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REVIEW

Model for planning and controlling the delivery and assembly of engineer-to-order prefabricated building systems: exploring synergies between Lean and BIM[1]

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Abstract: The adoption of prefabricated building systems has grown due to the need to reduce duration and cost of construction projects, as well as to improve quality and working conditions. However, the adoption of those systems requires an intense exchange of information to integrate the production of components, logistics operations, and site assembly. This is particularly important in engineer-to-order environments, in which the level of uncertainty tends to be high. This research proposes a model for planning and controlling the delivery and assembly of ETO prefabricated building systems, emphasizing the integration between site installation and logistics operations. This model was devised in an empirical study carried out in a company that delivers and assembles prefabricated concrete structures. The main theoretical contribution is a set of approaches to implement the "pull production" and "reduce variability" principles in this particular context, exploring synergies that exist between Lean Production principles and Building Information Modeling (BIM) functionalities.

Key words: logistics management, 4D BIM, Lean Production, prefabrication, engineer to order.

Résumé : L'adoption de procédés de préfabrication d'immeubles a augmenté en raison de la nécessité de réduire la durée et le coût des projets de construction, ainsi que d'améliorer la qualité et les conditions de travail. Toutefois, l'adoption de ces procédés nécessite un échange intense d'informations afin d'intégrer la production de composants, les opérations logistiques et l'assemblage sur chantier. Ceci est particulièrement important dans les environnements de fabrication pour projet, où le niveau d'incertitude a tendance à être élevé. Cette recherche propose un modèle de planification et de contrôle de la livraison et de l'assemblage des systèmes de préfabrication d'immeubles dans un environnement de fabrication pour projet, en mettant l'accent sur l'intégration entre l'installation du chantier et les opérations logistiques. Ce modèle a été conçu dans le cadre d'une étude empirique menée dans une entreprise qui fournit et assemble des structures préfabriquées en béton. La principale contribution théorique est un ensemble d'approches pour mettre en œuvre les principes de « production tirée » et de « réduction de la variabilité » dans ce contexte particulier, en explorant les synergies qui existent entre les principes de production allégée et les fonctionnalités de la modélisation des données du bâtiment (MDI). [Traduit par la Rédaction]

Mots-clés : gestion de la logistique, modélisation des données du bâtiment (MDI) 4D, production allégée, préfabrication, fabrication pour projet.

1. Introduction

The literature points out several advantages of prefabricated building systems when compared with traditional construction methods such as increase in productivity, improvement of working conditions, space savings for material storage onsite, better quality control, elimination of production waste, and higher sustainability performance (Pheng and Chuan 2001; Chen et al. 2010; Thuesen and Hvam 2011; Čuš-Babič et al. 2014; Jansson et al. 2014).

Those benefits are strongly related to the fact that many activities are carried out in a controlled environment (Ballard and Howell 1998*a*) and also related to the simplification of the production process by reducing the number of steps, parts, and linkages (Koskela 1992). By contrast, there are some additional challenges in the management of the overall construction process, due to the fact that there are two or more production locations (prefabrication plants and site), increasing the need for coordination efforts (Koskela 1992), especially regarding logistics management (Lessing et al. 2005).

The interdependence between construction sites and manufacturing plants is particular important for engineer-to-order (ETO) prefabricated building systems, which demands a fast-response capability to customer demands (Mcgovern et al. 1999). ETO production systems can be defined as the one in which the customer order decoupling point is located at the design stage, i.e., the customer order is delivered at the beginning of the design phase of a product (Gosling and Naim 2009). Such production systems have a growing importance in the construction industry (Viana et al. 2013) and are fundamentally different from the ones named make-to-stock (MTS), in which products are mass-produced and stored so that customers are able find these products right away (Tommelein et al. 2009).

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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. Those authors also state that the complexity of ETO systems can be associated to the high level of uncertainty related to sales volume and mix and the diversity of interdependent processes, including non-physical flows (e.g., design) and physical flows (e.g., manufacturing processes). In the case of ETO prefabricated building systems, there are some additional sources of complexity: (*i*) project lead-time is usually short, requiring some degree of overlapping between project stages; (*ii*) there are several unanticipated conflicts among different trades onsite (Trebbe et al. 2015); and (*iii*) some resources such as manufacturing plants and assembly equipment and crews must be shared among different construction projects, making them interdependent (Viana et al. 2013).

Matt et al. (2014) state that manufacturing processes are often disconnected from site assembly processes in ETO prefabricated building systems due to unreliable planning and control systems and ineffective communication between those two production units. Tommelein (1998) points out that assembly crews frequently face the so-called matching problem, i.e., resources are spent to ensure that the right component is delivered in the right place.

In this context, managing logistics plays a key role in the delivery of prefabricated systems. Logistics operations must be efficient and reliable, especially when there are long distances between the manufacturing plant and the construction site (Skjelbred et al. 2015; Bortolini et al. 2019). Pheng and Chuan (2001) suggest that time savings from faster assembly may wither away if logistics operations are not properly planned and controlled.

Moreover, Sacks et al. (2003) suggest that it is necessary to integrate the management of plants that produce prefabricated components and the construction sites where these are assembled, by using real-time feedback information. According to Lessing et al. (2005), industrialized processes require accurate and reliable information, considering emerging events, and information and communication technologies can provide solutions for information exchange and data storage. Effective communication is essential for the adoption of a pull approach for controlling production, in which production planning and control systems are able to respond to changes that might happen either at the construction site and at the plants (Tommelein 1998).

This research work proposes the combined use of concepts and principles from the Lean Production philosophy and Building Information Modeling (BIM) functionalities for planning and controlling ETO prefabricated building systems. Although these can be regarded as two separate approaches for improving the performance of production systems in the construction industry, there are evidences that there is much synergy between them (Sacks et al. 2010).

Lean Production is a production philosophy originated in the automobile industry that has been adapted with success in construction companies from several different countries (Tommelein et al. 2009; Sacks et al. 2010; Skjelbred et al. 2015). Two core Lean Production principles seem to be particularly relevant for the management of ETO prefabricated building systems: pull production and reduce variability.

Previous studies on production control of ETO prefabricated building systems suggest that production or supply of prefabricated components should be pulled from site assembly to keep a low level of work-in-progress, as well as to consider demand variability that typically exists in construction sites (Bulhões et al. 2006; Viana et al. 2013). A major challenge in the management of prefabricated building systems is to avoid stoppages due to the lack of components available while also avoiding increase in work-in-progress (Skjelbred et al. 2015).

Regarding the reduction of variability, Sacks et al. (2010) suggest that it is necessary to reduce not only product variability, but also upstream flow variability, which is particularly important for ETO industrialized building systems. Due to the importance of logistics in this kind of production system, it is necessary to standardize not only value-adding (transformation) activities, but also logistics operations, which are often neglected for being considered as non-value-adding activities (Koskela 1992).

BIM can be defined as a set of interacting policies, processes, and technologies (Succar 2009), which can be used to manage the building project data in digital format throughout its life-cycle (Penttilä 2006). The adoption of BIM can potentially improve the quality of information available for planning, possibly increasing the predictability of project delivery (Gledson and Greenwood 2017).

Several previous studies have investigated the use of four-dimensional (4D) modelling to support production management in construction such as workspace planning (Choi et al. 2014), detection of spatial and temporal conflicts (Kassem et al. 2015), testing alternative sequences of tasks (Chau et al. 2004), resource utilization management (Wang et al. 2004), construction schedules and site space arrangement (Ma et al. 2005), site material supply (Yu et al. 2016), internal site logistics (Bortolini et al. 2019), and analysis of the impacts of conflicts on health and safety (Zhang et al. 2015). However, none of those studies have fully addressed the role of logistics management in the integration between the production and delivery of prefabricated building components and site assembly.

This research work proposes a model for planning and controlling the delivery and assembly of ETO prefabricated building systems, emphasizing the integration between site installation and logistics operations. The main theoretical contributions of this investigation are concerned with how to implement the "pull production" and "reduce variability" principles in this particular context, by exploring synergies that exist between Lean Production principles and BIM functionalities. This research is based on the results of an empirical study undertaken in close collaboration with a company that designs, manufactures, and assembles prefabricated concrete structures in Brazil. This empirical study was carried out in a specific construction project, in which some improvements in logistics management were implemented.

2. Lean Production principles for managing ETO prefabricated building systems

Although pull production is considered one of the core concepts in the Lean Production philosophy (Hopp and Spearman 2000), there is no full agreement in the literature on the definition of a pull production system. Frandson et al. (2013) state that pull systems are driven by demand, so that they ensure a steady flow because output rates and demand rates are matched; whereas push systems are driven by a plan or a forecast, so that output rates and demand rates are not necessarily matched. Rother and Shook (1999) distinguish pull from push by the direction of information flows: in a push system, information flows in accordance to material flow or each process is scheduled independently; while in the pull system, information flows in the reverse direction in relation to material flows.

For Hopp and Spearman (2004), what distinguishes a push system from a pull system is the way in which work is released to the production system: in pull production, work is released according to system status rather than based on customer demand. That extended conceptualization of pull production seems to be more applicable to complex production systems, as in ETO prefabricated building projects. Hopp and Spearman (2004) consider the client as an external member of the system, arguing that the so-called benefits of pull production refers to the method of releasing work through internal processes and controlling work-in-progress. Hopp and Spearman (2000) point out that most production systems are hybrid, i.e., there are no pure push or pure pull systems.

The implementation of the pull production principle depends on the use of other principles. Hopp and Spearman (2004) point out that simply limiting work-in-progress is not a sufficient condition to improve performance and that the "continuous improvement" principle must also be applied, so that the level of work-in-progress can be gradually reduced. This practice is related to the effort to reduce the batch size, which contributes to the reduction of cycle time (Hopp and Spearman 2004). Working in small batches provide opportunities for construction teams to learn from the production of previous cycles (Koskela 1992). Moreover, short cycle times make production systems more adaptable to changes (Johnston and Brennan 1996), which is highly relevant for ETO prefabricated building systems.

The Last Planner System is a planning and control model widely used in construction sites, which is capable of dealing with the uncertainty and complexity in construction projects by involving crew leaders and lower level management in decision-making (Ballard and Howell 1998*b*). It is typically divided into three hierarchical levels. At a higher level, long-term (or master) planning establishes the general goals to be achieved during the execution of the project (Ballard and Howell 1998*b*). At the look-ahead (medium-term) planning level, constraints are identified and removed, ensuring that the necessary resources, e.g., materials, information, and equipment, are made available (Tommelein and Ballard 1997). Finally, at the short-term planning level, production reliability is increased by shielding planned work from upstream variation and by seeking conscious and reliable commitment of labour resources by team leaders (Ballard and Howell 1998*b*).

The Last Planner System can be considered as a combination of pull and push planning, based on the extended definition of pull planning proposed by Hopp and Spearman (2004). The master plan can be regarded as a coordinating map that pushes completions and deliveries, based on long-term forecasts. At both the look-ahead and short-term planning levels, production is pulled according to information on the status of the production system such as availability of resources (materials, space, design documents, etc.), whether the available capacity matches the demand, or emerging interferences among different crews.

A key issue in planning and control of ETO prefabricated building systems is how to connect the Last Planner System, which is commonly used for site installation, to logistics management, considering both internal operations in relation to the construction site and external operations, i.e., concerned with the delivery of components from prefabrication plants.

Logistics is concerned with a wide range of activities, including flows of information and also physical flows, being concerned with storage, handling, transportation, and distribution of resources (Sullivan et al. 2010), with the aim to provide an acceptable service to the customer (Rushton et al. 2010). Regarding the context of prefabricated building systems, different types of activities are involved in logistics management, including the following: (*i*) coordination of manufacturing plants, delivery of components onsite, and site assembly; (*ii*) design of loading and unloading operations; (*iii*) definition of site layout, including the location of temporary facilities, equipment, storage areas, and pathways; and (*iv*) decision-making in situations that involve conflicts related to space or time (Agapiou et al. 1998; Waly and Thabet 2003).

Regarding reduction of variability, it is important to define strategies that are suitable for ETO prefabricated building systems: (*i*) when variability cannot be eliminated, there must be a mechanism for protecting the production system from upstream variability such as in the Last Planner System (Ballard and Howell 1998*b*); and (*ii*) not all standards must defined at the beginning of the project, in a top-down fashion, but can be gradually established, considering the complexity that exists in this type of production system (Bortolini et al. 2019).

3. 4D BIM for managing ETO prefabricated building systems

Ergen and Akinci (2008) point out the role of information and communication technologies in the management of information flow in ETO prefabricated building systems. Those authors argue that due to the customization involved, each component needs to be tracked individually and component-related information needs to be exchanged and be either readily available or easily accessible between plants, expedition, and onsite assembly.

BorjeGhaleh and Sardroud (2016) discuss the potential benefits of applying BIM in the management of industrialized building systems, highlighting the use of 4D BIM for planning material, labour force, and equipment flows at different stages of the process. BIM adds a level of accuracy to both quantity and quality issues that overcomes the shortenings found when traditional processes of design and documentation are used and creates the possibility of building a virtual prototype for the whole project before physical construction begins (Zhang et al. 2016).

BIM can be very helpful in planning carefully the use of space, which represents a limited resource in the construction site (Kassem et al. 2015). This is particularly important in some construction sites located in central urban areas, where there are constraints regarding the delivery of components or operation of transportation equipment, including working times or number of deliveries per day (König et al. 2011). Choi et al. (2014) suggested a workspace planning process in a 4D BIM environment that considers characteristics of activity, workspace, and construction plan.

Bortolini et al. (2019) proposed a hierarchical model for managing internal site logistics using 4D BIM, based on an empirical study carried out in a steel fabricator company. Bortolini et al. (2019) proposed a set of tasks for defining logistics operations, including the following: (*i*) revision of the assembly sequence; (*ii*) definition of the construction site layout, including temporary facilities, storage areas, and routes for vehicles and pedestrians; (*iii*) analysis of conflicts between plans from different crews or companies working onsite; (*iv*) design of unloading operations; and (*v*) design of critical assembly processes. Another important contribution of the study undertaken by Bortolini et al. (2019) was the idea of using 4D BIM for supporting logistics management, at different hierarchical planning levels: (*i*) long-term logistics plan; (*ii*) batch logistics plan at the look-ahead planning level; and (*iii*) logistics control at the short-term planning level.

Finally, Bortolini et al. (2019) explored the connection of 4D BIM with visual management. In that study, some visual devices were used for controlling batch size and inventory level and also supported "pull production" by using colour coding to identify transportation batches and inventories. Some of those visual devices were printouts of the 4D model, as suggested by Sacks et al. (2010), by using the BIM functionality entitled "automated generation of drawings and documents".

4. Research method

4.1. Methodological approach

Design Science Research was the methodological approach adopted in this investigation. This approach has a prescriptive character, seeking to devise solution concepts, named artefacts, to solve classes of problems (Van Aken 2004; Holmstrom et al. 2009). In this research study, the proposed artefact is a model for planning and controlling the delivery and assembly of ETO prefabricated building systems, with the support of 4D BIM.

The research strategy adopted was similar to action research, in which some members of an organization are engaged over a matter that is of genuine concern to them (Eden and Huxham 1996).

Fig. 1. Overview of the construction site. [Colour online.]

The research process involved the implementation of changes in a construction project, which were devised in close collaboration with the managerial staff of the company. Those improvements were implemented along several learning cycles, in which problems are understood, the necessary actions are planned and implemented, the results are evaluated, and a reflection is made, as suggested by Susman and Evered (1978). The proposed model emerged along those learning cycles, as well as the theoretical contributions of this investigation.

However, a major difference between the research approach adopted in this investigation and traditional Action Research is that in the latter the main outcome is not usually the development or evaluation of an artefact. By contrast, in this investigation, the changes introduced in the project were regarded as a means to devise an artefact. This approach is named by Sein et al. (2011) as Action Design Research.

4.2. Description of the company and construction project

The company involved in this investigation (named company A) is a large firm that delivers and assembles prefabricated concrete structures in the southern and southeastern regions of Brazil. It had four manufacturing plants located in different Brazilian states, and most of their operations can be described as ETO projects.

Company A was particularly interested in implementing Lean principles and BIM for improving the performance of logistics operations. In fact, this company had recently started a production management improvement program that was strongly based on the Lean Production philosophy. The interest on the adoption of BIM was strongly motivated by the growing demand by some clients.

The empirical study was carried out in one specific project of the company, a university campus of approximately 55 000 m², located in Porto Alegre, Brazil. Two-thirds of the reinforced concrete structure were prefabricated. Company A was in charge of the design and production of components, as well as site assembly. The components were produced at two different manufacturing plants located far from the site (400 and 700 km).

Figure 1 shows an overview of the construction site. The project was divided into three stages, according to assembly zones, and deadlines were established for each of them. There were severe constraints in the construction site in terms of working space and access, mainly due to the need of a large excavation for building parking areas at underground levels. Moreover, there was only one vehicle entry, a relatively narrow ramp that had to be moved a few times along the project.

4.3. Research design

The research process was divided into three phases: understanding the problem, development of the artefact, and analysis and reflection (Fig. 2). The empirical study was undertaken for 11 months, covering the whole period of site assembly.

Table 1 presents the main tasks and sources of evidence for phase 1. The first step of the research consisted in identifying a gap in knowledge, based on a literature review, and understanding an existing practical problem, as suggested by Van Aken (2004). The aim was to understand the context and identify improvement opportunities for company A, regarding the management of logistics processes. The assessment of logistics processes involved both the flow of components from the plants to the construction site and the exchange of information between those production units. Moreover, an analysis was made of the production planning and control system adopted in the construction site, including connections with logistics management. The results of that assessment were presented and discussed in a workshop involving the research team and representatives of company A.

Moreover, a three-dimensional (3D) BIM model for the concrete structure and construction site elements was built during phase 1, including concrete prefabricated components, some temporary facilities, pathways, and the main equipment. The prefabricated elements were modelled at the level of development (LOD) 300, and the construction site elements was modelled at LOD 200.

Fig. 2. Research design overview.

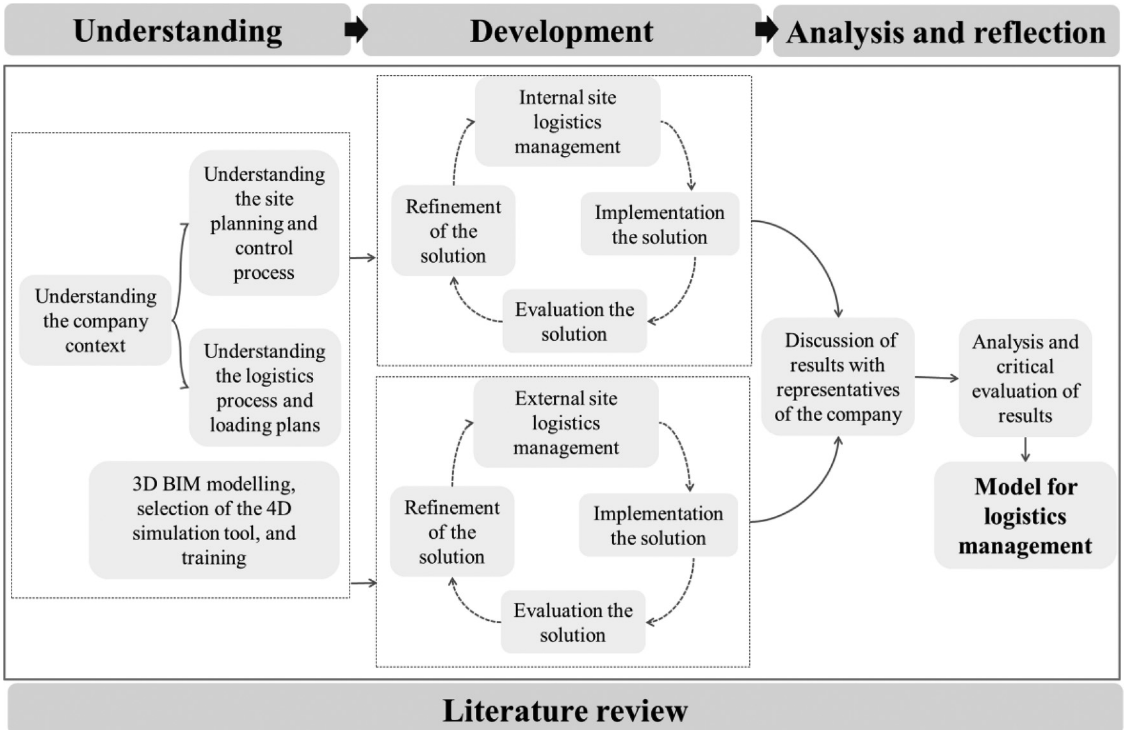


Table 1. Source of evidence adopted in phase 1.

Source of evidence	From	Aim
Direct observation and photographic record	Five visits to the construction site	Understand the process of planning and controlling the assembly process, understand the information flow between the manufacturing plants and the construction site; understand the process of planning the layout of the construction site
Participant observation	Four short-term planning meetings (1 h each), involving the site manager and representatives of the main contractor	Development of 4D models for site logistic planning
Documents analysis	Architectural and structural designs drawings, long-term plan	Development of 4D models for site logistic planning
Direct observation	Two visits to one of the manufacturing plants and plant yard	Understand the process of producing components
Unstructured interviews (around 1 h each)	Design coordinator, coordinator of the Integrated Planning Department, plant scheduling coordinator, quality manager, expedition manager, and assembly manager	Understand the interactions among the departments; understand the relationships between company A and their customers
Participant observation	First workshop, involving the coordinator of the Integrated Planning Department, construction manager, site manager, and trainee	Train the managerial staff on a set of core concepts (e.g., planning and control, pull production); present and discuss the assessment of company A's production planning and control system and logistics management.

Synchro PRO was the software package used for devising the 4D model, in which each component was initially linked to an assembly activity from the existing long-term plan, provided by the company. Thus, it was possible to cross-reference the semantic information of the model such as the name of the component according to the position (axis) or production batch with graphical information from the construction site layout such as pathways, possible areas for unloading, and inventories.

Table 2 presents the activities carried out in phases 2 and 3, as well as the sources of evidence used along the empirical study. In phase 2, participant observation was carried out in weekly planning meetings, in which 4D models produced by the research team were used to support decision-making related to logistics management. Some improvements were implemented by company A both in internal logistics (e.g., site layout, flow of components, and inventory areas) and external logistics (delivery from the manufacturing plants to the construction site), with emphasis on the integration of construction site and plant's planning and control systems. Participant observation was carried out in two medium-term planning meetings, in which a constraint board developed by the research team was used. Along this phase, two additional workshops involving the research team and representatives of company A were carried out for discussing the results of the implementation.

Table 2. Source of evidence used in phases 2 and 3.

Source of evidence	From	Aim
Direct observation and photographic record	21 visits to the construction site	Gather information about the layout of the construction site related to equipment, inventories, and temporary facilities, as well as assembly teams related to the activities in progress to compare with the planned activities. Analyse the needs for improvements based to informal conversation with the assembly team members. Analyse the implementation of the logistics plans, including the planning the loads.
Participant observation	One short-term planning meeting (1 h) involving the site manager and representatives of the general contractor	Implementation of the 4D modelling to onsite logistic planning.
Participant observation	Two medium-term planning meeting (1 h) with the site manager and the trainee	Constraint analysis: elaboration of constraint board related to each component to be assembled and which constraint should be eliminated.
Participant observation	18 short-term planning meetings (30 min each) with the site manager and the trainee	Discussion about the short-term plan and the load plans using the 4D models for the understanding the assembly sequence and improve the processes, as well as analyzing the PPC registers.
Analysis of documents	Design drawings and production plans	Obtain information for building and updating BIM models.
Participant observation	Second workshop, involving the company CEO, design manager, logistics manager, contract manager, coordinator of the Integrated Planning Department, construction manager, site manager, and trainee	Train the managerial staff on production planning and control concepts and the benefits of batch size reduction. Present and discuss results on the relationship between company A and the general contractor, as well as changes implemented in internal site logistics.
Participant observation	Third workshop, involving the company CEO, design manager, logistics manager, contract manager, coordinator of the Integrated Planning Department, construction manager, site manager, and trainee	Present and discuss the role of the load plans to integrate production, logistics, and assembly departments.
Open interviews	Five open interviews (30 min each) with the site manager and the trainee	Assess the results of the implementation process.

During phase 3, some open interviews were carried out with participants of short-term planning meetings with the aim of assessing the results of the implementation process. At the end of this phase, the final version of the model for planning and controlling the delivery and assembly of ETO prefabricated building systems was devised.

5. Research findings

5.1. Existing planning and control system

Participant observation in planning meetings and direct observation of the construction site indicated that there were major problems in logistics management, mostly due to failures in the information flow between the manufacturing plants and the construction site. In fact, the company had in practice two separate planning and control systems, one for site assembly and the other for the plants.

The focus of planning and control at the plants was to maximize the existing capacity. Based on the initial long-term site assembly plan, prefabricated components were produced in large batches to maximize the utilization of formwork and the reduce the time spent in setups. Therefore, by pushing the production of components in large batches, the existing uncertainty in site assembly was largely neglected. As a consequence, a large number of components were stored at the plant yards.

Likewise, the focus of the site assembly manager was to maximize the use of assembly team capacity. Although the site assembly process was divided into stages, the assembly batches were relatively large. Moreover, site assembly planning and control was not systematically carried out, which made the systematic exchange of information between the manufacturing plants and the construction site even more difficult. Therefore, site assembly planning and control process was largely ineffective due to the combination of two facts: (*i*) many changes had to be made in the assembly sequence, mostly due to changes demanded the client and delays in other processes; and (*ii*) the delivery of components was demanded by load plans produced by the assembly manager only two days before assembly data, as shown in Fig. 3.

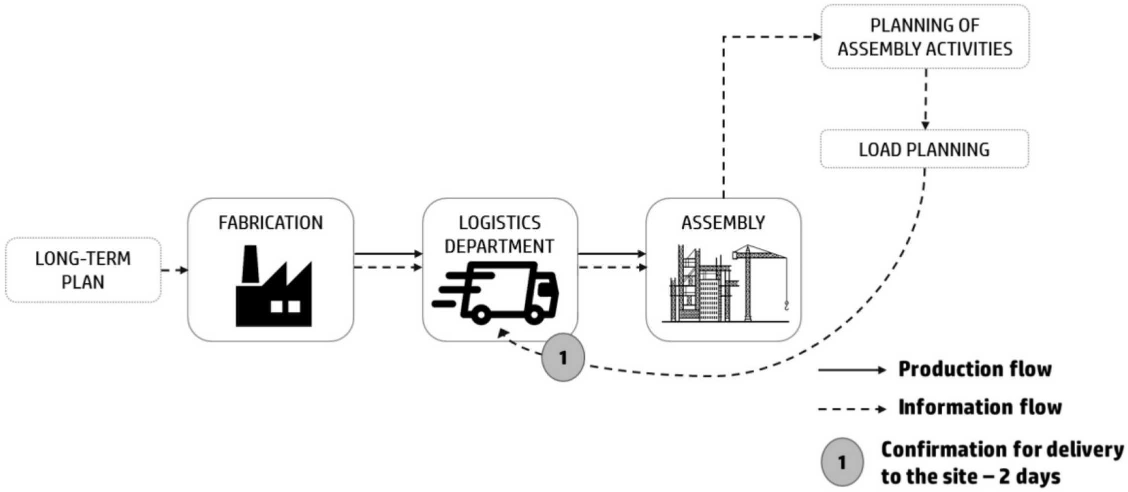
Due to variability, often the components contained in the assembly batch, as defined by the site manager, were not produced on time, resulting in delays in the assembly process. Consequently, only 22% of the planned loads were delivered on time to the construction site in stage 1, and the productivity of the assembly process was considered to be low (18 components per day) by the assembly team. The same problem occurred in stage 2: only 5% of the planned loads were delivered on time, and the productivity (26 components per day) was still lower than the goal of 30 components per day.

Therefore, the primary role of the logistics department was to fulfill the demands of site assembly, based on load plans. However, this department had also in mind the need to maximize the use of the existing capacity of trucks. Therefore, if there was available space in the trucks, some additional components not demanded by the construction site were also transported. Therefore, some unnecessary components were often delivered in the construction site, which increased inventories and restricted the area required for access and movement of equipment and people.

5.2. Internal site logistics management

At the beginning of phase 2, a plan for internal site logistics was produced, strongly based on the model proposed by Bortolini et al. (2019). Initially, a 4D model for site assembly was generated, based on a revised version of the master plan, in which the size of assembly batches was reduced in relation to the original plan. The decisions about site layout (e.g., access and inventory areas, loca-

Fig. 3. Existing confirmation point for the delivery of components.



tion of equipment and temporary facilities, pedestrian and vehicle traffic routes) and flow of components (e.g., storage areas, paths for transporting components) started to be systematically made by company A staff at medium-term planning meetings, with the support of the 4D BIM model. Then, the 4D model was frequently updated, based on refinements of the assembly sequence, made also at weekly planning meetings.

The areas for inventory and location of equipment required by each team was a critical decision in site logistics. Components were identified by colour, which represented batches defined for each team, as shown in Figs. 4*a* and 4*b*. Figures 4*c* and 4*d* illustrate the site assembly process. Temporary facilities were also positioned in easy-to-access places. Moreover, pedestrian and vehicle traffic routes were defined in a way to avoid interference between them, considering the need to improve safety.

Concrete prefabricated systems have some distinctive features when compared with other industrialized systems such as steel structural systems: components are heavier, and the number of components is relatively small. Components usually leave the plant ready to be erected and should be hoisted to be assembled directly from the truck. This increases productivity and reduce exposure to the risk of accidents. Sometimes it is necessary to store a small number of items (e.g., a supermarket inventory) as a slack. These inventory areas should be located as close as possible to the assembly working area to avoid unnecessary movement. The areas available for trucks and inventories in the construction site are shown in Fig. 4.

The main access was an important constraint mainly because the lowest underground level was 12 m below ground level. There was only one access ramp to the bottom level. The definition of the construction sequence was to some extent affected by the changing location of this ramp. Figure 5 shows the ramp positions in the 4D model. Some changes in that position were necessary due to the execution of foundations (e.g., positions 2 and 3). Some interactions among the processes of excavation, foundations, and concrete structure erection changed the execution sequence in such a way that caused the removal of the ramp before finishing the erection of the structure. As a consequence, one of the cranes that was used on the underground level had to be hoisted by another one located on ground level.

There was also a strong interaction between planning the physical (component, people, and machine) flows and the refinement of the assembly sequence, which was also carried out at both look-ahead and weekly planning meetings. Based on these two decisions, load plans could be produced. A load plan describes the component batches that must be transported in a truck to the construction site, including the delivery date. A visual board (Fig. 6) was then created to visualize the assembly sequence, indicating the location of components (by axes defined in design), assembly period (days), number of parts, and the volume of concrete to be assembled every day. This visual board was placed on a wall of company A's site office.

5.3. External logistics management

Regarding external logistics, the main change introduced was to produce load plans from updated information about the system status. Two sources of information were necessary for defining the system status: (*i*) definition of the components required for site assembly in the following week and (*ii*) confirmation whether the required components have been produced at the plant.

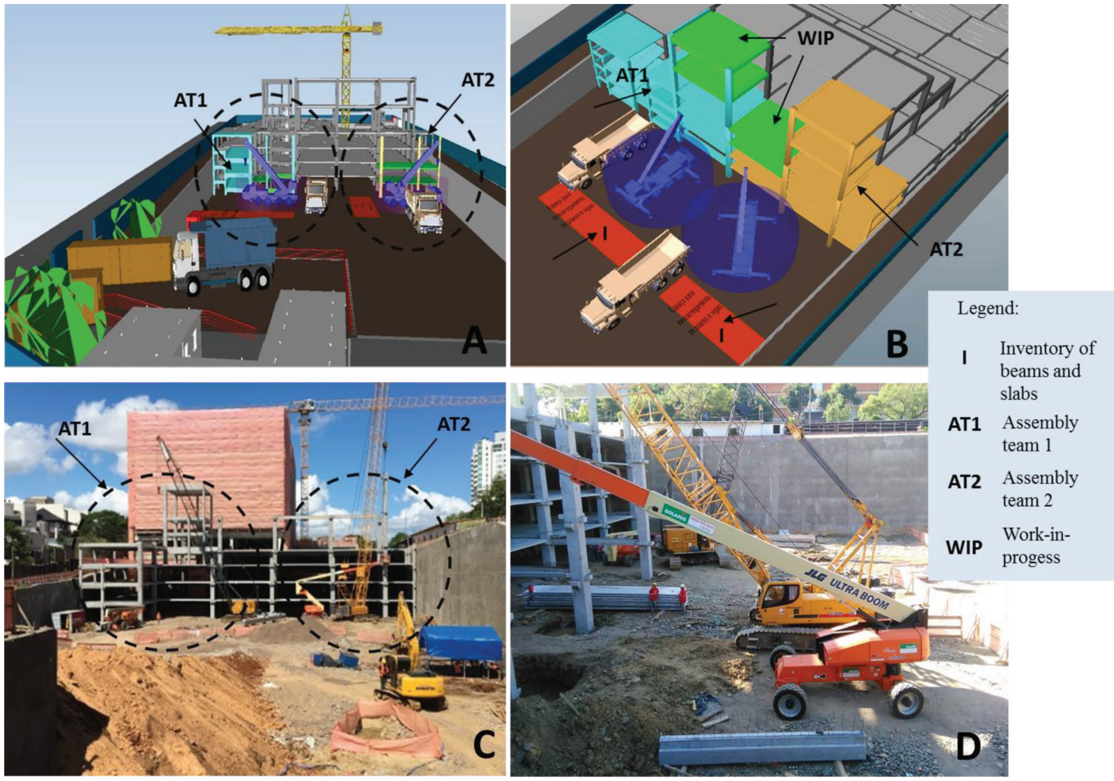
To facilitate the process of producing load plans, a spreadsheet was devised for tracking down the status of each component to be assembled, following the suggestion of Ergen and Akinci (2008). It contained data exported from the 4D model, including location, dimension, and assembly date of each component, as well as the status report from the plants (i.e., whether or not it had been produced). The development of this tool involved several cycles of data collection, analysis, and implementation, over a period of 3 months, during stage 3 of the project. Figure 7 shows the main information available in that spreadsheet, highlighting the required input information (dashed line) such as location axes and level.

An important characteristic of this kind of building system is the existence of some degree of repetition of components. For example, there were several slabs with the same name throughout different areas of the project. Therefore, it was necessary to cross-reference the description of the component and its location.

Length is a very important feature in the design of load plans. The components with a length longer than 12 m required a special type of logistics operation, as there are restrictions in terms of time of the day for transportation. For that reason, this type of operation was highlighted in orange (represented by circle in the length column in the Fig. 7). Production status was also highlighted in the spreadsheet: e.g., if a component has not been produced by the plant, the colour of the text was kept in red (represented by dashed–dotted line in the fourth line of the spreadsheet in the Fig. 7).

Regarding load plans, columns and beams could be in the same load. Other components such as slabs and stairs could only be transported with components of the same type. Thus, there were the following different load types: columns (PP), reinforced beams (VA), prestressed beams (VP), columns and beams (P+V), slabs (LA),

Fig. 4. Comparisons between 4D models and assembly process. [Colour online.]



and stairs (EC). In addition, there is a restriction referring to the maximum transport weight in Brazilian roads, which is 25 tonnes (Fig. 7, dotted line).

The people in charge of programming the operations at the manufacturing plants explained that one week was necessary for fabricating components and one additional week was required for including them in the plant schedule. Therefore, if the request for a component arrived 15 days before it was required on site, there was enough time to change the plant schedule.

Then, the construction site started to adopt confirmation points of 15 days in advance for producing components at manufacturing plants and two days in advance for delivering the components to the construction site. Soon, the same strategy started to be in other projects. The strategy of establishing confirmation points represents a way of decentralizing the planning process carried out in the company. This requires updated information on the system status to be available, so that the long-term plan is no longer the only source of information for scheduling at the manufacturing plants. In this process, 4D BIM played a key role by providing updated information concerned with assembly activities.

Figure 8 shows the number of loads delivered on time. In stage 3, there was an increase in the number of loads delivered on time compared with the previous stages, as well as an increase in productivity. Improvements in the load planning process, as well as the use of two confirmation points, made the exchange of information between the plant and the construction site systematic. The high percentage of deliveries on time (95% of the requests) indicates that site assembly planning and control became much more reliable, increasing the productivity to 39 components a day, on average.

5.4. Description of the model

Figure 9 shows an overview of the proposed model, which adopts the three hierarchical planning and control levels of the Last Planner System. Moreover, similarly to the model proposed by Bortolini et al. (2019), 4D BIM models are produced at different levels of planning, being gradually more detailed as more information becomes available.

The development of the 4D BIM model is the first activity to be performed, playing a key role in the initial discussions about the assembly sequence and logistics operations. The 4D model is produced by linking the 3D BIM model and the long-term production plan. When the information about the components to be assembled, the construction site, and the schedule are merged, the size and sequence of batches might be revised, with the aim of keeping the batch sizes small, and the sequence of batches as repetitive as possible. That long-term plan is also used to reserve the plant capacity to produce the necessary components for a specific project. At this level of planning, some overall logistics decisions are made about site layout, flow of components, storage areas, and position of equipment.

At the look-ahead planning level, it is assumed that the assembly sequence might need to be refined due to interferences from other onsite processes and changes demanded by the client. In planning meetings, 4D models can be used to visualize and assess the revised assembly sequence, as well as identify new constraints. Sometimes, it is also necessary to adjust internal site logistics decisions such as the flows of components, access and storage areas, location of temporary facilities, and definition of pedestrian and vehicle traffic routes. As those decisions are interdependent, they should be jointly discussed in look-ahead meetings in parallel with the revision of the assembly sequence.

At the short-term planning level, feedback concerned with site layout, flow of components, and assembly sequence is obtained. The traditional metrics of the Last Planner System can be used to measure planning effectiveness, the percentage of plans completed (PPC), and the causes for the non-completion of work packages, as suggested by Ballard (2000).

The proposed model contains an additional planning level in relation to the Last Planner System, which is concerned with two

Fig. 5. Different positions of the access ramp during the project. [Colour online.]

different triggers for starting the production and delivery of components. At the look-ahead and short-term planning meetings, activity lists can be revised, merging updated information from assembly plans and the status of each component. Based on that information, load plans can be defined. These are the source of information for the manufacturing plants to schedule the production of components and for the logistics department to plan the delivery of components on site.

However, before the loading plans can be used, there are two confirmation points (or triggers), one for the production of components at the manufacturing plant and the other for the delivery of components in the construction sites. The timing of those triggers depends on the lead times of manufacturing plants and the distance between them and the construction site. In the empirical study carried out in company A, the loading plans were checked daily, and the lead times were 15 and 2 days, respectively. This was the most important innovation introduced by the model regarding the connection between the planning systems from manufacturing plants and construction sites.

The introduction of confirmation points represents a change towards moving control from weekly planning meetings to process cycle time. Therefore, daily revisions are required, with the aim of checking possible changes in the status of each component, so that the production of components and their delivery to the construction sites can be pulled. Besides the traditional Last Planner metrics, other indicators can be used for assessing the performance of logistics operations such as reliability of load delivery, as shown in Fig. 8, as well as metrics for monitoring the number of components stored in plant yards or construction sites and the level of work-in-progress in the assembly process.

6. Discussions

Based on the description of the empirical study, there is evidence that the model has contributed to improve the performance of the project in two different ways: (*i*) by eliminating non-value-adding activities such as inventories, unloading operations, and waiting time; and (*ii*) by making the assembly process more reliable, despite of the uncertainty that exist in the assembly process.

Those objectives were achieved by implementing two core Lean Production: (*i*) pull production, based on the extended definition proposed by Hopp and Spearman (2004); and (*ii*) reduction of variability, by using the strategies of shielding the production system against unavoidable variability and standardizing both value-adding and non-value-adding activities, in a gradual and collaborative fashion.

Three approaches have been proposed for making pull production effective in ETO prefabricated building systems:

(*i*) Update the 4D model and logistics decisions at different hierarchical levels: by using three different planning levels, as in the Last Planner System, 4D models and logistics plans should be gradually detailed, considering the uncertainty that exists in ETO prefabricated building systems. If necessary, changes can be made in the assembly plan, based on up to date information on site conditions, interferences by other processes, or changes demanded by the client. Therefore, the long-term plan is used to reserve the capacity of the manufacturing plants for the project, rather than to push the production of components.

(*ii*) Display the system status by integrating information from fabrication and assembly: an important requirement for applying the pull production principle is to have information about the status of each component or batch in a single place. In the empirical case, an activity list stored in a spreadsheet was created, in which there was information about the design of each component, the assembly sequence (as designed in the look-ahead plan), and the status of each component in the manufacturing plant (e.g., produced or not produced). The first two pieces of information were directly imported from the 4D BIM model. Indeed, as suggested by Eastman et al. (2011), BIM is useful for providing precise, reliable, and up to date information for managing the flow of products in the supply chain.

(*iii*) Use confirmation points to pull the production and the delivery of components: two confirmation points (triggers) have been defined in the model, one for the production of components in the manufacturing plant and the other for the delivery of components on site, which are respectively connected to the mid- and short-term planning levels. By using those confirmation points, it is possible to limit the amount of work-in-progress, i.e., the inventory of prefabricated components, both at the plant yard and at the construction site.

Three approaches have been proposed for addressing the need to reduce variability:

(*i*) Define clearly the scope for the 4D BIM model that is necessary to support logistics management: the description of the BIM model must be based on standards to be used in the assembly process, including the identification and location of components and batch sizes and the sequence of assembly batches. The standardization effort must also be extended to several elements of the logistics plan such as site layout, position and size of inventories, transportation operations, and transportation batches. Therefore, non-value-adding activities that are often neglected in production management (Koskela 1992) must also be standardized to some extent, with the support of BIM.

Fig. 6. Assembly sequence board. [Colour online.]

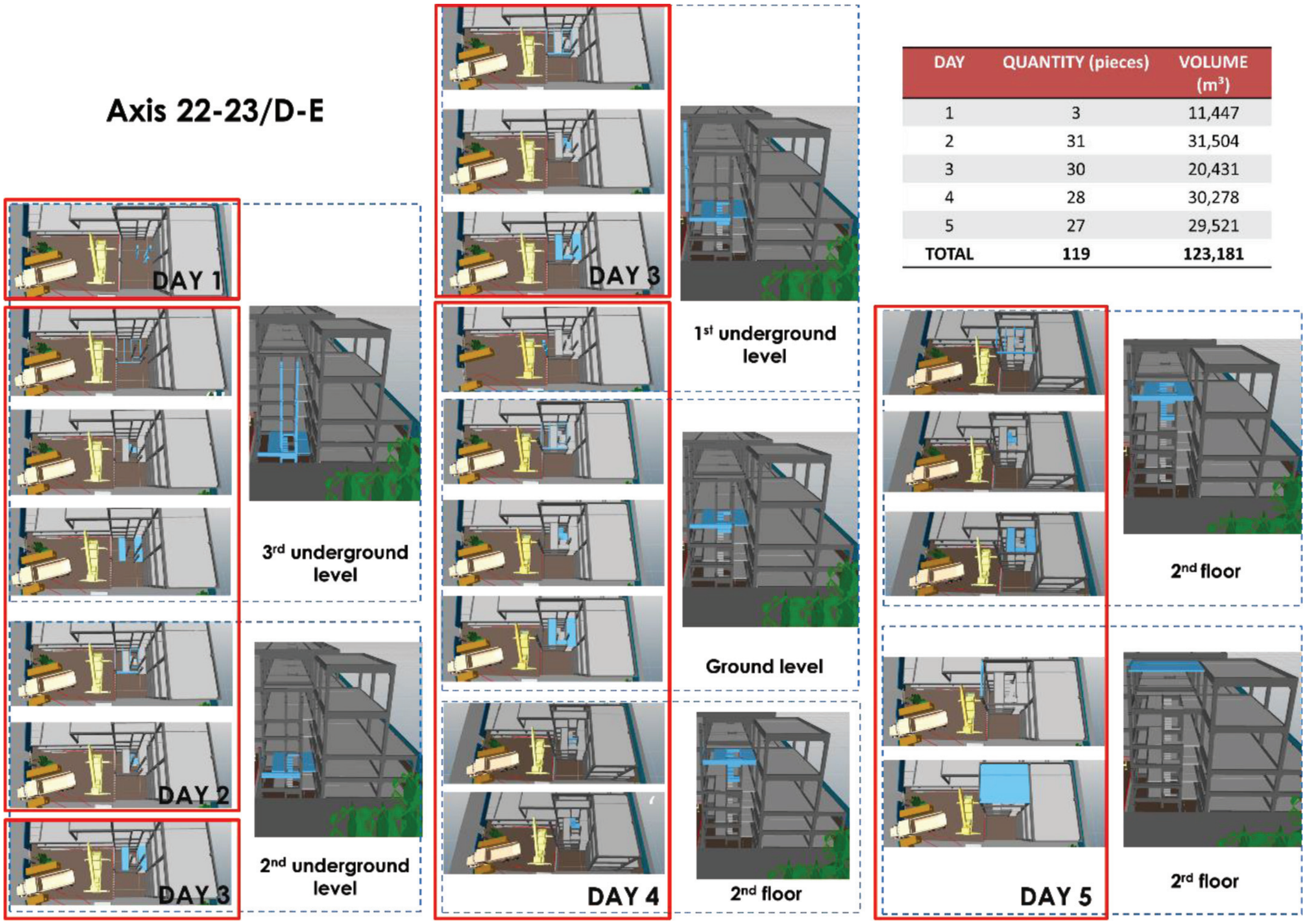
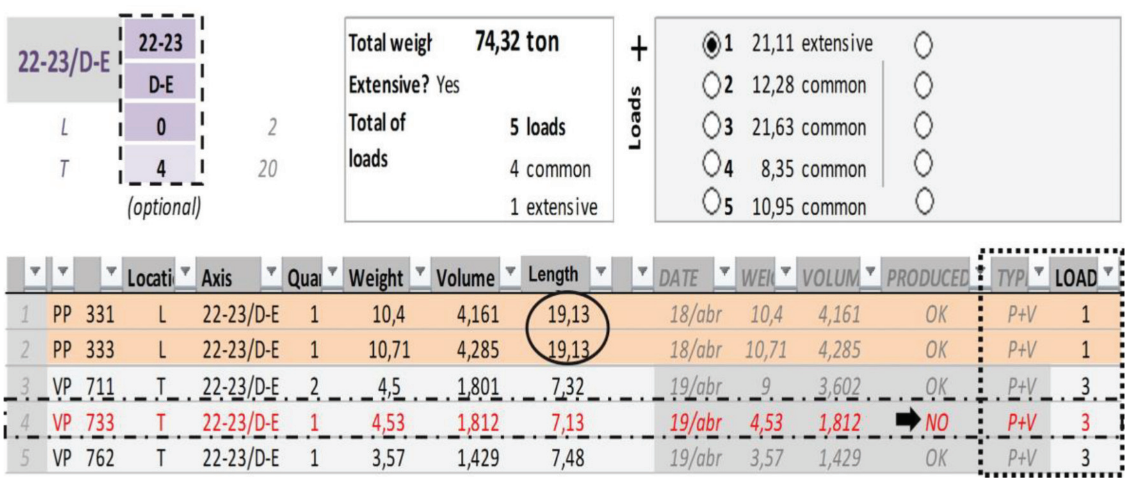


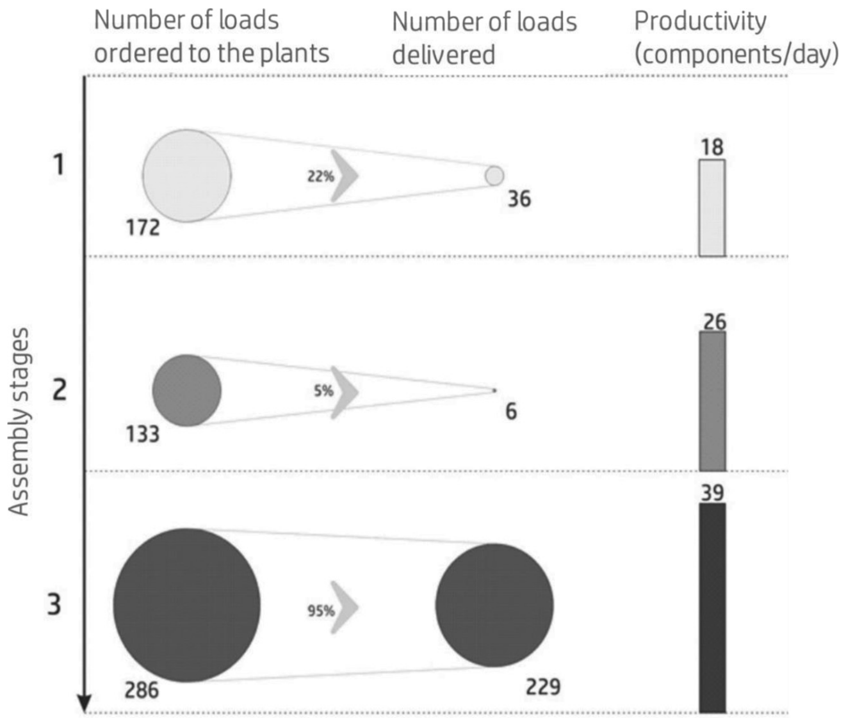
Fig. 7. Activity list developed to define load plans. [Colour online.]



(*ii*) Use BIM to support collaborative decision-making: in ETO environments, several changes often need to be made in middle- and short-term planning meetings, due to the high degree of uncertainty involved. 4D BIM models in planning can be used to support planning meetings by making the rapid generation and evaluation of construction plan alternatives possible (Sacks et al. 2010). As the definitions of the assembly sequence and logistics operations can be communicated easily among the participants of the planning process, team collaboration can be encouraged (Golparvar-Fard et al. 2009). By doing that, standards produced at planning meetings tend to be consensual and feasible, making the stakeholders more committed to them.

(*iii*) Use visual devices for disseminating information: besides the visualization of digital models, visual devices can be used to disseminate relevant information such as snapshots for representing specific details or they can be used for controlling the

Fig. 8. Reliability in load delivery and efficiency in the assembly process.



assembly process by comparing 4D models and real activities. Visual management can also help in the detection of possible deviations from standards.

7. Conclusions

This paper has two main contributions: (*i*) the development of planning and control model for the delivery and assembly of ETO prefabricated building systems, which emphasizes the integration between site installation and the production and delivery of prefabricated components; (*ii*) a set of approaches for implementing two core Lean Production principles, pull production and reduce of variability, which explore the synergies between Lean principles and BIM functionalities in this context.

The planning and control model can be regarded as the main practical contribution of this investigation and can be used as a reference for devising planning and control systems by companies that deliver ETO prefabricated building systems. The model adopts some of the core ideas of the Last Planner System such as hierarchical and collaborative planning. However, it proposes that part of production control should be carried out at a fourth hierarchical level, on a daily basis, which should be connected to the process cycle time, rather than only to weekly planning meetings.

The model also includes logistics management, in which two set of tasks have been defined: (*i*) internal logistics, which involves planning the site layout and the main flows involved in transportation, storage, and assembly of prefabricated components; and (*ii*) external logistics, which are concerned with the use of confirmation points for pulling the off-site production of components and their delivery to the construction site.

Data from the phase 3 of the project suggest that the implementation of the model has contributed substantially to the increase of the reliability of the overall planning process (95%) and to the increase in productivity (39 components per day).

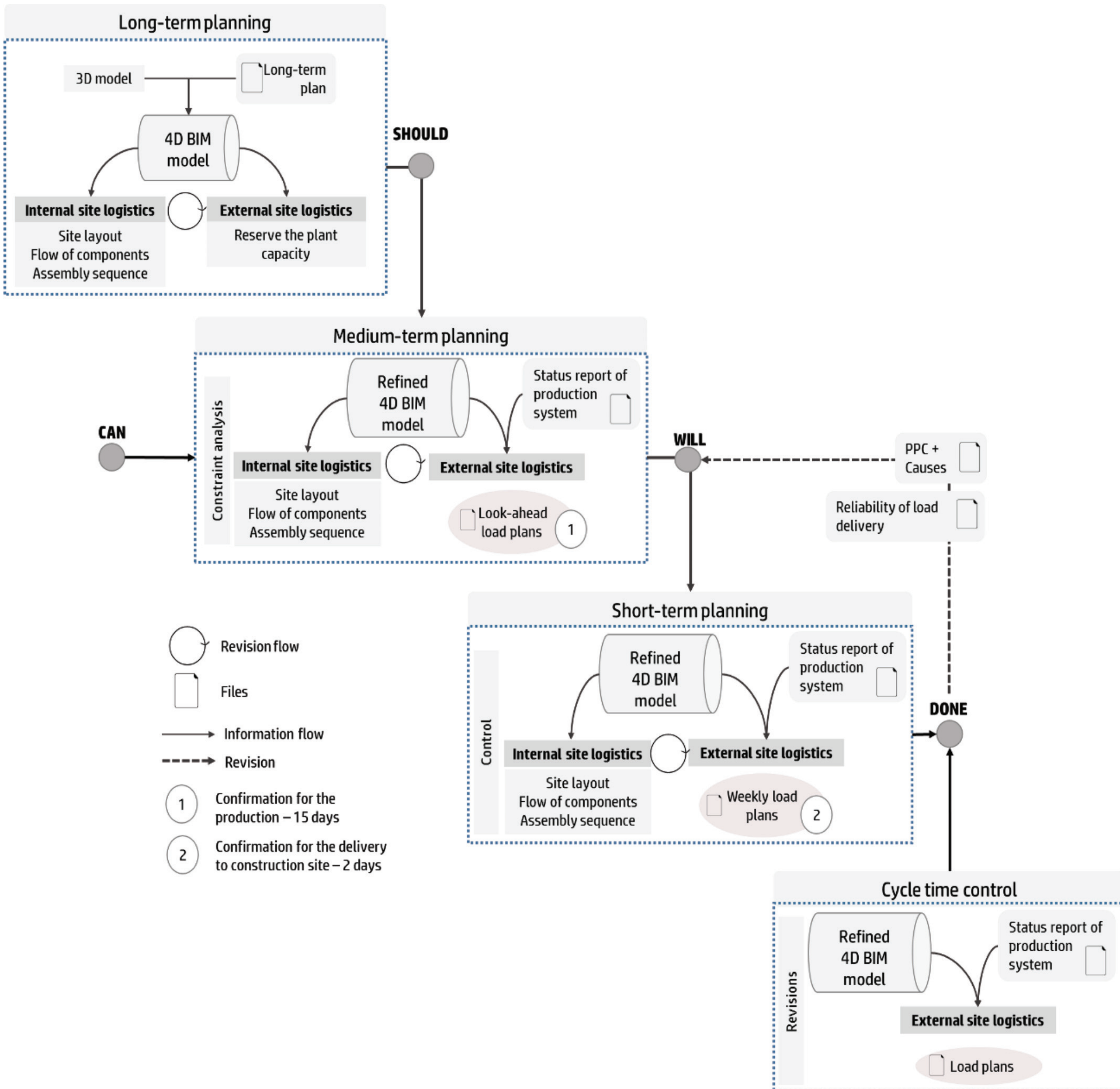
The main theoretical contributions of this study are concerned with the application of the pull production and reduction of variability principles to the specific context of ETO industrialized construction, in which a high degree of complexity exists due to the combined effect of interdependence between processes and variability.

Regarding pull production, the broader conceptualization proposed by Hopp and Spearman (2004), i.e., pulling as work released according to the system status, seem to be more suitable to the context of ETO prefabricated building systems, instead of the strict concept of pulling as work released according to the demand by the customer. This investigation suggests that the pull production principle can be applied by combining three different approaches: (*i*) divide logistics planning and control in different hierarchical levels, in which 4D BIM models and logistics decisions are revised according to up to date information about the system status; (*ii*) display information about the status of each component or batch in a single place, if possible extracting directly both geometric and semantic information from BIM models; and (*iii*) use confirmation points (triggers) to pull the production of components in the manufacturing plant and the delivery of components on site, based on information about the system status.

The application of the principle of reducing variability assumed that standards can be created later in the process, as more information about the system status is made available. Three approaches were combined for the implementation of this principles: (*i*) extend the scope of 4D BIM models to non-value-adding activities and temporary objects; (*ii*) use 4D BIM models to support collaborative decision-making; and (*iii*) use visual devices to disseminate information and allow the early identification of problems.

Regarding the limitations of this investigation, it must be pointed out that this research work was based on a single empirical study, and the focus was on pulling the production and assembly of components that had a relatively short lead time (15 days). Moreover, the site installation process involved only a single prefabricated system. Therefore, further research is necessary for investigating other contexts in which ETO prefabricated building systems are used such as construction projects that in-

Fig. 9. Proposed model for planning and controlling the delivery and assembly of ETO prefabricated building systems. [Colour online.]



volve several prefabricated building systems that need to be integrated, as well as also situations in which the production of some components need to be pushed due to long lead times.

Some other opportunities for further research have also been identified in this investigation: (*i*) explore the application of the concept of standardized work as a mechanism for synchronizing different processes in the construction site and manufacturing plants; (*ii*) investigate possible improvements in the design process that could contribute to the application of the principle of pull production such as the adoption of the concept of product modularity; and (*iii*) assess the impact of delays in the assembly process and large inventories at the plant yard and at the construction site to provide a cost estimate of the benefits of the proposed additional planning and modelling efforts.

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