CONTINUOUS FLOW FOR STRUCTURAL DESIGN IN PREFABRICATED CONCRETE STRUCTURES

Iamara Rossi Bulhões[1] **and Flavio Augusto Picchi**[2]

ABSTRACT

In industrial building, the assembly process is often carried out in large batches, i.e. a large number of structural elements (columns and beams) are assembled before placing slabs and roof parts, increasing the amount of work in progress. One of the factors that contribute for that is the large size of design batches. Often the first elements to be designed are the ones that have more repetition. This paper discusses the implementation of the principle of continuous flow on the structural design of prefabricated industrial buildings, emphasizing the reduction of design batch size. An action research empirical study was carried out in a large prefabricated concrete structure manufacturer from the State of São Paulo, Brazil. This study was divided into three stages: (a) an overall analysis of the design activities; (b) a detailed analysis of the design process of one project; and (c) preliminary results of the implementation of design, prefabrication and assembly continuous flow in a construction project. The implementation process is based on core Lean Thinking concepts and principles. The expected results are the reduction of total (design, prefabrication and assembly) cycle time, increase in productivity, work in progress reduction, and improved process stability.

KEY WORDS

lean thinking, continuous flow, small batch, design process,

INTRODUCTION

Several companies from the manufacturing industry have adopted Lean Thinking concepts, principles and tools (Womack e Jones, 1996), developed from the Toyota Production System (TPS), for improving the performance of their plants regarding the elimination of waste, including production inventory. One of the key elements in this system is to work in continuous flow, by introducing process small batches, increasing both flexibility and efficiency.

In the manufacturing industry the production of unitary items in a production line can be regarded as a reasonable way of production (cars, pens, mobile phones, etc). However, the implementation of continuous flow in manufacturing is not something trivial and also involves the introduction of major changes in production management, including plant layout, and also behavioral

[1] Ph.D. candidate, Faculty of Civil Engineering, Architecture and Urbanism, University of Campinas (UNICAMP), Group of Building Management and Technology, iamara@fec.unicamp.br
[2] Director, Lean Institute Brazil, Rua Topázio 911, São Paulo-SP, Brazil, CEP 04105-063, Tel.: +55 11 5571-6887, Fax: +55 11 5571-0804, fpicchi@lean.org.br

changes in the people involved, from line workers to company's senior management (Liker, 1996). Transferring the concept of the continuous flow to the construction industry is a major challenge. It is necessary to understand core Lean Thinking ideas at an abstract level and adapt them so that they can be applicable in the construction context (Lilrank, 1995).

Previous IGLC papers from the same authors (Bulhões *et al.*, 2005; and Bulhões *et al.*, 2006) proposed adaptations of the principle of continuous flow in construction sites. In the first study, tools proposed by Rother e Shook (1999) were used to model and design flows in a fairly conventional building project. In the second one, the results of the implementation of continuous flow in the assembly of reinforced concrete prefabricated structure were described, emphasizing the strategies adopted to reduce the assembly batch size. A major limitation in the implementation of continuous flow in the later was the lack of integration between design and production management, since there was a overlap between those two processes. The design in this type of project is often produced in large batches, and the parts that have more repetition are usually designed first.

Considering the flow view of production, a process is generally regarded as a flow of materials and information from raw materials to the final product (Koskela, 2000). Based on this concept, both design and production processes can be managed by using the same principles. It means that the design process can be improved by reducing waste (non value-adding activities), reducing duration, and increasing the value from the point of view of the client (Koskela and Huovila, 1997). Therefore, the time spent in transferring information, waiting for the development of subsequent process steps, inspections and other non value-adding activities should be considered as waste and be eliminated whenever it is possible (Koskela and Huovila, 1997).

This article discusses the preliminary results of a research project that involves the adaptation and application of Lean Thinking concepts and tools for both modeling the design process and supporting the implementation of continuous flow in the design of prefabricated concrete structures. Two empirical studies carried out in a company that produces and assembles concrete structures are presented. In the first study an analysis of the current situation was undertaken, while in the second one several changes have been introduced in the design process.

CONTINUOUS FLOW IN DESIGN

The concept of continuous flow presented by Rother and Shook (2002) assumes that each process produces only what is required by the following processes or the final client, without creating inventory. In this context, the production system needs to be flexible enough in order to change (speed and product type) according to the client demand.

Reis (2004) suggests that a major difference of implementing continuous flow in manufacturing processes and administrative processes is the fact that in the former there is not client pulling a piece. Therefore, it is necessary to understand upstream and downstream processes well so that the service is performed and its results are available at the right time, not before, nor after.

One of the key aspects of design management is the reduction of lead time, which is the time required for a product to move along all process stages, from beginning to start (Rother and Shook, 2002). In design, the lead time is the time needed to produce information, make decisions and produce design solutions, from the identification of client requirements to the delivery of the complete design (architectural, structural, building services, etc.).

This study adopted the model for implementing continuous flow proposed by Rother and Shook (2000) and Rother and Harris (2002) as a starting point. This model adopts value stream mapping (VSM) as the first step for developing improvements. VSM represents graphically all steps involved in material and information flows from order reception to delivery. Generally, two maps are prepared: (a) current-state map that represents existing value stream and points out process waste, and (b) future-state map that proposes improvements in the value stream, through the implementation of Lean Thinking ideas. The following concepts, among others, are useful to understand VSM (LEI, 2003; Rother and Shook, 2000; Rother and Harris, 2002): (a) the cycle time (C/T) measures how often a part is completed by a process; and (b) the takt time (TT) is the rate of demand by the customer.

According to Shook (2003), devising value stream maps for administrative processes is very similar to the way it is done for production processes, both for the current-state and future-state maps. The main difference is the difficulty of information flows. Based on Rother and Shook (2002), Picchi (2002) proposed a set of guidelines for adapting VSM to administrative processes:

- The value stream for administrative processes is an information flow, that should be defined from the left to the right;
- Each activity should be represented by a block, separating activities carried out by different people or in different moments;
- Each block should contain the following information: activity name; number of people involved; brief description of how it is performed, as well as materials and tools used; time for effectively carrying the activity (AD), and time that it stays at each workplace (W);
- Connections between activities, as well as their inputs and outputs should be documented, describing the type of materials or information that is produced and existing loops.

According to Reis (2004) *W* is the time that the information takes, from the end of the previous activity to the end of the current one, being indicated at the VSM blocks and at the time scale. It indicates the period of time that the information is waiting, queuing, or being transported, without adding any value. The process lead time is calculated by the sum of all *W*s, and it is indicated in the map time scale. The same author describes *AD* as the total time spent in work elements that effectively transform a unit in the process, which is smaller than *W*. In fact, *W* includes *AD*.

RESEARCH METHOD

Action research was the research strategy adopted in this investigation. Action research is a strategy for obtaining, at the same time, both knowledge and change in social systems. It is a cyclic process, involving an analysis of the problem, planning, action, and an assessment of the results (Eden and Huxham, 1997).

This research study was carried out in two job sites of Munte Construções Industrializadas, a construction company specialized in prefabrication and assembly of industrialized concrete structures. This company was founded in 1975, and currently has two prefabrication plants (F1 and F2) located in State of São Paulo, Brazil.

In 2004 the company had the support of the Lean Institute Brazil in the implementation of some Lean Thinking principles in one of the plants of the company. This included training courses on VSM and continuous flow for the company production managers. The initial implementation of those principles resulted in a productivity increase of around 30%. The fact that the company had received those training courses made it easier the development of these studies. In 2005, a new set of studies started, involving a partnership between Munte and the University of Campinas (UNICAMP). The initial focus was the implementation of continuous flow in the assembly of prefabricated structures (see Bulhões *et al.*, 2005; and Bulhões *et al.*, 2006). Due to problems of integration of design and production (see introduction section), the focus has changed to the implementation of continuous flow in the structural design process.

The study was divided into three stages. In the first stage, an overall analysis of the design activities carried out by the company and by external designers was carried out. In the second one, a detailed analysis of the design process of one project (named Project A) was carried out, from the demand made by the client for a quote to the final delivery of the project. The third stage has involved the implementation of improvements in another project (Project B), aiming to improve the design information flow. This implementation process is still going on. The main tool used in this study was VSM for administrative processes. Table 1 briefly describes the two projects that were investigated.

Table 1 Brief description of projects A and B

	Project A	Project B
Job description	Extension industrial building, including the following components: columns, beams, slabs, roof tiles and stairs	Assembly of a prefabricated concrete structure of a warehouse, including the following components: columns, beams, slabs, roof tiles and stairs
Project duration	22 days	225 days
Building area	2, 842.7 m²	89,846.9 m²
Concrete volume	385.9 m³	7,759.8 m³
Number of parts	223	6,569
Design duration	68 days	193 days
Design team company	1 design manager, 1 designer checking	1 design manager, 1 designer, and 4 drawing technicians
Design team external	1 structural designer, 2 designers and 4 drawing technicians	1 structural designer

RESULTS

OVERALL ANALYSIS

In the first meeting with the company internal design team the value stream map of the existing design process (Figure 1) was produced, with the aim of having an overview of this process, including its main stages, critical steps, and participants. Therefore, this map is mostly based on the perception of this design team.

The client is represented in the right side of the map, making explicit the production volume, based on the long term production plan agreed between the company and the client. The duration of the project (design, fabrication and assembly) is a key information in the process, since it is the starting point for producing design drawings. Regarding the information flow, the production planning and control process produced all design schedules. This information is usually based on goals established in the production long term plans. In the lower part of the map, the main design processes are represented: it starts by the initial design coordination meeting and finishes at the final design checking.

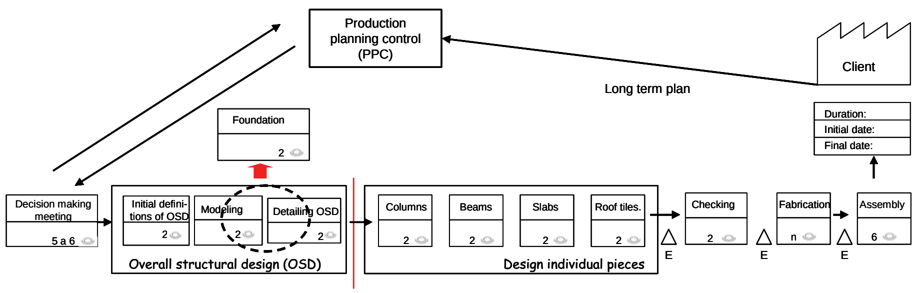

Figure 1 Value stream map of the overall project

Figure 1 indicates that the design of the prefabricated structure is divided into two stages: overall design of the structure, that involves the definition of its spatial geometry, and the design of individual parts (columns, beams and slabs). Those stages are normally carried out by external structural design offices, which hire different types of professionals: experienced designers that conceive the structure, designers that calculate loads on the structure and on the foundations, designers of individual parts, drawing technicians, and foundations designers (usually from a different company).

The internal design team of the company is usually involved in design coordinating meetings and in design verification (checking). The initial design coordination meeting usually involves: the company design manager, the designer in charge of conceiving the overall structure, the designer in charge of calculating loads, and the sales person. Before delivering design drawings to production these are checked by the internal design team. The design manager is in charge of managing the whole design process.

A second version of the map was then produced (Figure 2), in which the design of the overall structure is kept in one large batch (the whole building), but the design of individual parts is delivered in small batches, compatible with the batch sizes defined for the assembly process.

The research team was not sure whether it was possible from a technical point of view to implement small batches in this kind of design process, and follow the sequence defined by the assembly process. In October 2006 a meeting was held involving the internal design team and representatives of an external structural design office for presenting and discussing the new process map, and all agreed that it was feasible. When the external designers were asked why they did not usually delivered design drawings in the same sequence of the assembly process, they stated that they usually start by the parts that are the easiest to design. Two months later another meeting was held with other external designers and the same answer was given.

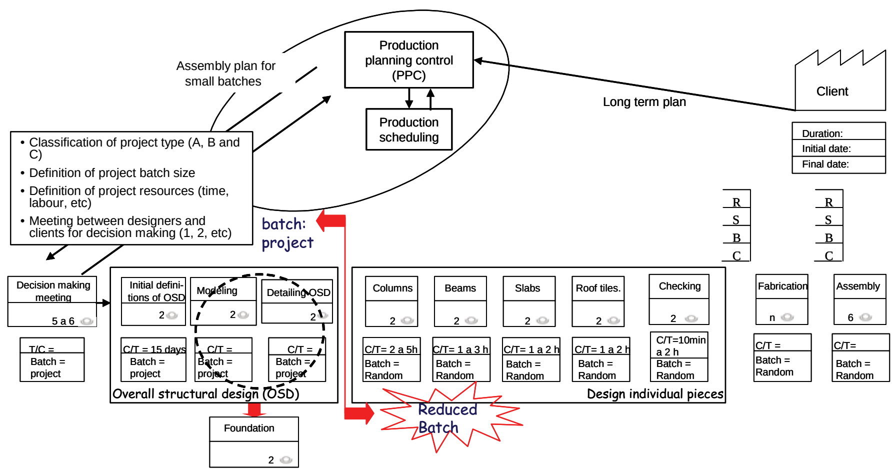

Figure 2 Future value stream map of the overall project after the reduction of batch sizes

At that stage, some other improvements in the design process were proposed:

- Create a classification of projects by type according to size, complexity, location, accessibility, etc. Currently, in general the same design lead time is established for any kind of project. For instance, the duration of the overall structural design is assumed to be ten days.
- Define duration of the design stage and the design team involved according to the type of project;
- Involve designers in the definition of design batch sizes;
- If necessary, hold other design coordinating meetings in order to improve the exchange of information and decision making.

DETAILED ANALYSIS

In this stage, a new value stream map was produced, containing more details in comparison to the first one. This map was based on information that was collected in a project from beginning (first contact by the client organization) to the end (delivery of the project). Part of the data for producing this map was collected by the external design team. Despite this map is concerned with the whole project, the focus of this study is the design process (0).

The design process started in the 4th of August 2006, when the client asked the company a cost estimate for Project 1. The agreement was reached only on the 22nd of January 2007, due to the long period that was spent in negotiation (94 days). This period was named independent information cycle, since there is much interference from the client and the company has little control over decision making.

Once the new job was confirmed, the period named dependent information cycle started. Then most activities are managed internally in the company (including hired external designers). Therefore, this agreement should be the starting point for the internal process, although sometimes a formal contract is not signed. In Project 1 there was a delay of 6 days between the agreement date and the communication of the job from the sales person to the design team, although the delivery time had started in the former date. The initial design coordinating meeting should be arranged as soon as possible after the communication of the job. In Project 1 it took 5 days to hold this meeting, which was when the external design team started working in the project.

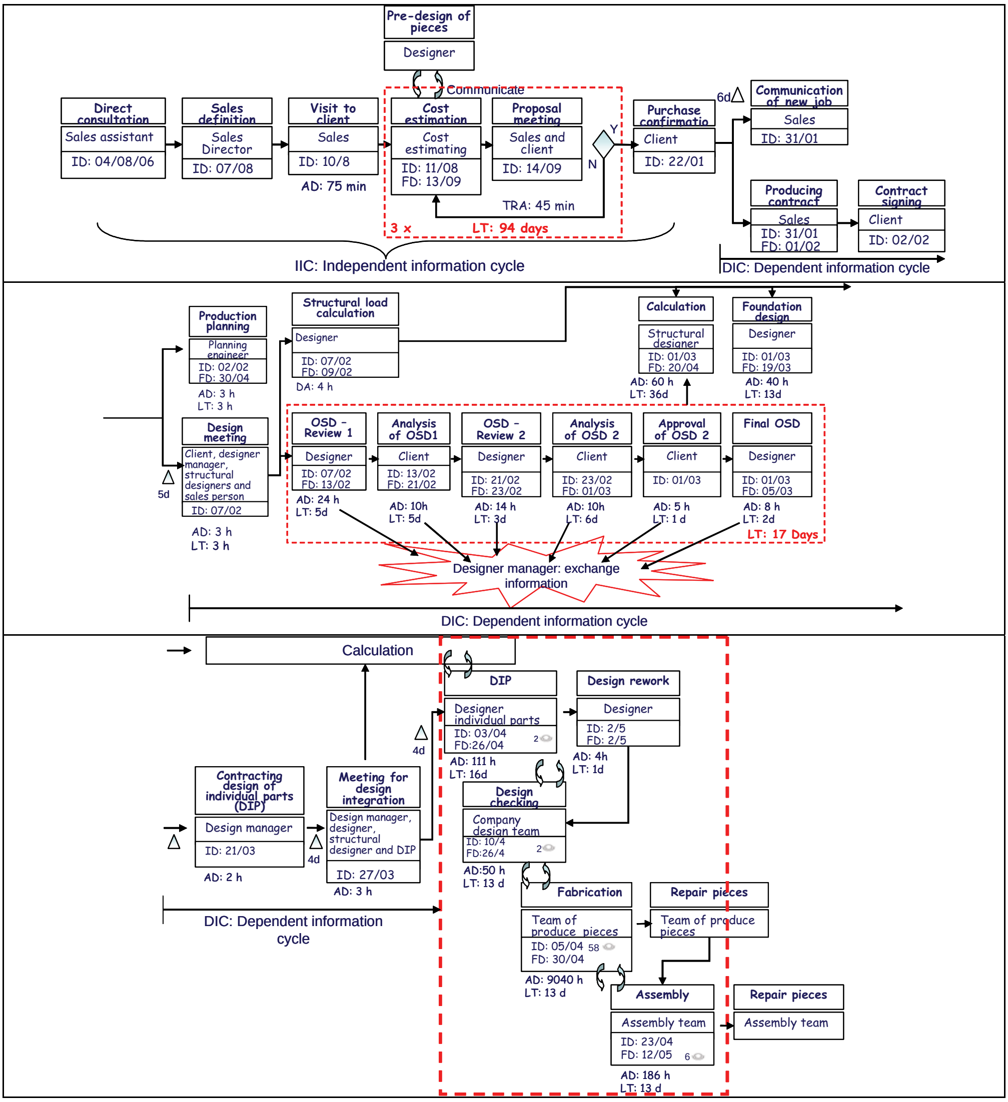

Figure 3 Current value stream map of the Project A

The expected duration of the overall design of the structure was 10 days, but it took 17 days. The design manager was in charge of the communication between external designers and the client. The communication between the design manager and the designer responsible for the overall structural design was made by electronic mail.

The calculation of loads started at the end of the overall design and lasted until the beginning of the design of individual pieces.

After the development of the overall structural design, it took 19 days to start the design of individual parts, although it could have started immediately. In general, a single structural design office is hired to develop the whole structural design, including overall design, calculation of loads and design of individual pieces. However, in this project, three different structural designers were hired to do each one of the design stages, with the aim of reducing the design lead time. This change demanded a new set of activities, such as coordination meetings. Also, it took 11 days to hire the designer in charge of the design of individual parts. Besides this delay, the division of design work was the main cause of a mistake in the design of a number of parts, which was only discovered after some pieces have been produced and others have been already been assembled. This problem resulted in re-work in both the prefabrication plant and in the construction site.

0 presents the current value stream map of the design process for Project A. It indicates that the design lead time is 69 days and the value adding time only 24 days, resulting in a waiting time of 30 days, from which the process was totally stopped for 11 days. It means that non-adding value time corresponded to 65% of the lead time. The value adding time for parallel activities was calculated considering the longest average activity duration per day. The lead time for individual process was calculated from the initial date and the finish date.

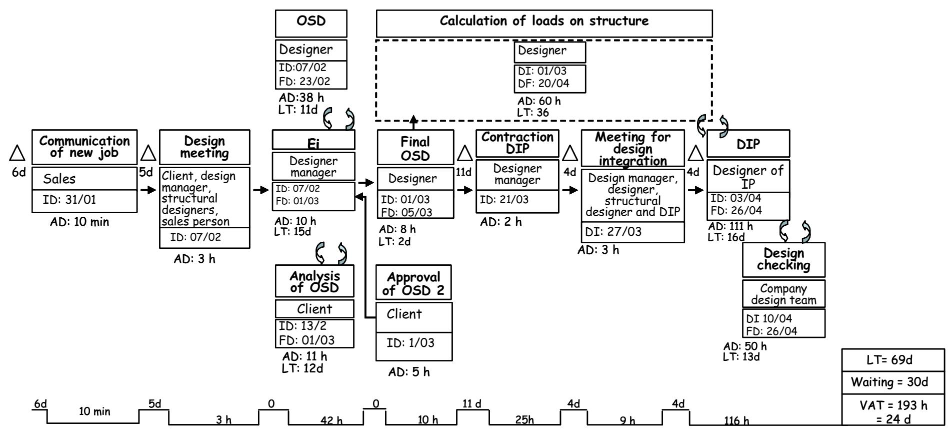

Figure 4 Current value stream map of the design process for Project A

In this type of commercial of industrial project the assembly lead time and the delivery time is relatively short, and concurrency between activities is necessary. By contrast, 0 and 0 indicate that the design decision cycles tend to be relatively long.

0 presents a proposal for the future state value stream map for the design process. The main changes introduced in the process are presented bellow:

- Reduce the batch size for the design of individual parts and design verification, based on the assembly batch size and sequence. The designer of individual parts sends production drawings to the company via a project extranet. There is a person in charge of receiving those drawing, who prints and delivers them to the design verification team – this activity is named control of production drawings delivery. Since designers work in small batches, they deliver drawings in a preestablished periods (e.g. once a week, twice a week, etc.), which makes it much easier to do such control. In fact, by reducing small batches this activity could be eliminated in the future;

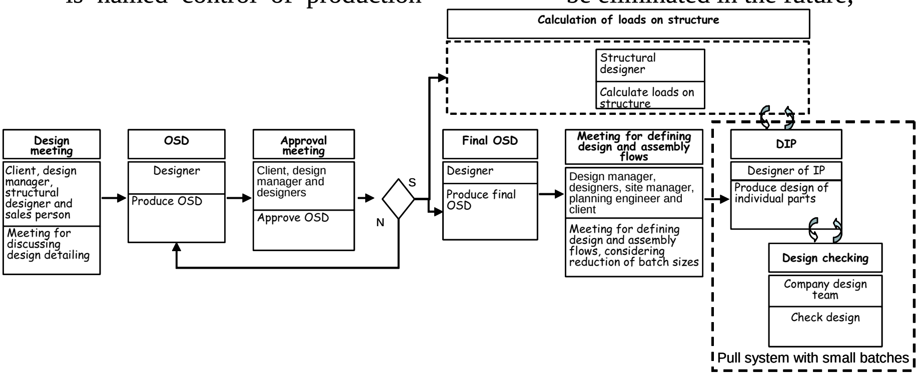

Figure 5 Future state value stream map for the design process

- Reduce or eliminate waiting time, since the causes of those delays could be easily eliminated;
- Improve the management of concurrent processes, including prefabrication, design of individual parts, and assembly. This requires the formalization of information, managing commitments. For that reason some meetings were included in map with the aim of improving design management;
- Reduce the duration decision cycles also by including meetings for expediting decision making. The design manager is expected to have a much more active role in this process, instead of being only an information manager.
- Define criteria for assessing the level of project complexity, which could be considered in the preparation of proposals and cost estimates, and also bids and also when hiring designers. Currently there is a standard duration for the production of overall design, without considering the differences between projects. The criteria initially defined in the meetings by designers, design manager and the research team were: duration (speed), degree of uncertainty, size, level of standardized parts, level of repetitiveness (number of parts/number different types of pieces), project type (warehouse, multi-story buildings, or supermarkets).

IMPROVEMENTS IN PROJECT B

Based on the actions suggested in the previous section, a set of improvements were implemented in Project B. This project is still going on and the design is expected to finish in July 2008. It will be delivered in two stages.

The priority in terms of delivery is the mezzanine, which is part of project stage one, since most of building works are concentrated in this area. However, this is the most complex part of the design, since it contains a larger number of parts, and the client tends to interfere more, compared to the rest of the building. In fact, the assembly of the mezzanine was expected to start on the 3rd of March, but by the 22nd of February the staircase had not been defined yet.

By contrast, the warehouse has a much larger area, but the number of repetitive parts is much higher, making it easier to design individual parts. However the production of parts for building the warehouse takes a longer time due to the large number of parts. 0 provides an overview of the design batches and the estimated delivery dates.

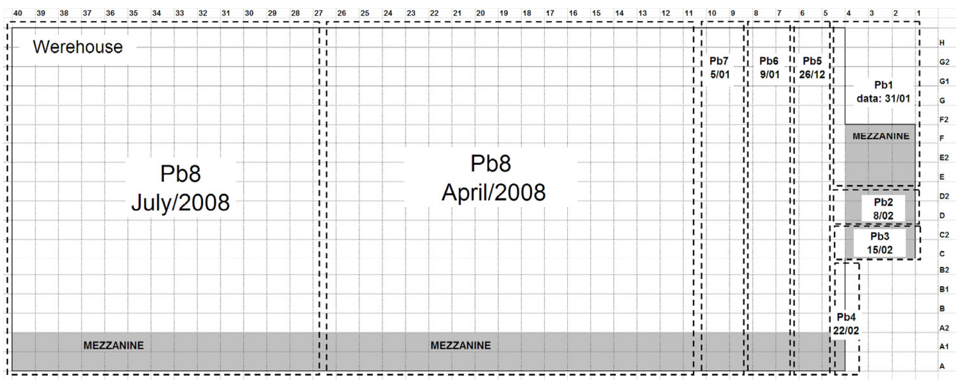

Figure 6 Design batches

Initially, the definition of design batches was based only on the assembly sequence, which is defined in agreement with the client. However, in this type of project it is important also to consider the combined capacity of the prefabrication plant and the assembly equipment available. For that reason, in the implementation process, the definition of design batches involved representatives from three different departments of the company: production management (construction site), planning (prefabrication plant), and design.

Eight design batches have been defined for the project. Despite the fact that the assembly process starts by the mezzanine (production batches PB1 to PB4), due to the large volume of parts to be prefabricated for the production batches PB7, PB6 and PB5, the design for the latter had to be produced before.

Currently, the planned sequence of design batches has not been followed completely, due to some delays of client decisions. As a result, there is an overlapping between PB2 and PB3: the beams of the former had not been finished, but the production of the columns of the later had already started. Despite this problem, by mid January 2008 the assembly schedule and the batch sizes have not suffered major changes

Another important change introduced in the design process was the adoption of design batches, instead of the design of individual parts, as the unit for paying external designers and also controlling design delivery.

CONCLUSIONS

This paper presented the initial results of the implementation of continuous flow on the structural design of prefabricated industrial buildings, emphasizing the reduction of design batch size. Although this research project is still going on, there are indications that the principle of continuous flow adopted in the production and assembly of prefabricated structure can be extended to the design process, despite the complexity of this process, due to the large number of different professionals involved, including external designers, and frequent changes demanded by the client.

VSM was very useful for understanding and representing the design process, playing a key role in the proposal for improvements towards getting continuous flow in design. The reduction of design batch sizes was successful, although the concept of batch size in production is slightly different, since is strongly based in standardized work. In the design process, the batch size should be more flexible, allowing changes demanded by the client to be considered. Moreover, design batches are pulled by both prefabrication and assembly system, rather than only by the second one. This is because the timing for producing some parts define a design sequence that is not necessarily the same sequence of on-site assembly.

The results of this study are promising, indicating that the proposed analysis steps and tools are effective for identifying waste and support the implementation of continuous flow in the design of prefabricated structures.

ACKNOWLEDGEMENTS

The authors would like to thank FAPESB (Foundation for the Support to Research of the State of Bahia) for the financial support and Munte Construções Industrializada for being a partner in this research project.

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