks in the BIM model (Figure 6a) and their lead times were used to prioritize BIM coordination. A “Last Responsible Moment” (LRM) for signing-off each building block was established. This pulling mechanism based on critical fabrication lead times allowed the team to work on maturing the BIM model as much as possible without posing a risk to fabrication activities. Figure 6b illustrates that the design changes made to building blocks direct or indirectly impact the design of ETO components.

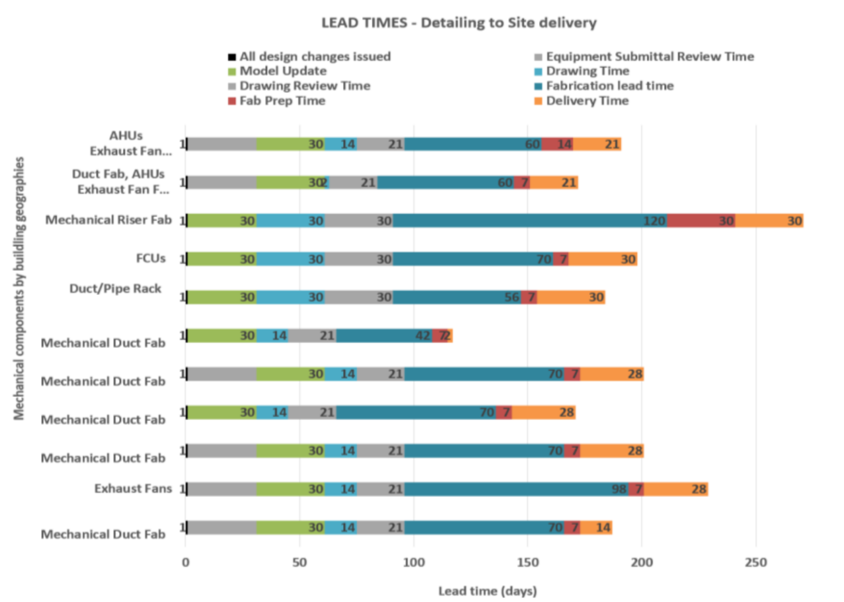

Figure 5: Mechanical components with long lead time

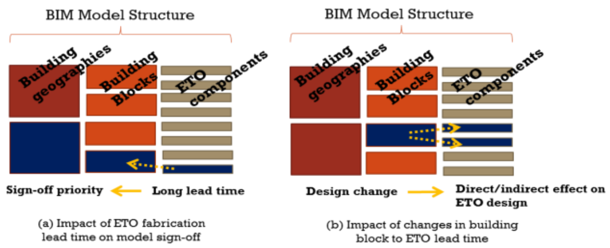

Figure 6: BIM model organization and interdependency with ETO components design

In order to mitigate such impact, the GC established a visual board demonstrating the progress of each building block towards sign-off and organized a committee for evaluating design changes. The board and the committee facilitated communication between the GC, subcontractors, and the owner. While the board had the purpose of allowing subcontractors to verify and update information about fabrication lead times, the committee played the role of communicating to the owner when and how design changes would impact cost and schedule due to late fabrication release. This understanding of impacts allowed the owner to make better decisions about desired scope changes. Also, subcontractors were able to see upfront if they would be affected by changes, so they could calculate the potential impacts and inform the GC and owner thereof. The techniques to calculate overall lead times were very beneficial to the project team and to fabricators, however, they required constant updating and verification. During the period of this study, the planned field-installation suffered some changes. As a result, priorities for fabrication and sometimes for design completion also had to be shifted. Efforts were made to keep the fabricators always up to date of the project's current situation. In this sense, by adopting the LPS internally, the mechanical contractor was able to increase the involvement of external parties in short term planning to remove design constraints and to keep track of overall progress of ETO components from design release to site delivery.

CONCLUSIONS

In this paper we investigated the topic of managing the production of ETO components on a complex project. We focused on understanding the challenges related to the design-production interface in an uncertain environment. It was observed that managing approaches for projects that use mainly ETO components need to be different from those that use off-the-shelf mass-produced components. The complexity of designing, testing, prototyping, fabricating, preassembling, and delivering these components to site poses major challenges for the successful installation of ETO components. Each ETO component offers a complex and unique solution that needs to be verified throughout the entire value stream before getting to the job site, so as to avoid mistakes that could be catastrophic. This requires a well-coordinated production system able to accommodate the participation of numerous participants in their intricate supply chain in the design and production phases, while facing high levels of design related uncertainty in the project environment.

We were able to initiate an investigation of how BIM and lean principles can support the design-production interface and help transitioning ETO components from design to production. BIM supports the fast verification of proposed design solutions and storage of information that can support fabrication and installation activities. Such fast verification was of great benefit when dealing with an uncertain environment. Lean techniques allowed for the visualization and better understanding of necessary lead times to produce ETO components, supporting increased communication among different project participants so they could produce components on time.

We observed that in order to be fully successful in an ETO environment, contractual relationships need to support the integration of design and production. However, even on a project where a fragmented approach was used for procuring design and production of certain disciplines, the combination of BIM and lean techniques were found to provide a strong basis for the collaboration required to successfully produce ETO components in uncertain environments. This paper also raises a question as to what expectations to impose on BIM initiatives. BIM can facilitate an integrated management of ETO systems but the level of detail required to support production activities needs to be planned in advance. We learned that the benefits of BIM are directly related to the level of maturity the model achieves when it is time to start fabrication. The resources required to coordinate the model should be committed to upfront and match the expectations regarding how and when BIM will support the project (e.g., to support certain activities, a greater level of model maturity is required). This topic is worth exploring in future research.

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