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Planning and controlling design in engineered-to-order prefabricated building systems

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Abstract

Purpose – The purpose of this paper is to propose a model for planning and controlling the design process in companies that design, manufacture and assemble prefabricated engineer-to-order (ETO) building systems. This model was devised as an adaptation of the Last Planner® System for ETO multiple-project environments.

Design/methodology/approach – Design science research, also known as prescriptive research, was the methodological approach adopted in this research. An empirical study was carried out at the design department of a leading steel fabricator from Brazil, in which the proposed model was implemented in six different design teams.

Findings – The main benefits of the proposed model were shielding design work from variability, encouraging collaborative planning, creating opportunities for learning, increasing process transparency, and flexibility according to project status. Two main factors affected the effectiveness of the implementation process commitment and leadership of design managers, and training on design management and project planning and control core concepts and practices.

Research limitations/implications – Some limitations were identified in the implementation process: similarly to some previous studies (Ballard, 2002; Codinhoto and Formoso, 2005), the success of constraint analysis was still limited; some of the metrics produced (e.g. ABI, causes of planning failures) have not been fully used for process improvement; and systematic feedback about project status was not properly implemented and tested.

Originality/value – The main contributions of this study in relation to traditional design planning and control practices are related to the use of two levels of look-ahead planning, the introduction of a decoupling point between conceptual and detail design, the proposition of new metrics for the Last Planner® System, and understanding the potential role of visual management to support planning and control.

Keywords Engineer-to-order, Design process, Last planner system, Planning and control, Design teams, Prefabricated building systems

Paper type Research paper

Introduction

Despite the importance of the design process for the success of construction projects, it is widely recognized that not enough attention is given to design planning and control in this industry (Choo *et al.*, 2004; Tribelsky and Sacks, 2010; El Reifi and Emmitt, 2013). Design plans are often limited to a list of design deliverables, produced at the beginning of design process (Choo *et al.*, 2004). The ineffectiveness of design planning and control results in poor coordination between disciplines, unbalanced resource allocation, insufficient information available to complete design tasks and delays in the delivery of design information to

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downstream processes, among other problems (Koskela *et al.*, 2002; Ballard, 2002; Tribelsky and Sacks, 2010).

Indeed, design planning and control is often carried out informally (Tzortzopoulos *et al.*, 2001; Koskela *et al.*, 2002). This is partly due to the fact that traditional construction planning techniques, such as work breakdown structure, critical path method and earned-value method, tend to be ineffective for design (Austin *et al.*, 1994). Those techniques are not able to cope with the high level of uncertainty and the iterative nature of design and the complex interdependences that exist amongst design disciplines (Austin *et al.*, 2010; Koskela *et al.*, 2002). In fact, iterative processes are necessary and beneficial as these may add value to a project, but should be controlled in order to avoid serious implications in time and cost (Knotten *et al.*, 2015).

The ineffectiveness of design planning and control tends to be more critical in complex projects, i.e. projects that have a high level of structural complexity (e.g. large number of stakeholders and interdependent components) (Baccarini, 1996) and uncertainty related to goals or methods (Williams, 1999). Those projects demand closer integration and better collaboration between construction project participants, especially at the design process (Emmitt and Ruikar, 2012).

Engineer-to-order (ETO) prefabricated building systems can be regarded as complex projects as the customer order penetrates into the design phase of a product, that needs to be conceived, manufactured and assembled to be delivered to the client (Gosling and Naim, 2009). Bertrand and Muntslag (1993) pointed out that a high level of uncertainty exists in ETO environments as it is necessary to define delivery dates when the customer order is placed, even though the product is not completely defined yet.

The integration of planning and control processes from different project stages, such as conceptual design, detail design, fabrication and site assembly, plays a key role in the management of ETO prefabricated building systems. Such integration is important because the project lead-time is usually short, requiring some degree of overlapping between project stages. Ideally, both the design and the production of prefabricated components should be pulled from the site assembly process (Bulhões and Picchi, 2008) in order to keep a low level of work-in-progress, as well as to consider demand variability that typically exists in site assembly (Viana *et al.*, 2013).

Moreover, in large construction projects complexity is also caused by design changes that are demanded by clients and designers after production has already started (Matt, 2014). This is partly due to the fact that large projects often involve many stakeholders, so the ability to coordinate changes across multiple companies is essential to avoid delays (Mello *et al.*, 2015).

A number of planning and control approaches for the design process have been proposed in the literature. Some studies have devised prescriptive models for the whole product development process (PDP) of construction projects, including the design process (e.g. Kagioglou *et al.*, 2000; Formoso *et al.*, 2005). However, those models represent product development at a high level, providing simply an overview of this process, and their use as a reference for planning and control is limited by the fact that they contain very little detail (Tzortzopoulos *et al.*, 2001). Austin *et al.* (2010) suggest the use of the Design Structured Matrix, originally developed by Eppinger *et al.* (1994), as a core design planning technique. Although this technique is useful for sequencing design activities and identifying design clusters, it has some limitations, such as the little emphasis on control, and the fact that fairly detailed plans need to be generated in the early stages of the process, demanding much effort for revising plans (Tzortzopoulos *et al.*, 2001).

Several researchers have reported on successful implementations of the Last Planner® System of Production Control (LPS) in the design process (Hamzeh *et al.*, 2009; Ballard *et al.*, 2009; Kerosuo *et al.*, 2012). Some of the core ideas of LPS seem suitable for the context of

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ETO prefabricated building systems: collaborative and decentralized planning seem to be more adequate in highly complex projects (Williams, 1999); it is possible to have confirmation points at the look-ahead planning level, based on information collected in downstream processes in order to deal with uncertainty in demand (Viana *et al.*, 2013); planning and control can be undertaken in a hierarchically organized set of meetings (Hamzeh *et al.*, 2009), making it possible to integrate planning and control among different processes and managerial levels.

However, there seems to be several gaps in the implementation of LPS in the design process, such as: the need to make design planning and control more systematic (Koskela *et al.*, 2002; Hamzeh *et al.*, 2009); the lack of success in implementing look-ahead planning for design (Ballard, 2002; Codinhoto and Formoso, 2005); the need to increase process transparency and, consequently, the involvement of planning team members (Tzortzopoulos *et al.*, 2001); and the need to devise metrics for assessing the impacts of LPS on the design process (Hamzeh *et al.*, 2009). Moreover, none of the previous studies have investigated the implementation of LPS for ETO prefabricated building systems in a multiple-project environment.

The aim of this research is to propose a model for planning and controlling the design process in companies that design, manufacture and assemble ETO prefabricated building systems. This research is relevant due to the need to make the design process in those companies more reliable, by improving the effectiveness of the planning and control process. The model was devised as an adaptation of the LPS for the design process in ETO multiple-project environments, exploring the need to cope with the high degree of variability, to have a short lead-time, as well as to keep a low level of work-in-progress.

Design planning and control in ETO production systems

A common mistake in devising planning and control systems for the design process is to neglect the nature of the design activity, which makes it very different from production.

First, there is much more uncertainty and variability in design. Although it is often possible to take some steps toward improving the initial definition of the problem, by questioning the client and collecting data, some of the customer needs cannot be easily made explicit (Crosby, 1995). Moreover, there are usually conflicting requirements, demanding an effort to manage trade-offs, and some decisions must be made without complete information (Kamara *et al.*, 2002).

Second, there is much more iteration in design, as the attention of the designer oscillates between understanding a problem and search for a solution (Austin *et al.*, 2010; Cross, 2008). Although there is a hierarchical structure of decisions, from overall concepts to details, most designers move freely between different levels of detail, especially in the early stages of design (Cross, 2008).

Third, design work tends to expand to the time available (Reinertsen, 2009). As a result, design tasks tend to be finished either on time or late: if a satisfactory solution is found early, then the available time is used to refine the solution (Ballard, 2000).

Therefore, the development of planning and control systems for design must consider that this is an ill structured, solution-focused, highly iterative and opportunistic process, and that the steps for producing a design solution cannot be pre-established at a very fine level of detail (Cross, 2008).

In ETO production systems, as products are custom-made and one-of-a-kind, there are three main types of uncertainties (Bertrand and Muntslag, 1993): as the product needs to be engineered at the start of a project, some decisions, such as capacity, lead-time, and price needs to be taken under uncertainty; it is difficult to make a detailed demand forecast in terms of mix and volume; and it is also difficult to make an estimation of the type and amount of resources required.

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One way of dealing with uncertainty in planning and control systems is to establish different hierarchical levels. The literature often suggest three planning levels: long-term planning, which is concerned with setting objectives (Laufer and Tucker, 1987); medium-term planning, which is mostly concerned with the means for achieving those objectives, such as determining what to work on, and who will work on it, within existing constraints (Ballard, 2000); and short-term planning, which addresses control by taking whatever actions are required to ensure that the system continues to function toward its goal (Hopp and Spearman, 2008).

Different planning horizons imply distinct planning frequencies, modeling assumptions and levels of detail (Laufer and Tucker, 1987). A major challenge in any planning and control system is to keep consistency between different decision making levels. In fact, its effectiveness depends on how well it coordinates the different planning horizons (Hopp and Spearman, 2008). Another important aspect is to define which processes will be pushed (release of work based on forecasts) and which ones will be pulled (based on system status) (Hopp and Spearman, 2008).

One of the key practices for managing the design process in ETO production systems is the reduction of design batch sizes, especially at the detail design phase. This allows designers to work simultaneously and iteratively, reducing the total design lead-time (Reinertsen, 2009). This approach contrasts with the traditional sequential design process that is often adopted in construction projects, in which designers are used to work in large batches, usually represented by a pack of design documents (Ballard, 2000). According to Reinertsen (2009), large design batches often result in a large amount of work-in-progress, especially in multiple-project environments.

The LPS is a planning and control model that attempts to deal with uncertainty and complexity by involving crew leaders and lower level management in decision-making (Ballard and Howell, 1997). It can be considered as a combination of pull and push planning. At the end of the short-term planning cycle, an overall assessment of planning effectiveness is carried out, by using an indicator named percent plan complete (PPC), proposed by Ballard and Howell (1997). This is the rate between the number of assignments concluded and the total number of scheduled work packages. The root causes for the non-completion of work packages are identified, so that corrective measures can be implemented.

Research method

Design science research, also known as prescriptive research, was the methodological approach adopted in this study. It is a way of producing scientific knowledge that involves the development of an artifact to solve a real problem (Holmström *et al.*, 2009). In contrast with traditional descriptive research, in which theories need to be validated, this artefact must be assessed against criteria of value or utility (March and Smith, 1995). In this research, the proposed artefact is a model that can be used as a reference for devising design planning and control systems for companies that deliver ETO prefabricated building systems.

This research process was carried out in close collaboration and engagement of the managerial staff of a company, being conducted through a strategy similar to action research. As suggested by Järvinen (2007), this type of action research project fits very well the design science research approach.

This company is a leading steel fabricator in Latin America. It had more than 2,000 workers, three manufacturing plants, and around 200 simultaneous contracts. This study focused on light steel structural systems for warehouse and industrial buildings.

Figure 1 presents an outline of the research design. Phase 1 (October 2011 to April 2012) aimed to understand the existing company process (e.g. metrics, difficulties in performing the work, and compliance with design deadlines) as well as to identify opportunities for improving the design planning and control process. In Phase 2 (May 2012 to January 2013), an initial version of the model was devised and implemented with two detail design teams (T1 and T2).

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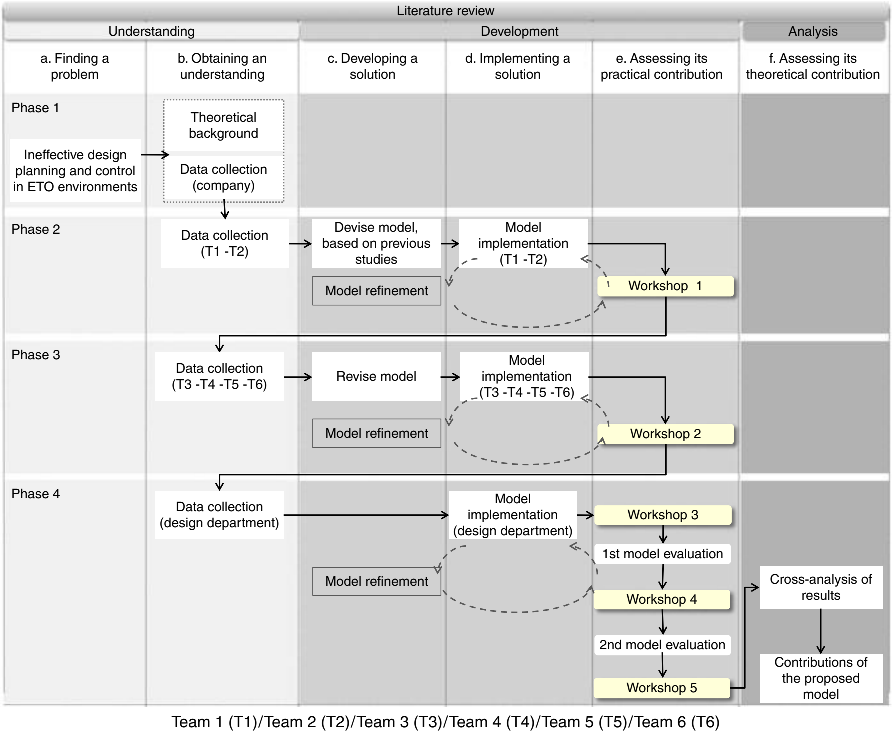

Figure 1.
Outline of the research design

Due to the initial results achieved by those two teams, the company decided to start a training program devised by the research team, and had the participation of technical staff from the Engineering Design Department (EDD), Planning Department, and Cost Estimating Department (overall around 50 people). The scope included design management, planning and control and client requirements management.

In Phase 3 (December 2012 to March 2013), the model was revised, and its implementation was extended to four other design teams, two involved in conceptual design (T3 and T4), and two involved in detail design (T5 and T6). Phase 4 (February to October 2013) focused on the connections between design planning and control and other planning systems in use by the company, aiming to enhance the final version of the model. At this stage, visual management boards were used to support decision-making. The results of the implementation were discussed in a set of five workshops, carried out along the research project.

At the end of Phase 4, a protocol was devised to assess the degree of implementation of 14 planning and control practices (see results in Figure 7) – that protocol was jointly devised and applied by the research team and design managers from the company. At the end of this stage, as suggested by March and Smith (1995) and Holmström *et al.* (2009), the benefits and limitations of the model were assessed based on two main constructs, utility and applicability. Those constructs were further divided into evaluation criteria: applicability: effort involved in planning meetings, and understanding of planning and control practices; and utility: shielding design work from variability, encouraging collaborative planning, creating opportunities for learning, increasing process transparency and providing flexibility according to project status.

Table I summarizes the sources of evidence used in each research phase.

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Research phase	Source of evidence	Description
1	Semi-structured interviews (18 respondents)	Cost estimating (3), planning (1), engineering design (10), fabrication (4)
	Survey (149 respondents out of 319 technical staff)	Sales (12/25), cost estimating (13/24), planning (2/6), engineering design (64/143), fabrication (44/91), assembly (14/30)
	Document analysis	List of employees, positions and dates of entry in the company (supported the selection of interviewees and survey respondents)
		Overall map of the product development process
		Design process flowchart
		Layout plan for design teams in the office
		Company design drawings and long-term plans
2	Unstructured interviews	Design managers (2) and designers (16)
	Document analysis	Design drawings and design plans
	Participant observation	25 weekly short-term design planning meetings
		4 integrated planning meetings
		13 meetings related to process improvement at EDD workshop 1(60 participants)
3	Unstructured interviews	Design managers (4) and designers (4)
	Document analysis	Design drawings and design plans
	Participant observation	5 weekly short-term design planning meetings
		Workshop 2 (40 participants)
4	Participant observation	4 design planning meeting, involving planning department representatives and design managers
		Workshops 3 (40 participants), 4 (50 participants) and 5 (60 participants)
	Planning and control practices protocol	Application of a protocol for assessing the degree of implementation of design planning and control practices (between March and August 2013)

Table I. Sources of evidence used in each research phase

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Existing planning and control system

The company's PDP comprised the following processes: sales, cost estimating, engineering design (divided into conceptual and detail design), fabrication, and assembly.

The EDD had nine design teams, which had on average 12 designers each, led by a design manager. This department carried out around 75 projects simultaneously. Four teams were in charge of conceptual design, while five teams carried out detail design. This configuration was adopted in November 2012 as an attempt to improve the EDD performance, by creating a decoupling point between conceptual design and detail design, with the aim of pulling the latter by manufacturing plants. An important change that had been gradually implemented by the company was the reduction of batch sizes. At the detail design, each project was divided into stages (building modules) that could be assembled independently from other batches.

The design process was mostly based on a long-term project plan deadlines (from design to assembly on site) produced by the Planning Department. A weekly design planning meeting was carried out between representatives of the Planning Department and design managers, in an attempt to devise an integrated plan for the EDD. At that meeting, the design managers reported the status of work in their teams, but little was done to increase compliance with deadlines.

Implementation process

Implementation in T1 and T2 teams

In T1, participant observation in short-term planning meetings was carried out in June and July 2012. During that period, only short-term planning was implemented and some

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difficulties occurred: planning meetings were often interrupted by other demands; the performance metrics were not well understood by the participants; the level of participation of design team members in the meeting was low; they had difficulties in defining work packages (there was a trend of simply copying from the long-term plan); and the dissemination of information was poor. Those problems were related to the fact that the design manager centralized decisions and information flows.

In T2, participant observations in short-term planning and control meetings were carried out non-stop from August 2012 to January 2013. Team members were strongly involved in the definition of work packages and usually expressed commitments to weekly goals. Furthermore, the causes for the non-completion of work packages were systematically recorded. The design manager's leadership was identified as a major factor for the successful implementation in T2.

In November 2012, T1 and T2 started systematic planning and control at the medium-term (look-ahead) level (T1 horizon: one month, updated monthly; T2 horizon: four weeks, updated every two weeks). However, it was only partially implemented and much of the effort involved in constraints identification and removal was carried out at the short-term.

In both T1 and T2, the average PPC was considerably high (76 percent and 79 percent), if compared to previous studies on the implementation of LPS in design: 50, 55, and 69 percent in the studies carried out by Tzortzopoulos *et al.* (2001), Ballard (2002) and Trescastro and Formoso (2006), respectively.

The causes for non-completion of work packages are presented in Table II. In both teams, around 50 percent of causes were external to the company, i.e. related to delays in decision-making by clients.

However, there were internal problems in design teams (25 percent in T1, and 19 percent in T2), and also problems related to other departments in the company (26 percent in T1 and 29 percent in T2). This indicated that it was possible to achieve improvements in PPC by improving those processes that were internal to the company. For instance, at the beginning of the implementation process, the main cause for the non-completion of work packages in both teams was the underestimated duration of design tasks. Between January and March 2013, that problem did not happen at all, indicating that the design teams had learned to balance load and capacity, and therefore to make the internal design flow more reliable.

The effectiveness of look-ahead planning was accessed by the constraint removal index (CRI), which was calculated by using the formula:

$$\mathrm{CRI}(\%) = \mathrm{NCR}/\mathrm{NCI} \tag{1}$$

where NCR is the number of constraints removed on time; NCI is the number of constraints identified for each period.

Design teams	Design phase	Number of weeks	Average PPC (%)	Causes for the non-completion of work packages	Categories of causes
T1	Detail design	26	76	Client delay in design decisions: 25% Client delay in design approval: 18% Underestimated time: 12%	EDD processes: 25% Other company's departments: 26% External to the company: 49%
T2	Detail design	39	79	Client request for design change: 23% Client delay in design approval: 15% Conceptual design delay: 15%	EDD processes: 19% Other company's departments: 29% External to the company: 52%

Table II.
Short-term design control data for T1 and T2

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CRI has been used by several construction companies in Brazil (Oliveira, 2010; Trescastro and Formoso, 2006), and it is similar to other metrics that have been applied for assessing the effectiveness of look-ahead planning, such as the percentage of tasks made ready (Hamzeh *et al.*, 2015). Both NCI and CRI are relevant measures for assessing the effectiveness of look-ahead planning, since it is necessary to be effective in both constraint identification and removal. If both NCI and CRI are higher, PPC tends to be higher.

Figure 2 presents the evolution of NCI and CRI in T1 and T2. The fact that look-ahead planning started to be systematic and had contributions of representatives from different design team members contributed to increase NCI in both teams. However, no trend was identified in terms of increasing CRI. On average, T2 was more effective (CRI 79 percent) than T1 (CRI 55 percent) in constraint removal. It was not possible to compare these results with data from other projects, since CRI has only been used for production control (Oliveira, 2010; Trescastro and Formoso, 2006).

A metric was also proposed to control the adherence of the monthly output of design teams in relation to the batches planned in the long-term plan. This was named as adherence to batch index (ABI):

$$ABI(\%) = NWC/NPW \tag{2}$$

where NWC is the number of planned work packages that were concluded; NPW is the number of planned work packages in the long-term plan.

This metric can be adjusted for different time periods, such as a fortnight or a week. It can be used to control the amount of work-in-progress, which is not usually done in LPS. An ABI is highly dependent on the effectiveness of both look-ahead and short-term (commitment) planning. Therefore, the higher NCI and PPC, the higher ABI tends to be. In T2, the average ABI for the period between November 2012 and May 2013 was 66 percent (Figure 3). Although no reference values were found in the literature, it is very unlikely that this indicator gets closer to 100 percent in ETO production systems, due to the high level of uncertainty involved. Similarly, to the PPC metric at the short-term planning level, the main causes for not adhering to the batches that have been planned should be monitored in order to generate information useful for learning.

The main conclusions of this phase were: first, PPC was lower in the first week of the month, especially in T1, which did not adopt a rolling look-ahead plan; second, considering that a relatively large percentage of work packages did not adhere the initial monthly plans (34 percent in T2), there was a need to monitor the execution of work packages that had not been planned, and identify the main causes for their inclusion; third, it was necessary to improve the identification of the causes for the non-completion of work packages; and fourth, there was a need to improve the integrated design planning meetings, when changing demands from downstream processes (fabrication and site assembly) were presented by planning staff to design managers.

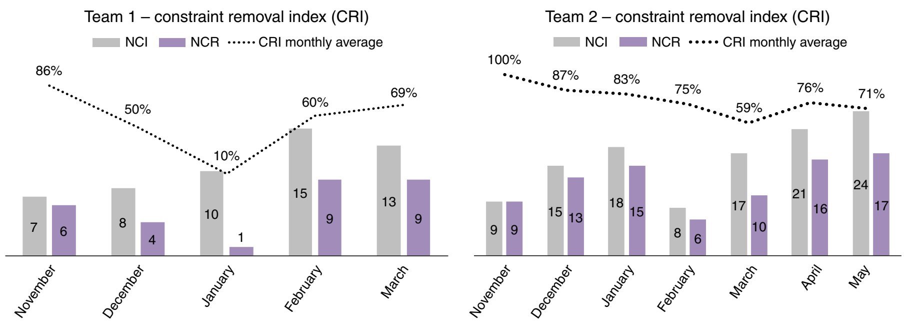

Figure 2.
NCI and CRI results for T1 and T2

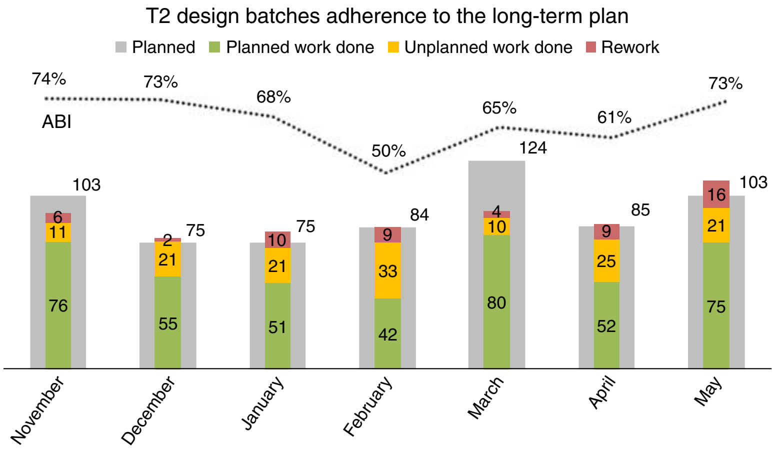

Figure 3.
ABI for T2

Implementation in T3, T4, T5 and T6

Implementation in T3, T4, T5 and T6 faced initial difficulties similar to those of Phase 2: relatively long duration of planning meetings (around one hour), mostly because input data (e.g. architectural design) had not been previously analyzed, making it difficult to estimate the duration of activities; difficulty in breaking down design activities into smaller work packages; difficulty in obtaining information for defining priorities at the look-ahead planning level; lack of understanding of the difference between resource constrains and design interdependencies; and difficulty in identifying the root causes for the non-completion of work packages.

However, during the implementation process, some of those difficulties were overcome due to the active participation and leadership of the majority of design managers in planning meetings. At the end of this phase, the weekly meetings had the duration of around 20 minutes.

Table III presents a summary of the data collected for T3, T4, T5 and T6, including the number of weeks, CRI, PPC, the main causes and their relative importance, and the classification according to the categories of causes. The average PPC for conceptual design teams (T3 and T4) was lower than the average PPC for detail design teams (T5 and T6). This was expected as there is much more uncertainty in early design, due to the need for client approvals. At the end of this phase, T6 was merged with T3, and T3 stopped the implementation of the model, due to lack of support from the design manager.

The analysis of causes for the non-completion of packages indicated several opportunities for improvement within the company, as a large percentage of problems were related to internal processes. For the detail design teams, late conceptual design decisions by the client indicate that the idea of having a decoupling point between conceptual and detail design had not been fully implemented.

The performance of the look-ahead planning was relatively poor among the four teams. CRI ranged from 33 to 75 percent, and T6, which achieved the highest figure, did not perform well in constraint identification – only eight constraints were identified in four look-ahead plans.

Regarding the execution of work packages that had not been planned, these should be considered as normal to some extent due to the nature of the design process, widely discussed in the literature (e.g. Reinertsen, 2009; Cross, 2008). However, as pointed out by Ballard *et al.* (2009), unplanned assignments should be identified and analyzed in short-term

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Design teams	Design phase	Number of weeks	Average CRI (%)	Average PPC (%)	Causes for the non-completion of work packages	Categories of causes
T3	Conceptual design	5	36	64	Changes in priorities (19%) Lack of design definitions by clients (19%) Underestimated duration (16%)	EDD processes: 37% Other company's departments: 16% External to the company: 47%
T4	Conceptual design	5	59	61	Underestimated duration (19%) Client request for design change (14%) Software related problems (9%)	EDD processes: 40% Other company's departments: 33% External to the company: 27%
T5	Detail design	5	33	68	Underestimated duration (24%) Client request for design change (18%) Lack of design definitions by clients (18%)	EDD processes: 37% Other company's departments: 63% External to the company: 0%
T6	Detail design	4	75	78	Software related problems (30%) Delays in conceptual design (15%) Changes in priorities (15%)	EDD processes: 35% Other company's departments: 15% External to the company: 50%

Table III.
Data for T3, T4, T5 and T6

planning in order to consider them in future planning cycles. The design teams decided to monitor the incidence of those tasks, and take sometimes this type of information to discuss in design meetings. Although no analysis of performance measures related to unplanned tasks has been made in this investigation, design team members consider that monitoring those tasks was useful for highlighting some planning failures, including urgent demands from downstream processes.

The main contributions of this phase for the development of the model include: a joint analysis of performance measures was undertaken for each team with the aim of encouraging improvement – a monthly feedback cycle was suggested for this set of metrics; the use of rolling look-ahead plans was extended to all design teams; the control of design deliveries was improved by monitoring their adherence to planned design batches in the long-term plan, in an attempt to limit the amount of work-in-progress; and the level of standardization of design planning was increased, e.g. creating lists of constraints and categories for the most common causes for the non-completion of work packages.

Integrated medium-term planning and visual management

At Phase 4, the use of visual management boards to encourage collaborative planning and support decision-making was proposed. Two types of boards were used: one that integrates medium-term planning across different design teams; and another one that supports individual team planning meetings and to encourage improvement initiatives. The integrated medium-planning board (Figure 4) was updated weekly at design planning meetings, which had the participation of staff from the planning department.

The planning horizon for conceptual design was four weeks, while in detail design a two-week horizon was adopted, since design batches tend to be smaller in the latter. As mentioned above, the company expected that downstream processes could pull detail

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	Week 1					Week 2					Week 3					Week 4				
Conceptual design teams	M	T	W	T	F	M	T	W	T	F	M	T	W	T	F	M	T	W	T	F
A																				
B																				
C																				
Assignment delayed																				

Design assignments

Figure 4.
Integrated medium-planning board (including schematic representation of the tool)

design work packages. Moreover, a board for managing constraints at design planning meeting was devised.

Figure 5 presents an example of visual device to support the work of individual design teams. That board contains the look-ahead plan (two or four-week horizon, based on the integrated medium-term plan), a list of constraints to be removed, printed copies of short-term plans, and some performance metrics, including PPC and CRI.

The visual boards were useful for EDD and the Planning Department, but also for other departments that were involved in removing constraints, such as sales and cost estimating. After the visual management boards were implemented, the duration of the integrated design meeting was reduced to half a day, making the participation of all design managers possible.

Overview of the design planning and control model

Figure 6 presents an overview of the proposed design planning and control model. It is divided into four hierarchical levels, and contains some key elements of the LPS.

Level 1 is concerned with long-term planning, considering all projects being undertaken by the company, and the capacity of each design team. That plan is produced by the Planning Department, based on deadlines defined in contracts and on the integrated

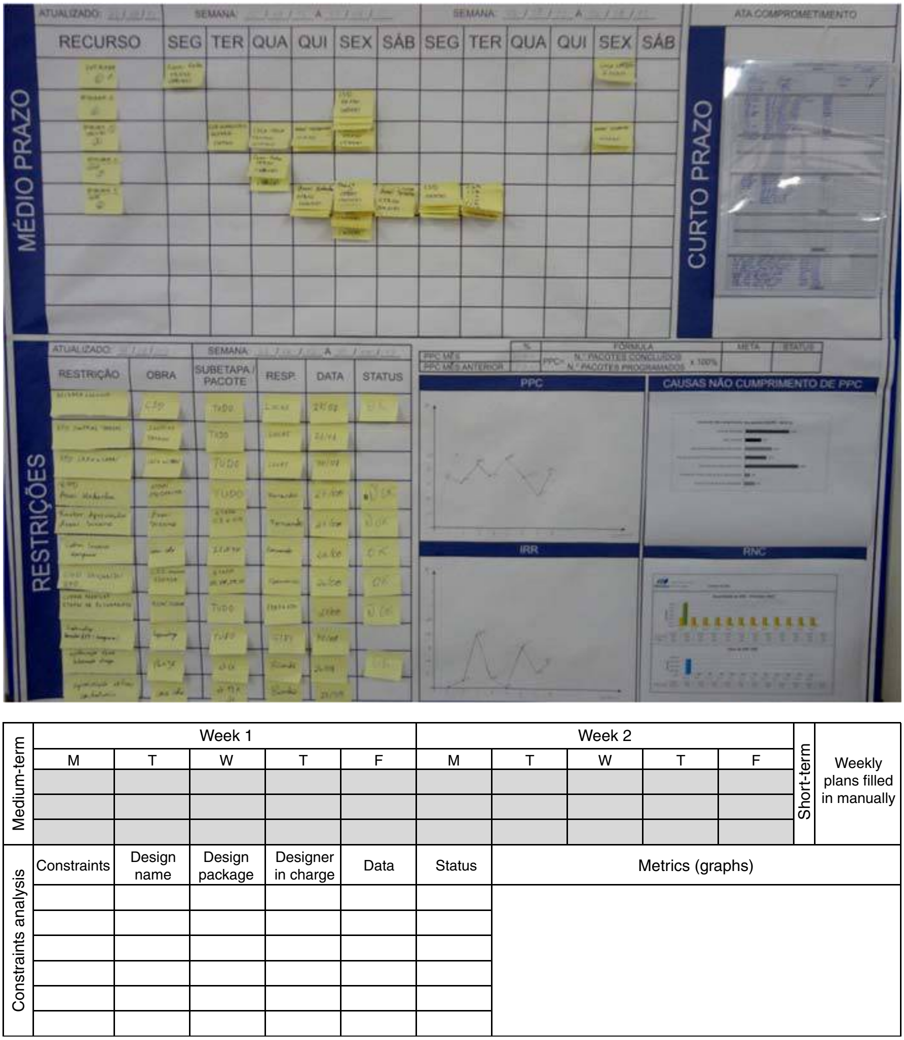

Figure 5. Individual team planning meeting board (including schematic representation of the tool)

medium-term design plan, in which monthly goals are established for EDD. ABI is the metric used at this level to control adherence of the monthly output to long-term plans.

At Level 2, a weekly integrated medium-term design planning meeting is carried out, in which the external constraints for design development can be jointly analyzed, supported by visual devices. This meeting should be connected with an integrated meeting between fabrication and assembly, so some information that could change design priorities come from that meeting (e.g. plant idleness, lack of payment by client and assembly delays). At this point, a decoupling point exists between conceptual and detail design. The integrated look-ahead plans are updated weekly, looking four weeks ahead for conceptual design and two weeks ahead for detail design, considering both the targets established in the long-term plan and also the level of work-in-progress for each team. CRI is the main metric used at this level.

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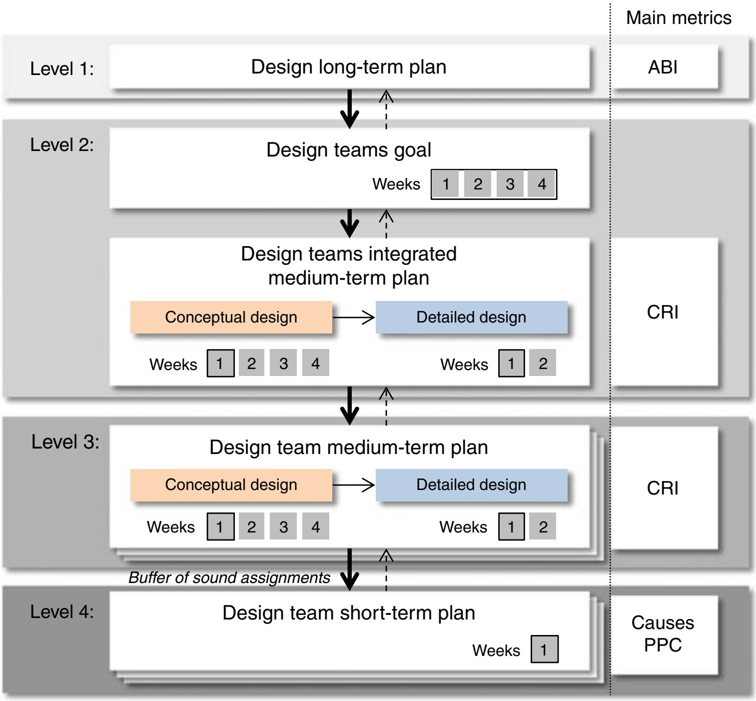

Figure 6.
Proposed design planning and control model

A weekly meeting is carried out separately by each design team, supported by visual devices, to produce a medium-term plan at Level 3 (same horizons adopted at Level 2) and a short-term plan at Level 4. In those meeting, an analysis of constraints is performed, and a backlog of sound assignments to be included in the short-term plan is prepared (operational level). CRI is the metric used at medium-term plan. Causes for the non-completion of work packages and PPC are the metrics used at short-term plan.

Evaluation of the model and discussion

As mentioned in the research method section, the model was evaluated according to two main constructs: applicability and utility. Figure 7 presents the assessment of the degree of implementation of planning practices in March 2013 (T1, T2, T3, T4, T5 and T6) and August 2013 (T1, T2, T4 and T5).

Applicability

In four out of nine design teams, look-ahead and short-term planning meetings were carried out systematically. As pointed out by Ballard (2002) and Kerosuo *et al.* (2012), systematic planning and constraints analysis allow a better understanding of the design interdependences by the designers. In fact, the degree of implementation of practices 1 and 7 (Figure 7) was high (75 percent). Another evidence of success is the fact that the duration of the meetings was largely reduced along the implementation process: short-term design meetings took around 30 minutes for T1 and T2, and the duration of the integrated look-ahead planning meeting was reduced from two days to half a day.

There were differences between design teams in terms of making planning and control systematic. This was largely due to the impact of design managers commitment and leadership.

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Planning practices	Teams										Degree of implementation of practices			
	Detail design				Conceptual design			Detail design						
	T1		T2		T3	T4		T5		T6				
	M	A	M	A	M	M	A	M	A	M	March 2013		August 2013	
Short-term plan														
1. Short-term planning and control routine	1	0.5	1	1	1	0.5	1	1	0.5	1	92%		75%	
2. Sound definition of work packages	1	0.5	1	1	1	1	1	1	0.5	1	100%		75%	
3. Only work packages that have no constraints in the weekly plan	0.5	1	0.5	1	0.5	0.5	0	0.5	0.5	0.5	50%	74%	63%	73%
4. Backlog of sound assignments	0	1	1	1	1	1	1	1	0.5	1	83%		88%	
5. Participative decision making in short-term meetings	1	1	1	1	1	1	1	1	0.5	1	100%		88%	
6. Corrective actions based on the reasons of non-completion of the plans	0	0	1	0.5	0	0	1	0	0.5	0	17%		50%	
Medium-term plan (lookahead)														
7. Look-ahead planning and control routine	0.5	0.5	1	1	0.5	0.5	1	0.5	0.5	0.5	58%	50%	75%	63%
8. Systematic removal of constraints	0.5	0.5	0.5	1	0	0.5	0	0.5	0.5	0.5	42%		50%	
Long-term plan														
9. Production of a visual long-term plan	0.5	0.5	0.5	1	0.5	0.5	1	0.5	0.5	0.5	50%		75%	
10. Use of metrics to evaluate compliance with the master plan	0.5	0.5	0.5	1	0	0	0.5	0.5	0.5	0.5	33%	61%	63%	71%
11. Systematic updating of long-term plans to reflect project status	1	0.5	1	1	1	1	1	1	0.5	1	100%		75%	
Planning practices at levels 3 and 4 of the model														
12. General design planning and control model implementation	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	50%		50%	
13. Monthly metrics analysis by teams (ABI, CRI, PPC, Causes)	0	0.5	0.5	0.5	0	0	0	0	0.5	0	8%	22%	38%	46%
14. Use of visual devices by teams	0	1	0	1	0	0	0	0	0	0.5	8%		50%	
	50%	61%	71%	89%	50%	50%	64%	57%	46%	61%	57%		65%	

Implemented (1) – Partially implemented (0.5) – Not implemented (0) | March 2013 (M) – August 2013 (A)

Figure 7.
Degree of implementation of design planning and control practices in March 2013 and August 2013

In the most successful teams (T2 and T4), the weekly planning meeting was always held, even when the design manager was unable to participate.

Following the suggestions of Tzortzopoulos *et al.* (2001), Ballard (2002) and Kerosuo *et al.* (2012), the training program, involving the six design teams, played an important role in disseminating the core design management and project planning and control concepts and practices among those teams. This program also helped to conceive the model, as implementation results were widely disseminated and discussed with representatives of different departments of the company, as suggested by Ballard (2002).

Utility

Shielding design work from variability. The main innovation introduced in the design planning and control process was the adoption of two levels of look-ahead planning: first, at a higher hierarchical level, the external constraints analysis was undertaken at the

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integrated design planning meeting; second, internal constraints analysis was carried out each design team. The average PPC (71 percent) for six different teams indicated that basic stability of design work was improved along the implementation process.

In fact, there were evidences that the proposed model was helpful in implementing medium-term planning: the practice "look-ahead planning and control routine" achieved the degree of 75 percent. This was pointed out as a major difficulty in previous studies (Miles, 1998; Tzortzopoulos *et al.*, 2001; Codinhoto and Formoso, 2005; and Ballard *et al.*, 2009). However, the design teams still faced difficulties in performing "systematic removal of constraints" (50 percent in August 2013) and no substantial growth was observed in CRI, especially at the conceptual design stage. Indeed, there was a large number of constraints related to client decisions that were identified late, only at the detail design stage. The strategy of making the design process more transparent to the client, especially at early design stages, was suggested by some design teams as an improvement opportunity related to that problem.

Encouraging collaborative planning. The company was also successful in terms of increasing the degree of participation in planning and control. Design team members increased the level of participation in planning meetings over time, and the level of collaboration between different teams increased with the introduction of the integrated design planning level. The practice "participative decision making in short-term meetings" achieved 88 percent. As a consequence, planning became less centralized and designers became more committed in terms of producing weekly design deliverables.

Creating opportunities for learning. There were also evidences that the model provided opportunities for learning due to systematic feedback obtained from performance metrics and the opportunities for discussion provided by participative planning meetings. For instance, the reduction in the incidence of the planning failure named "underestimated time" for T1 and T2 indicated that those teams improved their capacity of matching load and capacity.

Some of the feedback provided came from traditional LPS metrics (e.g. PPC, reasons for the non-completion of work packages, total number of constraints per week, and CRI). However, there were other metrics that played a key role in terms of pointing out improvement opportunities: adherence to batch (ABI metric), and monitoring unplanned design activities carried out weekly. In both cases, it is necessary to monitor deviations and also the reasons for it. Despite the importance of monitoring adherence to batch as a mechanism to limit the amount of work-in-progress, it was difficult to implement that measure in all design teams. This is partly due to the traditional practice adopted by the company of measuring design output in terms of weight (in tons).

Another practice related to learning, considered in the evaluation was the "monthly metrics analysis by teams," with the support of visual boards. Such joint analysis was performed by individual design teams once a month, in a meeting for reviewing the monthly performance. Participant observation in design meetings indicated that the analysis of metrics with the support of the design manager had a motivating role in design teams, although the degree of implementation of this practice was limited (38 percent).

The main improvement at the short-term planning level was performing "corrective actions based on the reasons for non-completion of plans," from 17 to 50 percent. That practice was much emphasized in the training program and it is often mentioned in the literature as a weak point in the implementation of LPS (Hamzeh *et al.*, 2009).

Increasing process transparency. The use of visual management boards was crucial for improving the effectiveness of the implementation process by increasing the availability of the information to support decision-making both at a tactical and operational level. The degree of implementation of the practice "production of a visual long-term plan" was improved from 50 to 75 percent. Such boards addressed one of the problems identified in Phase 1 of this research: lack of transparency in the design process, creating difficulties for the Planning Department to match the production capacity of EDD. Collaborative planning was also encouraged as more people were aware of project status.

Despite the importance of making visible LPS's metrics (Ballard, 2002), the existing literature does not report that as being systematic in design planning and control. Additionally, process transparency is particularly important in the context of ETO prefabricated building systems, due to the high level of complexity involved.

Flexibility according to projects status. Some degree of flexibility should be provided by allowing plans to be produced according to project status, due to the high uncertainty involved in ETO production systems. Therefore, some order confirmation points must be established in the planning and control process (Viana *et al.*, 2013), in which activities must be pulled from downstream processes (Hopp and Spearman, 2008).

The fact that the model divides planning and control in four hierarchical levels provides opportunities for revising plans, based on an update of project status. In this respect, the integrated look-ahead design planning meeting played a key role in providing such flexibility, as it involves both design managers, and planning staff that are able to confirm orders from manufacturing and assembly production units. This strategy can only be made effective if design batches are kept small. For that reason, monitoring the adherence to batch size, measured by ABI, can contribute to achieve the necessary flexibility.

Conclusion

The main outcome of this research is a design planning and control model for companies that design, manufacture and assemble prefabricated ETO building systems. In this type of production system uncertainty tends to be high, and many interdependencies exist among different production units, since these share resources (e.g. plants, equipment, crews, etc.).

The model was devised as an adaptation of the LPS for ETO multiple-project environments, being formed by four levels of planning, a set of metrics and visual devices that support communication and collaboration. By using a design science research approach, this investigation has a prescriptive character: the proposed model can be used by companies that deliver prefabricated ETO building systems as a starting point for developing engineering design planning systems.

Several contributions have been proposed to improve the design planning and control process: use of two levels of look-ahead planning, based on the assumption that there are two types of constraints (external and internal) and that these should be dealt with at different hierarchical levels in the company; introduction of the integrated design planning meeting, which is a mechanism to allow plans to be produced according to project status; introduction of a decoupling point between conceptual and detail design, allowing the latter to be pulled by the demands of construction sites and manufacturing plants; extending the set of metrics of the LPS, so that adherence to batch size is controlled as well as the incidence of non-planned work packages, including the causes of failures; and understanding the potential role of visual management to support collaborative planning and joint analysis of metrics in an environment of much complexity.

The implementation of the model indicated that it helps to shield design work from variability, support collaboration among design team members, as well as provide opportunities for learning by providing systematic feedback to decision makers. However, some limitations were identified in the implementation process: similarly to some previous studies (Ballard, 2002; Codinhoto and Formoso, 2005), the success of constraint analysis was still limited; some of the metrics produced (e.g. ABI, causes of planning failures) have not been fully used for process improvement; and systematic feedback about project status was not properly implemented and tested.

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Moreover, it must be emphasized that the development of the model was based on a single empirical study, carried out in a company that delivers steel structures. Further work is necessary to test and refine the model in other organizational contexts and also for other prefabricated building systems.

Finally, based on the development of this investigation, some other opportunities for future studies must be pointed out: investigate the role of leadership in medium and short-term planning meetings; explore the use of design batches as planning and control units, instead of design activities or deliverables (e.g. drawings); improve the integration between the different planning levels proposed in the model, such as between design and downstream processes (e.g. manufacturing and site assembly), and between individual and integrated medium-term planning level; further test the use of the metrics proposed in this research work (CRI and ABI), and establish a theoretical basis for analyzing those data; and investigate mechanisms to manage client related constraints at the conceptual design stage.

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