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GUIDELINES FOR INTEGRATED PRODUCTION CONTROL IN ENGINEER-TO-ORDER PREFABRICATED CONCRETE BUILDING SYSTEMS: PRELIMINARY RESULTS

Guillermina A. Peñaloza[1], Daniela Dietz Viana[2], Fernanda Saidelles Bataglin[3], Carlos Torres Formoso[4] and Iamara Rossi Bulhões[5]

• ABSTRACT

The use of prefabricated building systems has grown in several segments of the construction industry, especially in emerging economies, due to the need of reducing project duration and costs, improving safety, and dealing with the shortage of skilled labor. Most companies that operate in this market are engineer-to-order (ETO) organizations, in which there is a need to integrate the planning control processes concerned with design, manufacturing and site assembly. One of the approaches used to address these issues is to adopt hierarchical levels for planning and control, in which there are order confirmation points considering the lead-time of some tasks. The aim of this research project is to propose guidelines for integrated production planning and control in ETO prefabricated concrete building systems. It is based on two case studies carried out a leading company in this segment in Brazil. The research method involved interviews with different stakeholders, participant observation in planning meetings, and direct observations in two construction sites. The main contributions in this study are related to enhance the integration between plant and site assembly. Also, use of 4D BIM simulations for analysis of physical flows and evaluate and control the assembly process.

• KEYWORDS

integrated production control, prefabrication, lean construction.

[1] PhD student at NORIE/UFRGS - Built Environment Innovation Unit, Federal University of Rio Grande do Sul. Av. Osvaldo Aranha, 99. Porto Alegre, 3º andar, RS, Brazil. CEP 90035-190. +55 51 33083518 arq.guillerminapenaloza@gmail.com

[2] PhD., Researcher at NORIE/UFRGS danidietz@gmail.com

[3] M.Sc. student at NORIE/UFRGS fernanda.saidelles@gmail.com

[4] Associate Professor at NORIE /UFRGS formoso@ufrgs.br

[5] PhD., Professor at Interdisciplinary Department, Federal University of Rio Grande do Sul. Av. Osvaldo Aranha, 99. Porto Alegre, 3º andar, RS, Brazil. CEP 90035-190. +55 51 33083518 ibulhoes@yahoo.com.br

• INTRODUCTION

The use of prefabricated building systems has grown in several segments of the construction industry, especially in emerging economies, such as Brazil. This type of production system requires close coordination and synchronization between the design, manufacturing plant and construction sites, so that the assembly process is not interrupted and the level of inventories is kept low. Usually, prefabricated building systems faces a high level of uncertainty, due to the lack of predictability of the design process, long transportation distances between the manufacturing plant and construction sites, interference from previous construction stages, unreliable site installation plan, among other factors.

This production system can be defined as engineer-to-order (ETO) in which the "Customer order decoupling point" (CODP) lies in the design phase, that is, the customer order is made early in the design phase of a product (Gosling; Naim 2009). In this kind of production environment there is a strong dependence of the production system on client decisions, which might interfere even in the product specification during the fabrication process. Therefore, a major difficulty in managing engineer-to-order prefabricated building systems is to integrate planning and control of different processes, such as design, fabrication and assembly on site. ETO is characterized by low volume production, uncertainties, mix fluctuations and volume of non-standard product route, demand forecasting with low stock, high level customization, complexity, changing requirements, long lead times, flexibility and dynamism (Berkel 2010). The dynamism of the market requires flexibility of the ETO system to cope with demand fluctuations. Gosling and Naim (2009) and Little et al. (2000) mention the flexibility as a crucial factor for ETO companies. Commonly, managers set goals previously to the start of the project and controlling is limited to monitoring the progress of activities against a plan. In a highly uncertain environment, like ETO, Johnston and Brennan (1996) suggest another form of management in which managers need to learn from production to precisely define the following goals, called management-as-organising.

The potential benefits from prefabricated building systems are many and diverse (Blismas et al., 2006). For example, Zabihi et al. (2013) argued that with prefabrication, capacity and quality could be increased, while simultaneously offering more complex building components at a lower cost. Other potential improvements involve the reduction of construction waste (Lachimpadi et al., 2012) and a lower environmental impact and higher sustainability performance (Chen et al., 2010). Also, the delivery of prefabricated building systems has been seen as a means for additional productivity advancement (Jansson et al., 2013; Thuesen and Hvam, 2011). However, most implementations of Lean concepts on prefabricated systems have not explored opportunities for improving the overall system. An existing common problem is that the improvements are implemented in a specific subsystem or in a particular stage of the construction process, such as design, prefabrication or assembly.

The focus of this paper is on planning and controlling ETO prefabricated systems, in which a company is responsible for design, prefabricate and assemble components on site. The company is engaged on the implementation of some lean concepts, such as reducing batch-size, improving flows through pull production and 4D BIM simulations, increasing the product flexibility of the fabrication process to deal with uncertainties. This paper discusses the preliminary results of a research project of an on-going research project that aims to integrate design, prefabrication and assembly. This study has been developed in collaboration with a prefabricated concrete company in Brazil. A set of guidelines for devising integrated planning and control systems for ETO prefabricated concrete systems has been proposed in this paper.

• RESEARCH METHOD

Design Science Research (DSR), also known as constructive research, was the methodological approach adopted in this study. It is a way of producing scientific knowledge that involves the development of an innovative artifact to solve a practical problem, and simultaneously makes a kind of prescriptive scientific contribution (Holmstrom et al., 2009).

The research process was divided into two phases. The first consists of identifying and understanding a practical problem in the company, while the second is concerned with devising and implementing a solution. Finally, the applicability of the solution will be analyzed, and the relations to existing theoretical knowledge will be examined. There was participation and involvement of various sectors of the company. The sources of evidence used in this study was semi structured interviews with the different stakeholders, document analysis, participant observations in planning meetings with members of the construction company and the prefabricate contractor, direct observations in two construction sites, analysis of existing databases and workshops. Five semi structured interviews were carried out in Porto Alegre, where the construction sites were located. The interviewees were engineers responsible for the construction, assembly responsible and safety technician. Another seven semi structured interviews were realized in the company headquarters in Curitiba, and there were interviewed responsible from different sectors such as planning, design, expedition, quality, occupational safety and health, budget and research and development . The interviews were recorded and lasted an average of one hour.

Direct observations and case studies were carried out in Porto Alegre. Along a month were made six visits in a construction site in which the partner company was responsible for the design, production and assembly of structural components of a shopping mall. Three researchers collected data such as cycle time of piles, slabs and beams, work daily information, schedule and reports of security. The purpose of these visits was to carry out an exploratory diagnosis to understand the processes between plant and assembly as well as the problems and constraints that arose at the construction site. After diagnosis four researchers were involved from the beginning in a construction site where the partner company was responsible of the design, production and assembly of structural components of a university building. From August 2015 until February 2016 weekly meetings were carried out with the engineer responsible for the assembly on site. In this case efforts were performed to implement improvements.

Also, three workshops involving the research team and company's representatives were carried out to create a discussion group in order to provide a common understanding of concepts and practices. It was discussed some key lean concepts such as work in progress, size batch and continuous flow as well as diagnosis carried out in the visited construction site and some improvement opportunities were suggested.

• DESCRIPTION OF THE COMPANY

The company is a large fabricator and assembler of precast concrete in Brazil. It has more than 1.500 employees and four manufacturing plants. The businesses are basically carried out in two main business units: (i) commercial sales, which are sold standard products that always exist in the stock such as slabs, piles, tiles and panels; and (ii) global enterprise, when a whole new project, with customized components is requested. Those projects can be from different segments such as shopping malls, supermarkets, shops, sheds, vertical buildings and special constructions. This latter business is focused on engineer-to-order (ETO) products, while commercial sales on make-to-stock (MTS) products. This study is focused on the operations of the global enterprise business unit, in which projects are unique, designed with the client in order to meet specific requests.

Besides the fabrication of the structural components, the company also develops the structural design of the project, and makes the assembly on the site, as required by the client. The organizational structure is hierarchically organized, so for each unit there is a manager who leads a team and keeps constant feedback to the headquarters in Curitiba. Currently, the company intends to improve its methods and concepts for managing the production system as whole. For this reason, a new department called Integrated Planning has been created in order to achieve better integration among design, fabrication, and assembly on site. One of the first improvement efforts was to divide the delivery of the project in smaller batches. In this idea, the different production phases should deliver part of the project to the next phase, according to this batch. After the outline design, the project should be detailed in batches according to the needs of the construction site. However, until this moment this idea has not been fully implemented.

The purpose of this division was not only for controlling the assembly process, but also for controlling the design and fabrication processes, based on the benefits of reducing batch size. The challenge of this implementation process is explained in the next section.

• DESCRIPTION OF THE EXISTING PLANNING AND CONTROL SYSTEM

By dividing projects into stages, it is assumed that the company would not produce all the products at once, emphasizing the importance finalizing a batch, or stage, before moving to the next. Though the company's intention is to base design, production and assembly control on those stages, each unit had a different focus.

In design, the implementation of controls based on stages is still a challenge. Firstly, the project outline has to be designed as a whole. After customer approval, the project is divided into batches for detailing of parts according to the assembly sequence. In many cases the project combines construction technologies, such as metallic or molded in place structure which need to be defined by others. This process is often time consuming, making it common for the detailing to start the project by the easiest parts, which has no critical interdependencies with other technologies, or that has been already defined by the customer. This implies in production out of sequence, generating inventories in the plant yard.

The focus of the manufacturing plant is to use the maximum capacity, producing in large batches to better utilize the molds. The disadvantage of this process is the programming and production of parts belonging to subsequent stages and often undefined by the customer. As a result they end up generating a lot of stock in the plant yard.

At the construction site, the assembly process needs to fit into the requirement of the construction site. The division in stages in this case helped in controlling the parts for assembly, but the division in large batches do not allowed to give flexibility for some challenges that are presented, such as uncertainties or changes in the project by the customer, change of sequence assembly due to problems in the production or at the request of the contracting company, and was difficult to be able to view a particular sequence.

• RESULTS

After the assessing the existing system, the main focus of the implementation process was to develop and propose improvements in the planning and control system of the company. The lack of synchronization between planning department, production and logistics units, and assembly in site construction lead to a preliminary set of guidelines that was established for guiding this implementation process. Those guidelines aim to integrate and promote collaboration between sectors in order to generate stability in the workflow and enhanced the feedback. These are presented below.

• ALIGNING FABRICATION AND SITE ASSEMBLY RHYTHMS

The prefabrication process is often desynchronized from the assembly process on the site. In the analyzed company, each component would take around three to four weeks to be fabricated. The scheduling of the plant is set two weeks in advance, which means that throughput time inside the plant is one week.

The time required for erecting a pillar on the site, for example, takes less than an hour, which is one of the longest site processes. This uneven peculiarity of the production process is often workaround through the use of high levels of inventory after fabrication. Inventory means longer throughput times, and, in this kind of environment in which there is uncertainty in design specification, is very risky to produce in advance. In both of the analyzed cases, the overlapping between detailing design and the assembly process was common. Those components under discussion were left aside while the ones with no issues were produced regardless the assembly sequence. This was one of the difficulties for implementing the control in batches.

In order to better synchronize the production, the plant needs to fabricate components at the last responsible moment to deliver to the site, giving enough time for the detailing decisions to be taken, and still delivering on time at the site. The mismatch between fabrication and assembly has to be considered together with the plant capacity and the amount of construction sites carried out at the same time. The discrepancy in rhythms, or the production takt time, is what will reveal the need for inventory or not.

The second case had a long process of design compatibility, which delayed the detailing and hence the fabrication process, affecting the site assembly. However, during the second stage of production, a decrease in the demand for components from other sites enabled the scheduling department to dedicate one of the plants for the site under analysis. At that moment, most of the components were produced, but still before it was really required by the site. The scheduling department was planning the plant based on the predicted site demands from the master schedule. The event revealed that fabrication and site assembly could be better connected, but there was a need to understand the real demand from the site, so that the plant could be flexible to attend site needs and still having a good utilization of capacity. The need of this confirmed demand leads to the second guideline.

- **ENHANCE THE INTEGRATION BETWEEN PLANT AND SITE ASSEMBLY THROUGH A LOOK AHEAD OF THE DELIVERY SEQUENCE**

The use of an ETO approach in the construction leads to an important constraint: the logistic process. The precast concrete has some peculiar characteristics as a product. It is configured by heavy components and a relative small number of components: a four-pavement pillar is one component, a beam is one component. For this reason, an important tool for integrating plant and site assembly is the transportation batches, which were defined by the site manager through a loading plan. The loading plan describes what should go in the truck, and when it should arrive in the site. It was related to the sequence of components required, and to the truck capacity. This tool was already been used by the company when the study started. However, during the first case, the site manager would send the loading plans only to the expedition department, two days before it was required. It means that the loading plans had to be based on the produced components and had no impact on the production sequence. This problem was leading to a high level of work-in-progress, as shown in Figure 26.

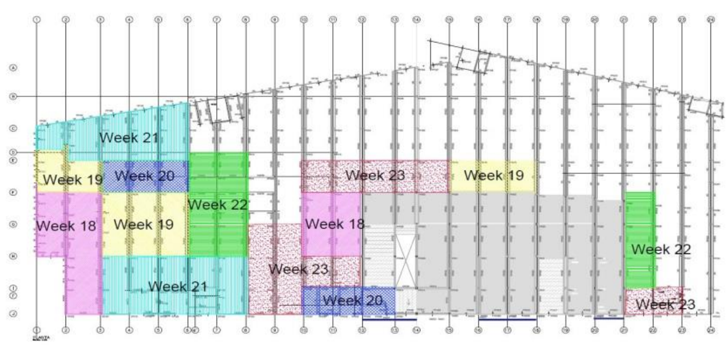

Figure 26: Execution sequence of the first case

During the second case, the researchers suggested a longer horizon of loading plans, which should be sent to the scheduling department, instead of going directly to the expedition. The scheduling department could make the plans according to a confirmed demand from the construction sites, rather than the early-defined master schedule. Figure 27 shows the amount of components already produced by the plant in a 7-weeks look ahead of loading plans, from the construction site.

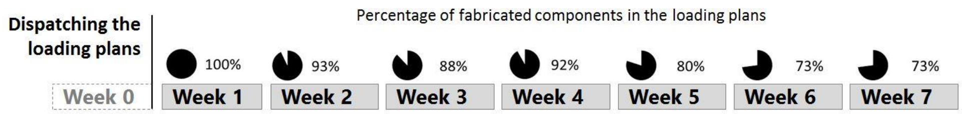

Figure 27: Percentage of already produced components in the loading plans

According to the coordinator of the scheduling department , this practice was adopted by five different construction sites and was helping them to be aware of the construction site demands, decreasing the time components were waiting in the plant yard before going to the site. It is important to configure the look ahead horizon in the construction site larger than the time lead time required by the scheduling department to produce the component. In the case of the company analyzed, this lead time was around three weeks, so the minimum horizon for the site look ahead was four weeks. It is worth acknowledging that there was still a need for confirming the delivery of the components with the expedition, as shown in Figure 28. As there are a large number of interactions between the structure and the other services in the construction site, there is a high level of variability. Therefore, the site manager would keep the practice of confirming the deliveries two days before, in order to expedite or delay critical deliveries.

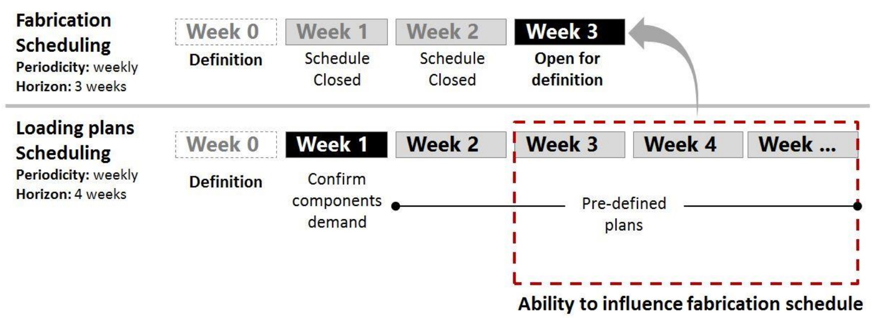

Figure 28: Relation between short-term planning horizons

The benefit of this practice is more than having a confirmation of the demand; it provides a means for decentralizing the planning process from the company headquarters. Before this implementation, the master schedule of the company was the only source for the plant scheduling. Considering that this type of schedule is developed at the very beginning of the project and that there are contractual barriers for making changes, it was not a reliable source of information.

In order to develop a more reliable look ahead, the site manager of the prefabricated system needs to deeply understand how the construction as a whole should work. It requires a well-defined production system design of the site. Although this task will be often under the scope of the construction company or the general contractor, the contractor responsible for each system should be aware of the different possibilities they are able to produce the building, this leads to the third guideline.

- **FOCUS THE LOOK AHEAD PLANNING IN THE ANALYSIS OF PHYSICAL FLOWS WITH 4D SIMULATION SUPPORT**

The environment of construction is considered very dynamic. Changes happen quickly over time and end up requiring a more systematic review of management system. This system should make the integration of all construction stages and their various stakeholders. Still, agility in receiving information and the fastest possible identification of errors or poorly designed solutions, help decision making.

The use of Building Information Modelling (BIM), particularly the 4D simulations, has become an important ally to managers. The simulations allow improvements in communication, visualization and serve as a tool for evaluation and control of physical flows. In this study, the simulation BIM 4D was used for the simulation of different assembly scenarios with realization of execution plans of activities and use of available resources. Resources include here prefabricated components, equipment and manpower.

The simulation BIM 4D helps to understand the construction components and the schedule progress that, in turn, results in a better construction planning. The analysis of execution plans assists in optimizing the assembly of the elements and control of idleness work teams and equipment used in the assembly. Figure 29 shows the similarities of 4D simulation model with the executed work in this area.

Figure 29: Comparison between 4D simulation and real executed work

In the second case, in which some assembly scenarios were tested, there were some important constraints in the site. The precast concrete was allocated to an enclosed area, four pavements underground, restricting the area for trucks and cranes. The uses of two different teams at the same time were, at some moments, not possible because of space constraints. The completion of the structure was especially critical because of the lack of space for the main equipment: truck, crane, and elevating work platform.

The evaluation of 4D model with the physical flow analysis was made during the weekly planning meetings. These planning meetings were carried out with members of the construction company and the prefabricate contractor. The use of 4D simulation in those meetings enabled a better understanding of the assembly process and execution sequence by the parties involved. Information was updated in the model from the discussions in the meetings. Figure 30 illustrates an assembly sequence from 4D simulation screenshots.

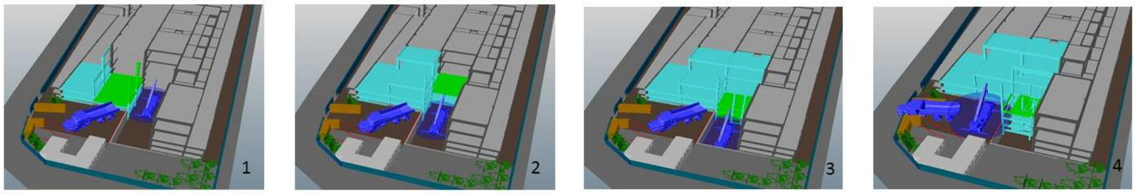

Figure 30: Screenshots of 4D simulation

Although the use of 4D simulation was not yet adopted by the company, the study revealed that the use of the BIM model for developing the 4D could affect more than the physical flow analysis. The control tools that the site manager had to deal with required a lot of paperwork, while the simulation provided a platform in which the semantic information of the components, mainly their names, was related to the location of these components in the project. This simple realization revealed how complicated and time consuming were the control tools, leading to the fourth and last guideline.

• FACILITATE THE EVALUATION AND CONTROL OF ASSEMBLY PROCESS WITH 4D SIMULATION SUPPORT

In both cases, it was observed the time spent by the site manager for making the production control. More than controlling their teams, the site manager should also respond to the construction company of the site and to the integrated planning department from the company headquarters. The first control was carried out in a visual manner, by painting the project floor plans, the marked components were then converted into report for the headquarters and were also used to measure productivity. The construction company used a control system based on the Last Planner System, so the control was based on the committed work packages.

Although the study still does not have final results over the implementation of new control tools, some attempts have been made in order to make the control process easier and more reliable. The first attempt was to facilitate the development of the loading plans using the information from the 4D simulation model, linking names and locations together with updated information of the fabrication process. Until this moment, it was possible to see a strong decrease in the time spent by the site manager to develop the loading plans.

• CONCLUSIONS

The basis for the discussion and establishment of the guidelines emerged from the process which aims to integrate planning and control in a complex engineer-to-order environment. Some important contributions such as understanding the real demand from construction site enables the plant to be flexible to attend site needs and still having a good utilization of capacity, as well as decreasing the time components were waiting in the plant yard before going to the site. Another contribution was related to configure a look-ahead horizon for the loading plans. The development of the loading plans was facilitated by 4D simulation model that helped to understand the construction components and the schedule progress resulting in an accurate construction planning. Information from the 4D simulation model enabled to understand how the construction as a whole should work and the trends to optimize the assembly of components and control of work teams idleness and equipment used. The guidelines suggested here were a useful starting point for enabling more reliable information of the construction site. This paper is part of an on-going research which intends further deepening of the topics developed.

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