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Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling

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ABSTRACT

There has been a growing demand for engineer-to-order (ETO) prefabricated building systems, in which a unique product must fulfill the requirements of specific clients. Although industrialized building systems can potentially simplify the production process, there is usually a high level of complexity in ETO production systems, such as uncertainty in client demands, short lead-time, overlapping between project stages, and resources that are shared among different projects. In this context, logistics management plays a key role in terms of achieving project goals related to cost, time and safety. This research work proposes the combined use of principles from the Lean Production Philosophy and Building Information Modeling (BIM), as a mechanism to cope with the complexity involved in those types of projects. 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. This paper reports the development of a logistics planning and control model for site assembly of ETO prefabricated building systems using BIM 4D modeling. The main theoretical contribution of this research work is the understanding of the synergies between Lean principles and BIM functionalities that are applicable to site logistics management, providing an example of how this body of knowledge can be expanded. This investigation also provides some practical contributions on how to carry out logistics planning and control at different hierarchical levels, with the support of BIM 4D modeling, aligning this process with the Last Planner System of production control. Design science research was the methodological approach adopted in this investigation, and the proposed model was developed and tested in empirical studies carried out in a steel fabricator company that designs, fabricates and assemblies steel structures.

1. Introduction

The potential benefits from prefabricated building systems are many and diverse: increase in productivity [1,2], improvement in working conditions [3], better quality, opportunity for producing complex building components at a lower cost [4], reduction of construction waste [5], and higher sustainability performance [6].

Differently from the idea of mass-producing off-the-shelf parts, there has been a growing demand for Engineer-to-order (ETO) prefabricated building systems, in which a unique product must fulfill the requirements of specific clients [7]. ETO production systems can be defined as the ones 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 [8]. Such production systems are fundamentally different from the ones that produce to a stock, namely make-to-stock (MTS), in which there is much repetition and products are mass produced, so that customers are able find these products right away [9].

Although industrialized building systems can potentially simplify the production process by reducing the number of steps, parts and linkages [10], there is usually a high level of complexity in ETO industrialized building systems: (i) the lead-time often needs be short, requiring some degree of overlapping between project stages [11]; (ii) a high level of uncertainty usually exists as it is necessary to define delivery dates at the early project stages, when the product is not completely defined yet [7]; (c) like any other construction project, there are several unanticipated conflicts among different trades on-site [12]; (d) it is usually necessary to deal with a complex supply chain that involve several companies or business units [13]; and (e) some resources, such as manufacturing plants and assembly equipment and crews, must be shared among different construction projects [14].

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A common mistake in the management of ETO production systems is to assume a high level of predictability, neglecting the complexity that exists in such environments [7,15,16]. In that situation, goals tend to be based on long-term estimates of demand and performance, and control consists of checking the adherence in relation to those goals [17]. In the case of industrialized building systems, a major consequence is that inventories tend to be large as the components are not produced and shipped to the construction site according to the assembly sequence, but following prioritization policies that favor large batches and freight optimization [3]. Another common problem is that planning and control is carried out separately for each production phase (design, manufacturing, logistics and assembly), increasing the project lead time [18]. This fragmentation tends to affect downstream flows, making the assembly process less reliable due to delays in the delivery of components, and the need to solve problems related to the poor integration of parts [19].

The focus of this paper is on logistics management, which plays a key role in the context of ETO prefabricated building systems [20], both at the preconstruction and construction phases [21]. Different types of activities are involved in logistics management of prefabricated building systems, such as the coordination of the delivery of components on-site, planning loading and unloading operations, defining the location of temporary facilities and equipment on-site [22,23], planning storage and handling of materials [24], and making decisions in situations that involve conflicts related to space or time [25]. In this context, logistics management must consider the need to pull the production and supply of components to the construction site from the assembly process, so that the share of non-value-adding activities (including inventories) is reduced. At the same time, logistics operations in prefabricated building systems must be efficient and reliable, especially when there are long distances between the manufacturing plant and the construction site.

This research work proposes the combined use of concepts and principles from the Lean Production Philosophy and Building Information Modeling (BIM). 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 [26].

Lean Production is a production philosophy originated in the automobile industry, which has been adopted in several different sectors, such as aerospace, consumer products, metal processing, construction and health-care [27]. The underlying concepts and principles of this philosophy provides a distinctive approach for logistics management. It emphasizes the reduction of waste, understood as resources or tasks that do not add value, such as transportation and inventories [28]. In the context of the construction industry, the Last Planner System®, proposed by Ballard and Howell [29], has been widely used as a collaborative planning and control model, being founded on a set of core Lean ideas, such as reduction of variability, pull planning, and continuous learning. In fact, Last Planner System® seems to be suitable for the context of ETO prefabricated building systems: (a) collaborative and decentralized planning seem to be more adequate in highly complex projects [30]; (b) it is possible to have confirmation points at the medium-term planning level, based on information collected in downstream processes in order to deal with uncertainty in demand [14]; (c) planning and control can be undertaken in a hierarchically organized set of meetings [31], making it possible to integrate planning and control among different processes and managerial levels.

BIM can be described as a set of tools, processes, and technologies that are facilitated by digital machine-readable documentation about a building, including its performance, construction plans, cost estimates, among other information, being able to provide the basis for new construction capabilities and changes in the roles and relationships among project team members [32]. Regarding construction logistics, one of the most relevant uses of BIM is to create 4D virtual simulations of the construction phase. Indeed, 4D models can support decision making, allowing the identification of possible problems in the construction phase, which may affect project performance in terms of cost, time and safety [33]. Numerous research studies have investigated the use of 4D modeling to support production management, such as testing alternative sequences of tasks [34], predicting logistics problems [35], detecting spatial conflicts between tasks [36], analyzing conflicts related to health and safety [37], monitoring progress discrepancies [38], improving site layouts [39], planning resource utilization [40], and analyzing workspace congestion [41].

However, none of those studies have fully addressed logistics management in industrialized construction, including the design of loads, detail planning of unloading and assembly operations, and control of inventories in construction sites. Only few and very specific aspects of logistics have been discussed so far, mostly related to positional planning of inventories and workspaces [39–41]. Moreover, in previous studies little emphasis has been given to the interactions between the implementation of Lean Production principles and BIM functionalities in logistics management of prefabricated building systems. In fact, in many practical situations 4D BIM models are simply a translation of the output of a CPM (critical path method) network [42,43] that contains only value-adding activities, a practice that has been widely criticized from the Lean Production perspective.

This paper reports the development of a logistics planning and control model for site assembly of ETO prefabricated building systems using 4D BIM. The main theoretical contribution of this investigation is to provide an understanding on the interactions between Lean Production principles and BIM functionalities, in the context of site logistics management. The matrix proposed by Sacks et al. [26], that contains 56 interactions between Lean Production principles and BIM functionalities, was used as a starting point for understanding this synergy. The scope of this research work is limited to construction site logistics, due to the important role played by the assembly process in that type of building system in terms of pulling upstream processes.

The proposed model was developed and tested in empirical studies carried out in a steel fabricator company that designs, fabricates and assemblies steel structures, mostly for industrial buildings, warehouses, supermarkets, and high-rise buildings. In those studies, 4D BIM was used to support logistics planning and control at different hierarchical levels.

2. Literature review

2.1. BIM functionalities for logistics management

Based on the matrix of interactions between Lean principles and BIM functionalities proposed by Sacks et al. [26], a set of functionalities was selected as the most applicable ones to site logistics management for ETO prefabricated building systems.

In the functional area of “rapid generation and evaluation of construction plan alternatives”, two functionalities are relevant for logistics management: “construction process simulation” and “4D visualization of construction schedules”. Regarding the simulation of construction processes, 4D models can be generated at multiple levels of details by connecting scheduled activities to 3D BIM models [32]. Alternative scenarios can be rapidly generated by 4D models, which allows the comparison and the simultaneous viewing of different alternatives for the sequence and pace of construction activities [44]. The functionality “4D visualization of construction schedules” is related to the capability that 4D models have to reduce the need for mental representations of how each co-builder schedules relate to each other on-site. It is possible to generate an overall view of the construction process, as well as the detail design of some key site operations [12]. Moreover, it is possible to use 4D models for integrating traditional construction plans, that include value adding activities only, with 3D representations of the existing conditions, including temporary facilities, equipment, and inventories, in order to identify conflicts [12].

In the functional area of "collaboration in design and construction", another functionality concerned with logistics management is "multiuser viewing of merged or separate multidiscipline models". Multidisciplinary coordination between disciplines is facilitated by the visualization of BIM models, enabling early identification of conflicts. Multidisciplinary models are already used in some proprietary software tools to check the coherency of design decisions from different disciplines [45]. In this respect, performing clash detection can contribute to enhance work flow reliability during the construction phase and, therefore, reduce rework in the field [46,47].

Another BIM functionality that can be associated to lean principles is "automated generation of drawings and documents". As construction progresses and changes in the plans are made, workers and operational managers need to have access to some consistent up-to-date information so that proper control can be undertaken [46]. In fact, logistics management is concerned not only with the flow of goods, but also with the flow of information. BIM can provide some support in that respect, as a single representation of the building model is made available, from which all reports can be produced automatically [32]. Therefore, automated generation of drawings, as well as images or videos from 4D models can be pulled in small batches by production managers [26].

Besides the BIM functionalities proposed by Sacks et al. [26], a new one is proposed in this research work: "visualization of flow activities and temporary objects". Flow activities are related to the space needed for the movement of people, equipment and materials, including unloading of materials, pathways, inventory areas, and working areas for the labor-force (e.g. pre-assembly and assembly areas in the case of prefabricated systems). Regarding the temporary objects, there are different types of equipment (e.g. crane, trucks), inventories, collective safety equipment, and temporary facilities that need to be considered in 4D BIM models. Those models can be used not only to visualize value-adding work, but also the flows and temporary objects that are relevant for site logistics.

A number of research studies have explored some of these BIM functionalities. The detection of conflicts between workspaces using the functionality "4D visualization of construction schedules" was analyzed by Chavada et al. [41]. Moreover, the analysis of simultaneously progress of parallel activities located in adjacent spaces using the same functionality was investigated by Moon et al. [48]. Trebbe et al. [12] explored the use of 4D models to coordinate different construction designs and schedules of co-builders using the functionality "collaboration in design and construction". Golparvar-Fard et al. [38] investigated the use of 4D photographs to visualize and analyze construction progress and workspace logistics. Said and El-Rayes [49] explored the use of BIM to facilitate automated detection and retrieval of construction site spatial data, which was used in a system to integrate and optimize material supply and site layout decisions. Chin et al. [50] explored the use of 4D with radio frequency identification (RFID) technology, to support the logistics and progress management of structural steel works.

Therefore, several previous studies have focused on specific problems, such as the use of 4D models to detect conflicts between scheduled production activities, monitor construction progress, and support the coordination of activities. Moreover, although 4D models has been used for simulation and analysis of production systems, it has been used mostly during the preconstruction phase, and rarely to support production control during the construction phase [50]. Although several researchers have investigated the use of BIM for supporting logistics management, none of them have focused on the specific problems faced by ETO production systems, such as the need to pull production, cope with uncertainty, as well as planning and controlling non-value adding activities. In fact, temporary objects such as inventory, pathways, equipment, flow of materials have received far less attention by research on BIM than value-adding activities [51].

2.2. Lean principles for logistics management

This section presents a set of Lean principles that were considered as relevant for site logistics management, using the matrix of interactions proposed by Sacks et al. [26] as a starting point.

The "reduce variability" principle is frequently suggested in the literature as one of the core principles of the Lean Production Philosophy [28,52]. Sacks et al. [26] emphasize that it is necessary not only to reduce product variability, but also upstream flow variability, which is particularly important for ETO industrialized building systems, as variability in logistics processes may have a negative impact in the assembly process on-site. The "standardize" principle can be regarded as one of the means to reduce process variability [28]. In the case of Logistics Management, it is important to point out that not only to standardize transformation activities (value-adding work), but also logistics operations, which are often neglected for being considered as non-value-adding [10].

It has been argued that the Last Planner System® is an effective way for protecting production from variability [53]. It is able to increase the reliability of short term planning by shielding planned work from upstream variability, and by seeking conscious and reliable commitment to plan execution by the leaders of the work teams involved [29]. At the medium-term level, constraints are identified and removed: the prerequisites of upcoming assignments are systematically identified, with the aim to ensure that the necessary inputs, such as materials, information and equipment are available [54].

"Introduce continuous improvement" is another the core principle of the Lean Production Philosophy: it is an internal, incremental, and iterative effort to reduce waste and to increase value that must be carried out continuously [10]. In complex projects, the principle of "decide by consensus" is also highly applicable, as it is necessary to work in multidisciplinary teams and to decentralize decision making [30,55].

In ETO prefabricated building systems, the "use pull systems" principle plays a key role in logistics management. Both the design and the production of components should be pulled from site assembly, in order to keep a low level of work-in-progress, as well as to consider demand variability that typically exists in site assembly [14]. Moreover, this also contributes to the application of the "reduce inventory" principle both at the manufacturing plant and in the construction site [14]. In that context, the extended definition of pull production, i.e. work released according to the system status rather than based on the demand by the customer, proposed by Hopp and Spearman [56], seems to be more applicable.

Reduction of work in progress is also strongly related to the "reduce batch sizes" principle, especially in relation to the need of transferring batches between different crews [56]. The application of the principles of "reduce batch sizes", "simplify" by reducing the number of steps, parts and linkages, and "use parallel processing" contribute to the application of the "reduce production cycle durations" principle, which creates favourable conditions for learning from mistakes in previous cycles ("continuous improvement" principle) [10].

The principle of "use visual management" is concerned with making the production process observable in order to facilitate control and improvement [57]. Visual management has an important role to play in providing clarity and availability of information [58]. In complex projects, it can be used to support the coordination of a large number of stakeholders and the execution of highly interdependent tasks, as well as to provide some degree of flexibility to adapt to short-term changes in product specification, workload balancing and personnel assignments [59].

2.3. Interactions between BIM functionalities and lean principles

Table 1 shows all interactions identified by Sacks et al. [26] for the BIM functionalities and Lean principles pointed out in the previous

Table 1

Selected interactions between BIM functionalities and Lean principles (see notes 1, 2, 3).

Lean production principles		BIM functionalities			
		Rapid generation and evaluation of construction plan alternatives		Collaboration in design and construction	Automated generation of drawings and documents (8)
		Construction process simulation (12)	4D visualization of construction schedules (13)	Multiuser editing of a merged or separate multidiscipline model (10)	
Reduce variability	Reduce product variability (A)		2	2, 13	11
	Reduce production variability (B)	15	40*	24	
Standardize (J)			17*		
Institute continuous improvement (K)					
Decide by consensus, consider all options (W)			49*	49*	
Select an appropriate production control approach: Use pull systems (H)			37		
Reduce batch sizes (E)					53*
Reduce cycle times	Reduce production cycle durations (C)	25*	25*	24	22
	Reduce inventory (D)		(29)	(29)	(52)
Design the production system for flow and value	Simplify (N)	(41)			
	Use parallel processing (O)		40*		
Use visual management	Visualize production methods (L)		40*		
	Visualize production process (M)		40*		

Notes:

[1] The numbers associated to lean principles, and the letters associated to BIM functionalities are the ones used by Sacks et al. [22].

[2] The interactions that were considered in this investigation are marked by a "*".

[3] Number between brackets means that it is a negative interaction.

sections. However, only five of them were initially chosen to be analyzed in this investigation, because these were considered as relevant for site logistics management of ETO prefabricated building systems: (i) "rapid generation and evaluation of construction plan alternatives" with the lean principle of "reduce cycle times" (interaction #25); (ii) "4D visualization of construction schedules", with the Lean principles of "use visual management" and "standardize" (interactions #40 and #17); (iii) "4D visualization of construction schedules" and "collaboration in design and construction", with the Lean principle of "design the production system for flow and value" (interaction #49); and (iv) "automated generation of drawings and documents" and the principles of "reduce batch sizes"(interaction #53).

2.4. Selected interactions between BIM functionalities and Lean principles

The interactions #1, #2, #11, #13, #22, #24, #29, and #52 were not considered relevant because these are concerned with the design process, while the interactions #15 and #37 are out of the scope of this investigation because they are only related to discrete-event simulation. The case study presented bellow explores some additional interactions between Lean principles and BIM functionalities that have not been pointed out by Sacks et al. [26].

3. Research method

3.1. Research strategy

Design Science Research was the methodological approach adopted in this investigation. It is a way of producing scientific knowledge that is different from the research strategies that are often adopted in the Social Sciences, such as Case Study and Action Research. A major difference is that Design Science Research has a prescriptive character, involving the development of solution concepts, named artefacts, that are meant to solve classes of problems [60]. By contrast, Case Study and Action Research are descriptive research strategies, which aim to explore, describe, explain existing social systems [61].

This research project was carried out in close collaboration with the managerial staff of a company (named here Company A), being similar to the research process that is usually conducted in Action Research. As suggested by Järvinen [62], some Design Science Research projects involve implementing changes in close collaboration with members of an organization over a matter which is of genuine concern to them. However, a major difference is that in Action Research the outcome of a research project is not the development or evaluation of an artefact. In this investigation, the intervention carried out in Company A was regarded as a means to devise an artefact. This approach was named by Sein et al. [63] as Action Design Research.

Fig. 1 presents an outline of the research design.

March and Smith [65] suggest that Design Science Research projects usually have a set of outcomes: (i) constructs, which form the conceptualisation in a specific domain, being used for describing a problem and specifying possible solutions; (ii) a conceptual model, i.e. a number of premises that express relationships among constructs or concepts; (iii) a method, which is a set of guidelines or steps for performing a task; and (iv) instantiations, which can be described as the implementation of a combination of constructs, models, and methods, with the aim of assessing the proposed solution [64]. In this research study, the proposed artefact, the site logistics planning and control model, is a method (or process model) that can be regarded as a practical contribution for companies that deliver engineer-to-order- prefabricated building systems. This method is founded on a set of Lean principles which interact with BIM functionalities. The main theoretical contribution is a conceptual framework that explains the synergies between those principles and functionalities. Three instantiations were produced in different construction projects for devising and testing the method.

This investigation was divided into the following stages: (a) literature review; (b) understanding the problem; (c) development; and (d) analysis and reflection, as shown in Fig. 1.

In the "understanding the problem" phase, two exploratory studies were carried out in different projects, focused on the analysis of site logistics problems faced by Company A, considering unloading operations, inventories, transportation of components on-site, and assembly operations. The aim of those studies was to get a deep understanding of the existing logistics management problems faced by that company, as well as to obtain the first insights for devising the model.

In the "development" phase, the main empirical study of this investigation was developed, in which the model was fully devised and implemented. As in most design science research projects, the development of the solution involved several cycles of planning, execution, data collection, and analysis. At each cycle, logistics plans were revised, based on feedback from site operations and also due to additional demands of information from site managers.

At the "analysis and reflection" phase, an evaluation of the proposed artefact was undertaken, and the practical and theoretical contributions of this investigation were depicted.

While descriptive theories need to be validated, in Design Science Research the proposed artefact must be assessed against criteria of utility [65] and usability [64]. In this investigation this was based on the multiple sources of evidence used in the empirical studies. Moreover, some generalizable lessons learned from the development and implementation of the artefact, mostly related to the interactions between Lean principles and BIM functionalities, have been drawn.

3.2. Description of the company and choice of projects

Company A is a large steel fabricator in Brazil that had more than 2000 employees, 3 manufacturing plants, and around 200 simultaneous contracts when this research study was carried out. Short delivery times and design flexibility are two key competitive dimensions for this company.

At the beginning of a project, the building(s) is(are) divided into stages with the aim of reducing batch size and keeping a low level of work in progress. This division also allows this company to have similar production batches at least in some parts of the project, which should make it easier to detect errors, as well to establish a relatively stable pace of work. Each stage of the project is divided into sub-stages, which consist of building modules that can be assembled independently from each other (e.g. primary structure, secondary structure, roof, finishings).

Table 2 presents a brief description of the three projects involved in this research work as well as the main challenges involved in site logistics in each of them. Those challenges were the main reasons for choosing those projects. In all of them, it was necessary to improve site logistics planning and control, and for Company A the implementation 4D BIM and the Lean principles represented improvement opportunities.

Project 1 was chosen due to the fact that the construction site had fierce limitations of space for moving equipment and material storage. Therefore, the focus of this study was to define the position and size of inventories and the type of equipment to be used in site assembly.

Project 2 was a large automotive site, comprising a car factory, park vendors, training center, research and development center, and test track. Company A was in charge of building the steel structure for nine industrial buildings. This study was chosen because of the challenge of supplying components to several buildings located sparsely in a very large construction site.

Project 3 consisted of a car manufacturing building, which was chosen because the client organization was very demanding in terms of schedule, safety and organization of the construction site. Moreover, this car manufacturing company was also strongly engaged in terms of improving the performance of the assembly process. In contrast with the practice often adopted by Company A of using a wide variety of

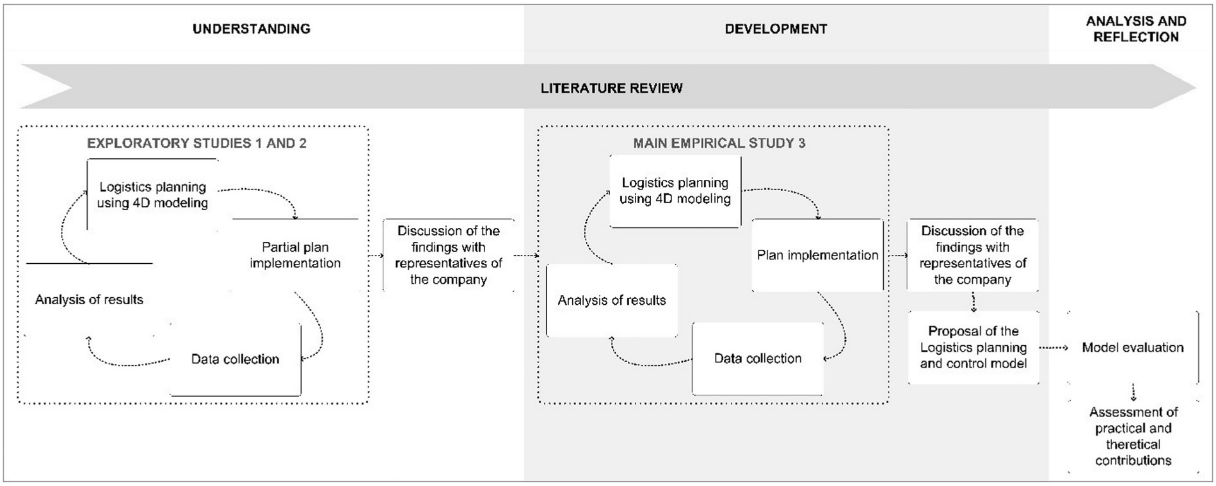

Fig. 1. Research design.

components for minimizing the weight (and the cost) of steel primary (beams, frames) and secondary (space trusses) components, the client organization demanded the structural design to be modified in order to reduce the number of different space trusses from 50 to 17 types. From one hand, this action resulted in an increase in the total weight of the structure and in the cost of materials. On the other hand, the processes of handling and assembling components became simpler.

3.3. Modeling process

BIM was not used at the design stage in any of the projects. Therefore, 3D BIM models were produced by the research team from the existing 2D drawings, using the ArchiCAD® software tool. Regarding the development of 4D models, the Synchro Pro® software tool was chosen. Long term plans, similar to a line of balance, were used as the starting point for the modeling process. The BIM model contained not only information about the steel structure components and assembly activities, but some temporary elements of the construction site were also included, such as cranes, articulated boom lifts, trucks, pathways, and position of inventories.

Several 4D BIM simulations were generated in each project, in order to support decision making in planning meetings. As suggested by Leite et al. [66], the intended use of a BIM model affects substantially the richness of the information embedded in it. Considering that logistics planning and control was carried out at different hierarchical levels, different levels of development (LOD) were used. In the case of the 4D BIM model, an important question that was addressed in this investigation was the LOD that a BIM model must have for different tasks involved in logistics planning and control.

3.4. Description of the empirical studies

The first exploratory study was divided into six phases, as shown in Table 3. Initially, an analysis of logistics management processes at the company level was made. Then 3D and 4D BIM models were produced, based on the analysis of project documents and site conditions, considering the existing long-term plan. After that, a site logistics plan was produced, including the site layout and the main flows of components and equipment, based on eight meetings held with the project coordinator and the site manager. The 4D BIM model was then refined in several meetings with the site manager, and the resulting logistics plan was partially implemented. At the end of the study, site visits and participant observation in planning and control meetings were carried out for assessing the implementation of site logistics plans.

The main phases of the second exploratory study are shown in Table 4. After a visit to the construction site and analysis of project documents, 3D and 4D BIM models were produced. A site logistics plan was then produced, based on four meetings held with the site manager. After that, the 4D BIM model was refined in several meetings with the site manager. The resulting logistics plan was partially implemented and three site visits and participant observation in planning and control meetings were undertaken for assessing the implementation.

The main empirical study was divided into seven phases, as shown in Table 5. A visit to the construction site was initially conducted to analyze site conditions, and to have a meeting with a client representative in order to understand the main client requirements. In the next phase, 3D and 4D BIM models were produced, considering the existing long-term plan and project documents. A site logistics plan was then produced, including the site layout and the main flows of components and equipment, based on four meetings held with the site manager and a client representative. Moreover, a loading plan was produced based on four meetings with the team responsible for shipping components. The 4D BIM model was then refined in several meetings with the site manager and a representative of the assembly subcontractor. The logistics plan was fully implemented and refined in this study. Participant observation was carried out in planning and control meetings, and fifteen site visits were carried out for assessing the implementation of site logistics plans.

4. Results

4.1. Existing site logistics planning and control system

Based on exploratory studies 1 and 2, the conclusion was made that Company A did not use to carry out logistics planning and control formally. In fact, the company did not have standard operations for site logistics, and most decisions were made informally, based on the experience of site assembly subcontractors.

In exploratory study 1, the location of inventories was defined by site management staff mostly at the time of arrival of components on site. Therefore, there were several problems related to site logistics, such as inadequate location of inventories, mixing of components from different project stages, and time-consuming transportation operations. Moreover, large inventories of components were unnecessarily stored on-site, which was critical due to the fact that this construction site was small and narrow. Fig. 2 illustrates these problems, showing the inadequate position of steel components, and a large inventory of thermal insulation parts which were delivered on site two weeks before being installed. Direct observation in the construction site indicated that productivity was negatively affected by the lack of site logistics

Table 2
Brief description of the projects.

Project	Type of project	Area (m^2)	Main challenges in site logistics	Duration
1	Eight-floor hotel building and four-floor garage building	7000	Lack of space to store materials and handling equipment	7 months
2	Nine industrial buildings in a car manufacturing complex	200,000	Large land plot, being necessary to avoid unnecessary transportation operations, and mixing materials to be used in different buildings	3 months
3	Single floor industrial building for a car manufacturing company	20,000	Need to coordinate logistics with the aim to avoid mixing sub-stage components on-site and flow conflicts with other suppliers. Client organization required a low level of inventories of components on-site.	5 months

planning.

In exploratory study 2, large inventories were particularly common on site, mostly due to the fact that the logistics department often mixed components from different buildings or stages in the same load due to the goal of minimizing freight costs. As this project had nine different buildings located sparsely in a large construction site, the task of organizing inventories adequately was very time consuming: a large number non-value-adding activities were necessary, mostly related to internal transportation and identification of components, before the assembly of steel structures. It is worth mentioning also that some components (e.g. ventilation and roof parts) were fragile and the need to move them around often caused damages.

4.2. Empirical study 3

In this construction site, some elements of the Last Planner System were implemented. Production planning and control was divided into three different hierarchical levels. A master plan was defined at the beginning of the project, in which there was an initial division of the steel structure into assembly stages. There were look-ahead planning meetings every two weeks involving the site manager and representatives of the assembly teams. At the short planning level, a weekly meeting was informally held between the assembly subcontractor manager and members of the assembly team.

Based on the master plan, a long-term logistics plan for the whole construction site was defined. Five meetings were held on-site to devise the overall layout of the construction site, based on the general sequence of assembly stages, including the position of inventory areas and temporary facilities, as well as equipment and pedestrian routes. Those meetings had the participation of the project coordinator (responsible for managing several projects simultaneously), representatives of the logistics department (in charge of defining shipping loads), the site manager, and client representatives (in charge of monitoring the project).

Some construction plan alternatives were rapidly generated and evaluated in planning meetings by using BIM 4D simulations. Those alternatives were analyzed by considering their impact in the logistics operations and site layout. Using a collaborative approach, the long-term logistics plan was refined several times, with the aim of eliminating non-value adding work and reducing cycle time.

Fig. 3 presents a long-term logistics plan, which includes the main stages and the overall layout of the construction site. The inventory area was located close to the preassembling area in order to reduce unnecessary transportation activities and increase productivity. This area was divided into zones according to the assembly stages to prevent mixing of materials.

Using the long-term logistics plan as a starting point, an action was taken to improve the delivery of components from the factory. In close collaboration with the research team, the Logistics Department of Company A became engaged in producing a detail plan for each shipping load, considering constraints related to weight and size of components. The first step was to refine the assembly sequence by detailing the components involved in each assembly stage (Fig. 3). The content of each load was defined according to the subdivision of project stages into sub-stages.

Three main assumptions were adopted when devising loading plans: (i) each load should only contain components of the same assembly batch (sub-stage); (ii) the position of each component in each load must not cause any damage on others (e.g. fragile components should be on the top); and (iii) when possible, the position of components should consider the unloading operation and the assembly sequence. Fig. 4 shows the main steps for developing the loading plans, starting from the project design, separating each component size and shape, distributing them in truck layers, and finally analyzing toppling risks. Among the different types of sub-stages, the loading plans of the primary structures were the most difficult ones to be designed, as these involved

Table 3
Activities and sources of evidence of exploratory study 1.

Activities	Sources of evidence
Analysis of logistics management processes at the company level	Open interviews with project coordinator and site manager Open interviews with representatives of the logistics department 1 visit (3 h) to the prefabrication plant and the plant yard
Analysis of site conditions and of the assembly process	Analysis of project documents (2D drawings, assembly instructions manuals) 1 visit (1 h) to the construction site
Development of a 3D and 4D BIM models, considering the existing long-term plan	Analysis of project documents: manufacturing and architectural design drawings, long-term plan
Production of a site logistics plan	8 meetings (1 h each) with the site manager and project coordinator for defining the site layout and the main flows of components and equipment Refinement of 4D model based on the analysis of different scenarios
Implementation and refinement of logistics plan	Participant observation in 8 weekly planning and control meetings (30 min each)
Control and assessment of the logistics plan	9 visits (30 min each) to the construction site

components of several different sizes and weights.

In addition, color labels were adopted to identify the component batches for each stage. Those visual devices adopted the same colors used in the BIM 4D models. The aim of using those color codes was to increase process transparency both in the preparation of loads at the plant yard, and in the organization of inventories at the construction site.

Using the BIM functionality "automated generation of drawings and documents", some visual devices were also produced from screenshots taken from 4D models (Fig. 5). These devices were placed on boards located near the assembly area, and in both Company A and client's site offices. Direct observation in the construction site indicated that those boards were used to monitor the assembly process and deviations in the position and size of inventories. They also supported discussions and facilitated the exchange of information about production plans and site layout, being used by different stakeholders, including the site manager, client representatives and subcontractors.

The implementation of site-logistics plans was monitored during a period of three months. Several unloading operations were observed, as well as the movement of equipment and workers. The aim was to identify the main causes of deviations and, when necessary, to revise logistics plans at the look-ahead planning level.

In one of the look-ahead planning meetings, the decision was made to produce a logistic plan for one repetitive assembly batch by using 4D BIM. This plan was named batch logistics plan, and the level of detail was higher than the long-term logistics plan. Stage 6 of the project was selected due to the fact that the previous stages had already been assembled and existing data on productivity and durations could be used to produce this logistic plan. The pre-assembly and the lifting of space trusses were specific processes considered in this plan, due to its importance in the assembly process, in the perception of Company A managers.

The existing look-ahead plan for the pre-assembly activities had to be revised, due to the large amount of work in progress. Besides reducing the batch size, a detail plan of this operation was produced in order to standardize and increase the efficiency of this process (including preassembly, lifting and assembly). The 3D BIM model was improved at this stage, including space trusses components at a level of development similar to LOD 350. The storage area and the assembly area were modeled in detail, and the schedule of the activities involved was represented in a 4D BIM model. Based on the measurement of the duration of different types of operations, the exact number of trusses to be assembled before a lifting operation was defined. The components were organized in line and positioned as close as possible to the preassembly area to avoid long transportation distances (Fig. 6).

This process was simulated by using 4D BIM several times as a virtual prototype, with the aim of having uninterrupted operations and a minimal inventory of trusses to be lifted. Using the tacit knowledge of both the site manager and the assembly subcontractor, an initial design for this operation was proposed. Client representatives also participated in the discussions, with the aim of considering their requirements. By visualizing construction schedules in 4D, the assembly process was refined in three look-ahead planning meetings. A further refinement of the 3D model was made in a first run study (as a physical prototype), in which the assembly team had the opportunity of suggesting improvements. Once this process was fully standardized, some visual devices were produced, based on screenshot images taken from the 4D model (Fig. 7).

A comparison was made between the performance of the assembly process before and after the implementation of the batch logistics plan, using three metrics: (i) number of assembled trusses in the storage area (work-in-progress); (ii) number of man-hours spent in the transportation of components, and (iii) the average distance walked by the assemblers. These metrics were monitored by a period of one week using a chronometer and videotaping, and compared to existing data in the company. As shown in Table 6, the average storage of assembled trusses was reduced in 60% and the number of men-hours spent in transportation operations was reduced in 38%, mostly due to the reduction of walking distances (on average 88%).

Fig. 8 illustrates some similarities of the preassembly and assembly areas in the virtual model and in the real construction site. Fig. 8(a) and (b) shows that the assembly and pre-assembly areas are near to each

Table 4
Activities and sources of evidence of exploratory study 2.

Activities	Sources of evidence
Analysis of site conditions and of the assembly process	Analysis of project documents (2D drawings, assembly instructions manuals) Open interview with site manager 1 visit (1 h) to the construction site
Development of a 3D and 4D BIM models, considering the existing long-term plan	Analysis of project documents: manufacturing and architectural design drawings, long-term plan
Production of a site logistics plan	4 meetings (1 h each) with the site manager for defining the site layout and the main flows of components and equipment Refinement of 4D model based on the analysis of different scenarios
Implementation and refinement of logistics plan	Participant observation in 3 weekly planning and control meetings (30 min each)
Control and assessment of the logistics plan	3 visits (30 min each) to the construction site

Table 5
Activities and sources of evidence of empirical study 3.

Activities	Sources of evidence
Analysis of site conditions and of the assembly process	Analysis of project documents: 2D drawings, assembly instructions manuals Open interviews with the site manager and the project coordinator 1 visit (2 h) to the construction site
Understand the client requirements	1 meeting (1 h) with a client representative and the site manager
Development of a 3D and 4D BIM models, considering the existing long-term plan	Analysis of project documents: manufacturing and architectural design drawings, long-term plan
Production of a site logistics plan	4 meetings (1 h each) with the site manager and a client representative for defining the site layout and the main flows of components and equipment Refinement of 4D model based on the analysis of different scenarios
Loading plans development	4 meetings (1 h each) with the team responsible for shipping components to the site; analysis of project documents (2D drawings)
Implementation and refinement of logistics plan	Participation observation in 4 weekly planning and control meetings (30 min each) with the site manager and client representatives 2 meetings (1 h each) with the site manager and a subcontractor representative Refinement of 4D model
Control and assessment of the logistics plan	15 visits (30 min each) to the construction site

other in order to reduce transportation waste. Fig. 8(c) and (d) shows that the storage of components is near the pre-assembly area. Further direct observations on-site have confirmed that assembly process became much more standardized due to the collaborative refinement cycles of the medium-term (batch) logistics plan.

5. Logistics planning and control model

A schematic representation of the proposed site logistics planning and control model for ETO prefabricated building systems, with the support of 4D BIM, is presented in Fig. 9. This model divides logistics planning and control in different hierarchical levels (long-term, medium-term and logistics control), similarly to Last Planner System®. Table 7 explains the scope of each activity at different hierarchical levels.

At the higher level, a logistics long-term plan is produced. The main decisions involved are: (i) revision of the project assembly stages; (ii) definition of the overall layout of the construction site; (iii) analysis of conflicts between plans from different crews or companies working on-site. Although the model proposes a sequence steps to be followed, as each process is defined, previous decisions might need to be revised. For instance, if a conflict between different crews is detected, the assembly sequence may be revised.

The first decision in the long-term logistics plan is the revision of the sequence of project batches that were defined in the beginning of the project. This revision is typically based on local constraints, interference from other teams, and priority changes by the client. 4D BIM simulation can be used to support this decision. Then, the overall layout of the construction site is defined by using 3D BIM, including the space needed to perform the main activities, inventory areas, temporary facilities, equipment and pedestrian routes. It is suggested that inventory areas should be divided according to project stages, in order to avoid mixing of components. The selection of the equipment should take into account not only the capacity needed to carry out logistics operations, but also the availability of space.

4D BIM simulation should also be used to detect conflicts between plans from different crews or companies working on-site. Such a simulation model must have the project assembly stages, flow activities, and the main construction site artefacts, such as equipment (e.g. crane, trucks), inventories, collective safety equipment, and temporary facilities.

This long-term logistics plan does not require a very high level of detail. Components can be represented generically, with approximate quantities, size, shape, location and orientation. It is suggested the use of LOD 200, considering that there is not much information available for defining detail logistics operations.

Some conflicts between moving objects can be detected by visual observation of the 4D BIM model. However, considering that the visual inspection may have failures, the use of time-based clash test to automatically detect conflicts is suggested. This functionality is available in some 4D BIM software tools.

Based on the definition of the long-term logistics plan, the detail design of transportation batches can be produced. Those batches should be delivered only when pulled by the construction site, based on look-ahead plans. In fact, the sequence of batches might be changed in case of emerging local constraints, interference from other teams, and changes demanded by the client organization. Therefore, there must be confirmation points before delivering transportation batches in the


(a) (b)

Fig. 2. Problems found in exploratory study 1: (a) inadequate location of steel component inventories and (b) a large inventory of thermal insulation parts.

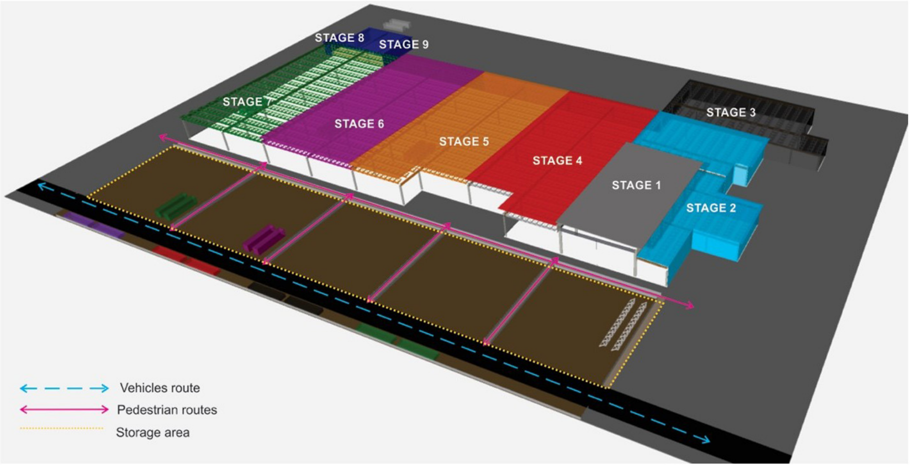

Fig. 3. Long-term logistics plan.

construction site, demanding effective communication between site managers and external logistics managers. Each load should only contain components of the same assembly batch (sub-stages), and some criteria for positioning the components in the load should be defined, in order to avoid damages and facilitate unloading operations and site assembly, rather than simply considering the need for freight optimization.

The medium-term logistics planning level involves three main activities: (i) refine the site layout; (ii) produce a detail design of operations, named batch logistics plan; (iii) refine the batch logistics plan by using both virtual and physical prototyping.

The refinement of site layout consists of making some detail decisions regarding the position and routing of equipment, position and size of inventories, and the movement of crews in the working area.

Based on the look-ahead production plan, a 4D BIM model is used to represent the batch logistics plan, as a virtual prototype of this set of operations. LOD 350 was considered to be suitable to represent the components at this level of logistics planning, containing the precise location and necessary geometrical level of detail. This 4D BIM model must be refined on a sequence of look-ahead planning meetings and also in first run studies (physical prototypes).

At the short-term level, the control of the logistics plan should be conducted. This phase involves the production of visual devices for controlling both the completion of tasks and the status of site logistics. Among possible visual devices to be used, screen images captured from 4D BIM models can be used to support the work of different stakeholders (e.g. site managers, assemblers, and client representatives).

Moreover, unloading operations as well as the movement of equipment and workers must be monitored according to existing logistics plans. When necessary, logistics plans at the look-ahead planning

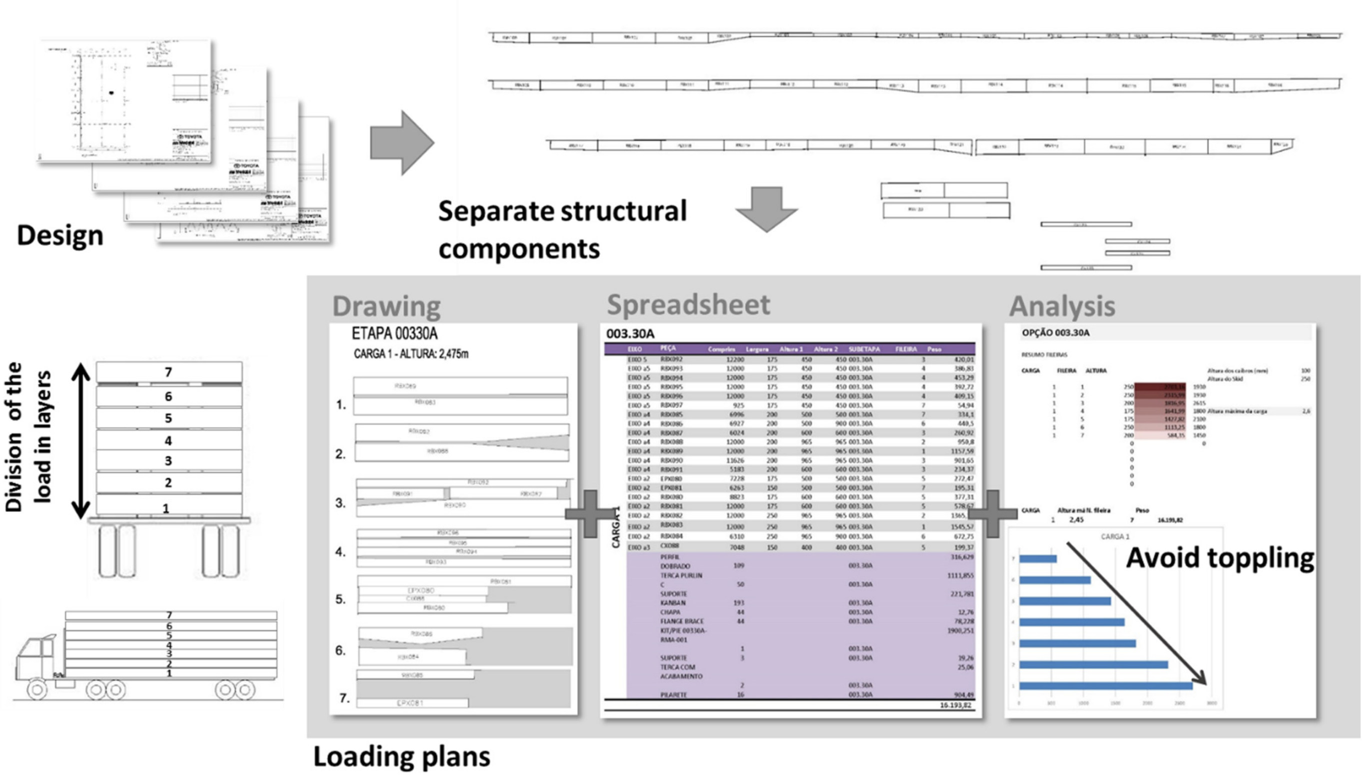

Fig. 4. Schematic representation of the development of loading plans.

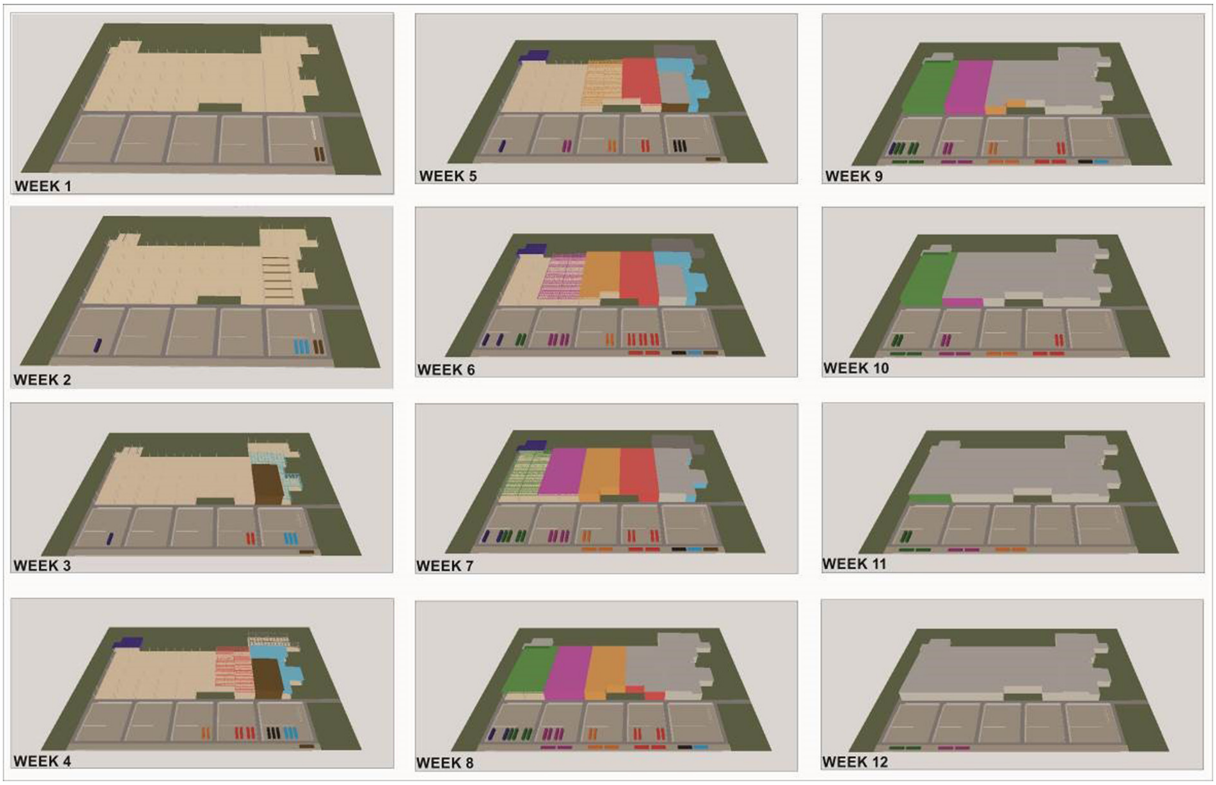

Fig. 5. Visual devices produced from screen-shots of the 4D BIM model.

level should be revised, and the causes of deviations must be identified.

6. Model evaluation

6.1. Utility

The utility criteria aim to assess the artefact in practical use and its ability to accomplish its objectives. Four different criteria were defined for the proposed model:

(i) Supporting collaboration in logistics planning and control: participant observation in planning meetings provided evidences that the model has contributed to improve communication and participation among the people involved in decision-making regarding internal logistics. Visual plans and 4D models were systematically used to encourage discussions and to make explicit the impact of decisions, creating a common understanding among project participants;

(ii) Generating alternative assembly and logistics plans: the fact that the model was divided in hierarchical levels created opportunities for producing alternative assembly and logistics plans, which were discussed by the main stakeholders. Moreover, some of those plans were refined as more information from the construction site was made available. As a consequence, those plans become more reliable;

(iii) Increasing process transparency: several visual devices were used

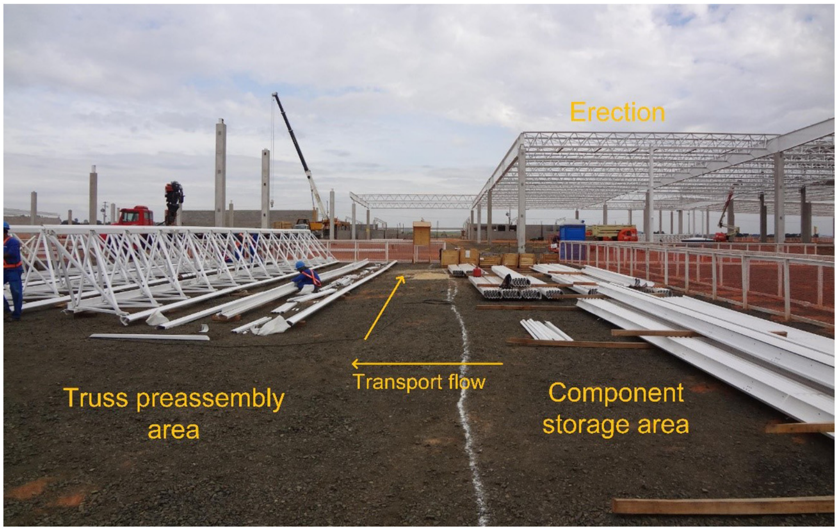

Fig. 6. Organization of components based on the batch logistic plan.

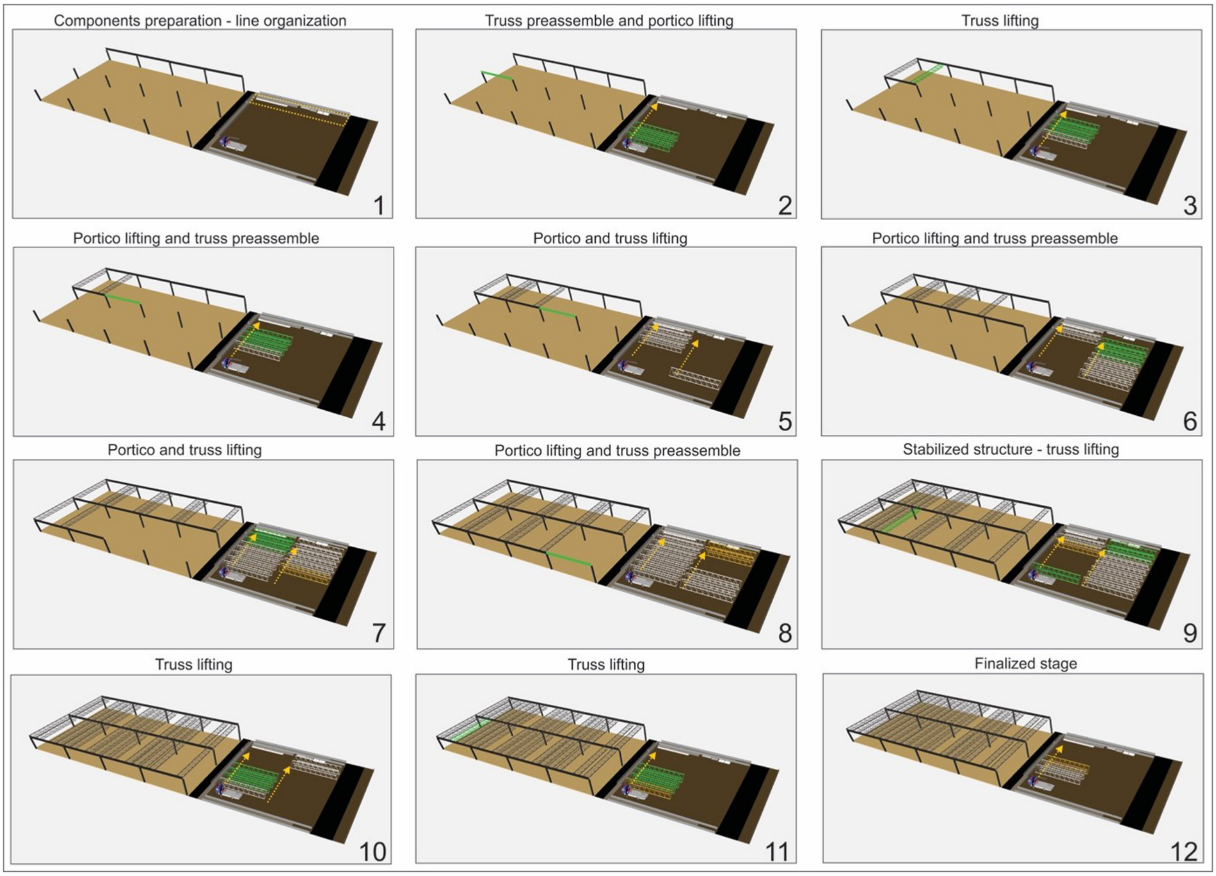

Fig. 7. Visual device produced from the batch logistics plan.

in the construction sites, besides the use of images displayed in computer screens. Open interviews, and direct observation in the construction sites indicated that the dissemination of information has improved among construction managers, assembly teams, and client representatives;

(iv) Increasing effectiveness of the planning and control process: formal planning of logistics operations at both long- and medium-term production planning levels reduced the number of decisions that had to be made in short-term planning meetings. As a consequence, less improvisations were observed in transportation tasks and inventories, contributing to the elimination of non-value adding activities. Data from Empirical Study 3 provided some evidence of performance improvement.

6.2. Usability

Participant observation in planning meetings and open interviews with managers provided evidences that Company A became interested in incorporating some elements of the proposed logistics planning and control model in the existing managerial system. In fact, after that project, the company decided to change the way loading plans were produced at the Logistics Department.

Due to limitations of time and resources, it was not possible to test or adapt the model to other companies. It is likely that for other prefabricated building systems, such as concrete structures or light steel frame, some changes need to be made in some of the tasks involved in the logistics planning and control model, as the number of components delivered to assembly sites tend to be much smaller than for the type of structural system adopted by Company A.

Regarding the effort involved in producing 4D models, the number of hours spent in were relatively small in all three projects (less than 65 h per projects), despite the fact that no 3D models were available at the beginning of the research study. This was due to the simplicity of some logistics plans (e.g. site layout), and also to the fact that detail logistics plans were only produced for critical processes, such as assembly and erection of trusses. The full implementation of the model would probably require a more intensive modeling effort, but this investigation suggests that this would still be negligible compared to the potential improvement of performance in the logistics and assembly process.

7. Theoretical contributions

Based on the description of Empirical Study 3, it is clear that the

Table 6
Impacts of the implementation of the batch logistics plan (based on one-week observation).

Performance measures		Before implementation	After implementation
Level of work in progress	Total number of trusses in the inventory	36 trusses	14 trusses
Productivity (for each truss)	Transportation of components	3.2 man-hours	2.0 man-hours
	Inspection	0.2 man-hours	0.2 man-hours
	Preassembly	4.4 man-hours	4.4 man-hours
Distance	Average walking distance for each assembler	40 m	5 m

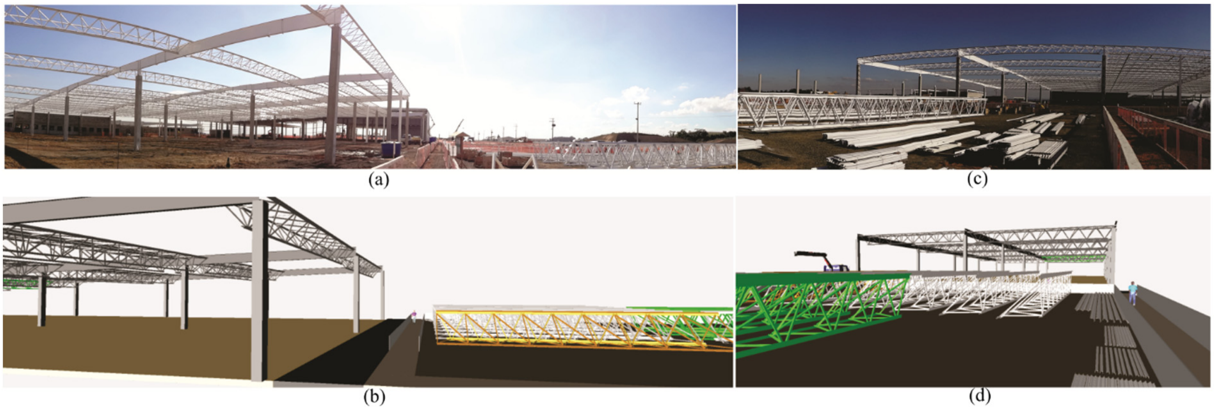

Fig. 8. Comparison between the virtual model and the real construction site: (a and b) preassembly and assembly areas, (c and d) storage of components.

model has contributed to improve the performance of the project in two different ways: (i) elimination of waste (non-value-adding activities), which include "reduce inventories", as well as other types of waste, such as transport operations and rework; and (ii) value generation, by making the process more reliable, and creating an environment in the construction site that was required by the client organization (e.g. well organized, low level of inventories). The elimination of waste contributes to increase efficiency (and therefore reduce costs), and to reduce lead time.

The main contribution of the model towards achieving those goals is strongly related to the implementation of two core Lean Production principles. The first is the reduction of variability, focused on logistics operations, which are often neglected in production management, as these are non-value-adding activities [10]. Several elements of the logistics plan have been standardized, such as site layout, position and size of inventories, transportation operations, and transportation batches. Those standards have not been defined at the beginning of the project, in a top-down fashion, but have been gradually established, with the participation of managers, assembly team members, and even client representatives, considering changes that are necessary in an ETO environment.

The second core principle is pull production, according to the definition of Hopp and Spearman [56], discussed in the literature review section. By using three different hierarchical levels, similarly to the Last Planner System®, logistics plans should be gradually detailed and, if necessary, changed, according to up-to-date information about system status, such as site conditions, interference by other processes, or changes in client demands. The delivery of transportation batches to the construction site should be pulled by the site assembly process at certain confirmation points. In Empirical Study 3, the confirmation of the sequence of batches and expected delivery dates was made at the look-ahead planning level (every 14 days).

At a lower level, three other principles contribute to the reduction of variability and to the implementation of pull production:

(i) "Reduce cycle time" was clearly implemented at the batch logistics planning process, by eliminating non-value-adding activities and by controlling work in progress. It is a major requirement for the implementation of pull production;
(ii) "Reduce batch size" was implemented both at the assembly

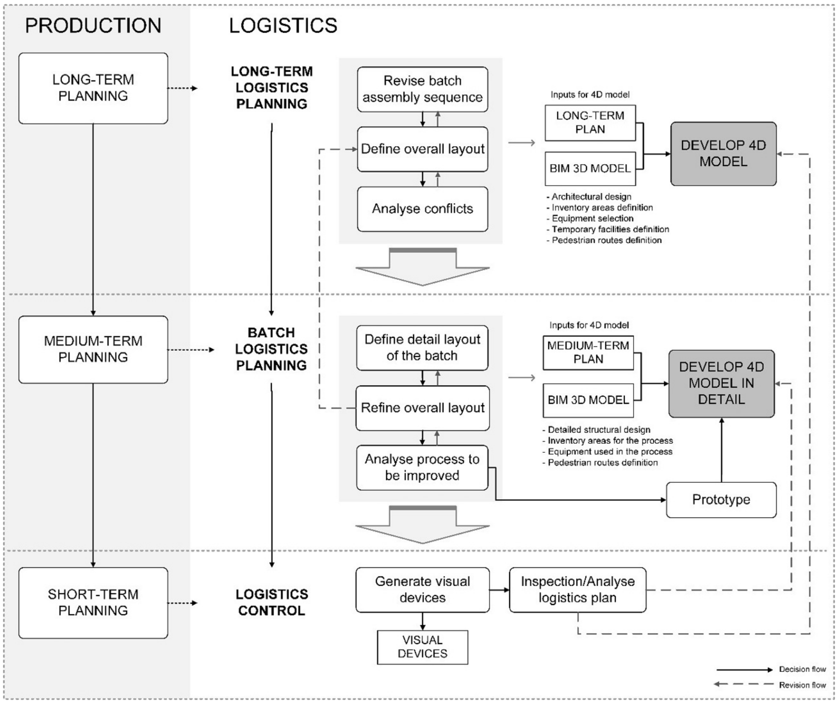

Fig. 9. Proposed logistics planning and control model.

Table 7
Scope of each hierarchical level in the logistics planning and control model.

Last planner level	Logistics planning level	Scope of each activity
Long-term planning	Long-term logistics planning	Revise batch assembly sequence, considering local constraints and new demands from the client Define the overall layout of the construction site including the space needed to perform the main activities, the inventory areas and temporary facilities on-site, the equipment and pedestrian routes by using 4D BIM modeling Analyze conflicts between plans from different crews or companies working on-site
Medium-term planning	Batch logistics planning	Define the detail layout of specific areas, including the areas for assembly operations, equipment and pedestrian flows, the exact position of component inventory for each production activity by using 4D BIM modeling Refine the overall layout Discuss with the crew opportunities for process improvement, and build a virtual prototype by using 4D BIM
Short-term planning	Logistics control	Generate visual devices from logistics plans with screenshots images taken from 4D model, using colors to identify each project batch Collect data and analyze logistics processes based on site inspections Refine batch logistics plans

process, and at the Logistics Department, by planning assembly activities and transportation loads according to predefined stages and sub-stages. Moreover, as suggested by Koskela [10], the reduction of batch size at both long- and medium-term planning levels contributes to cycle time reduction; and

(iii) "Institute continuous improvement" was adopted by implementing a set of practices: collaborative planning, establishing control cycles at medium- and short-term planning levels, and using site logistics indicators. Besides contributing to the reduction of variability, this principle also has a positive impact in the reduction of cycle time and in the reduction of batch size.

Finally, at the lower levels of abstraction, the remaining principles are the ones that had a direct interaction with the BIM functionalities:

(i) The principle "standardize" is strongly related to the reduction of variability, as mentioned in the literature review, but also has affected positively the implementation of the principles "reduce batch size", and "institute continuous improvement". Both 3D and 4D BIM models communicated standards such as assembly batches, position and size of inventories, pathways, and transport operations. Those standards can be used to control site logistics operations. Therefore, this principle has a strong interaction with two BIM functionalities: "Rapid generation and evaluation of construction plan alternatives", and "Collaboration in design and construction";

(ii) "Decide by consensus, consider all options" was implemented at different planning levels with the aim of improving and standardizing logistics operations, i.e. that principle has a positive impact in other principles, such as "standardize" and "continuous improvement". 4D BIM was used to support collaborative processes, involving different stakeholders (e.g. site managers, assembly team member, and client representatives). Therefore, the "Decide by consensus, consider all options" principle also had a strong interaction with two BIM functionalities: "collaboration in design and construction", and "rapid generation and evaluation of construction plan alternatives".

(iii) The "simplify" and "use parallel processing" were mostly involved in the effort of process improvement, by eliminating non-value-adding activities and reducing distances, which had a direct impact in the reduction of cycle time. Those improvements were defined mostly in collaborative planning meetings, being positively influenced by the "decision by consensus" principle. In those meetings, 4D models were visualized and construction processes were simulated. The "visualization of flow activities and artefacts" functionality was particular important due to the focus on logistics operations; and

(iv) "Use visual management" was implemented for both reducing variability, by adopting visual devices for controlling batch size and inventory level, and supporting "pull production" by using color-coding to identify transportation batches and inventories. As suggested by Santos [67], there is a strong interaction between the "standardize" and "use visual management" principles. Some of the visual devices used were print-outs of the 4D BIM model, i.e. concerned with the functionality "automated generation of drawings and documents".

Fig. 10 represents the hierarchical relationships and the interactions that exist between the Lean Principles. This figure does not represent all Lean Principles, neither all possible interactions that may exist between them, but only the most important principles that were identified within the scope of this research study. It indicates that the high-level

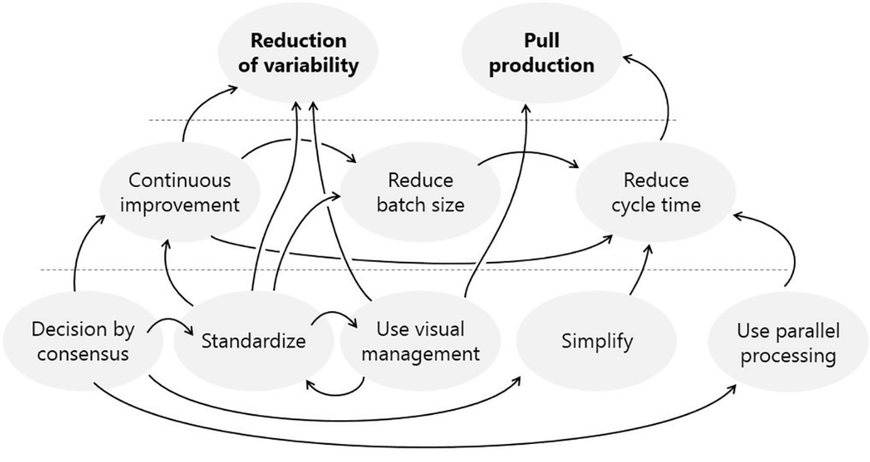

Fig. 10. Hierarchical relationships and interactions between Lean principles.

Table 8
Synergies between Lean principles and BIM functionalities.

Lean production principles	BIM functionalities				
	Rapid generation and evaluation of construction plan alternatives			Collaboration in design and construction	Automated generation of drawings and documents (8)
	Construction process simulation (12)	4D visualization of construction schedules (13)	Visualization of flow activities and temporary objects	Multiuser editing of a merged or separate multidiscipline model (10)	
Standardize (J)	X	X, Z	X, Z	X	Z
Decide by consensus, consider all options (W)	X, Y	X, Y	X, Y	X	
Simplify (N)	Y	Y	Y		
Use parallel processing (O)	Y	Y	Y		
Use visual management (L, M)		Z	Z		Z

principles are more abstract and depend on the implementation of the ones from the lower levels. There are also interactions between principles at the same level.

Table 8 represents three synergies (X, Y, and Z) between some Lean principles and BIM functionalities described above. These were considered as the most relevant ones in the context of site logistics planning and control for engineer-to-order prefabricated building systems:

(i) Synergy X: it involves two Lean principles that are highly interdependent – "standardize" and "decide by consensus, consider all options" and two different BIM functionalities: "collaboration in design and construction", and "rapid generation and evaluation of construction plan alternatives";
(ii) Synergy Y: it refers to the "simplify" and "use parallel processing" principles and the "rapid generation and evaluation of construction plan alternatives" BIM functionality. Although, this synergy is mostly concerned with to process design (e.g. sequencing of tasks), the application of those two principles become much more effective if decisions are made by consensus, considering several options;
(iii) Synergy Z: it is between the "visual management" principle and BIM functionalities that are related to the production of visual devices, either virtual (e.g. visualization in a screen) or physical (e.g. print-outs of BIM models). As mentioned above, the implementation of visual management has a strong interaction with the "standardize" principle.

It is worth pointing out that none of the three synergies (X, Y, and Z) involve a one-to-one relationship between a Lean principle and a BIM functionality, as suggested in the matrix proposed by Sacks et al. [26]. Those synergies seem to be better explained by clusters involving sets of Lean principles and BIM functionalities (as shown in Table 8) that need to be implemented together in order to be effective.

8. Conclusion

This paper has two main contributions: (i) the development of a site logistics planning and control model based on a set of Lean Production principles and BIM functionalities; and (ii) a theoretical framework that provides an in-depth analysis of the synergies between Lean principles and BIM functionalities in this context.

The proposed site logistics planning and control model is a practical contribution. It can be used as a reference for companies that deliver ETO prefabricated building systems. As a mechanism for coping with the uncertainty involved in this type of project, a hierarchical approach for logistics planning and control was adopted, similarly to the planning levels that exist in the Last Planner System®. Three planning and control levels were suggested: (i) long-term logistics planning; (ii) batch logistics planning; and (iii) logistics control. Each of those three planning levels can be associated with distinct and specific roles regarding the logistics management. Existing commercial tools for 3D and 4D BIM have been used in the exploratory and empirical studies. However, the main contribution of the proposed model is concerned with a set of managerial tasks that must be carried out for planning and controlling site logistics, based on Lean principles.

This research work has also emphasized the importance of collaborative planning as a way to overcome the complexity involved in ETO production systems. In the empirical study carried out in this investigation, 4D BIM has played an important role in terms of improving process transparency, by supporting collaboration in planning and control meetings. In fact, several stakeholders took part in planning meetings, such as the site engineer, the project coordinator, logistics managers, assembly subcontractors and client representatives. At the look-ahead planning level, logistics plans were refined and BIM 4D models were revised, making it possible to systematically pull the delivery of components from the manufacturing plan by site assembly. Therefore, this study provided empiric evidences on how the combination of Lean principles and BIM functionalities helped aligning individual objectives of different stakeholders in a construction project: controlling the cost of shipping (logistics department), increasing the reliability in the delivery of components (site management), increasing productivity of site assembly (subcontractors), keeping inventories organized on-site, and reducing lead-time (client).

This research work also pointed out the importance of detail design of transportation loads when shipping prefabricated components to construction sites. The sequence and the content of transportation loads need to be based on an updated version of the assembly plan, which is defined at the look-ahead planning level. Moreover, a number of requirements need to be considered in the design of transportation loads, such as avoiding damages to components during transportation, and defining an unloading sequence that facilitates the organization of inventories in the construction site.

Data from Empirical Study 3 suggest that the implementation of the model has contributed substantially to the reduction of work-in-progress (61%); increase in productivity, due to reduction of man-hours spent in transportation operations (38%); and reduction in the average walking distance for each assembler (88%). A major limitation of this investigation is that those benefits were measured in a single empirical study. Further work is necessary to refine the model and assess its benefits in a wide range of situation.

Some further limitations of the model should be pointed out: (i) the 4D BIM models used in this investigation were relatively simple and no sophisticated programming techniques or libraries of objects were used for automating the generation of models, or for simulating logistics operations in a stochastic way; (ii) logistics planning was carried out from the perspective of a steel fabricator in charge of delivering structures – other processes that were being undertaken in the same construction site were not included in the plans.

Regarding the theoretical contribution of this investigation, although this investigation used the matrix of interactions between Lean principles and BIM functionalities proposed by Sacks et al. [26] as a starting point, it makes a contribution towards understanding those interactions in more detail:

(i) The synergies between Lean principles and BIM functionalities should be represented in a more complex way, compared to the matrix proposed by Sacks et al. [26]. Instead of one-to-one relationships, there seems to be clusters of Lean Principles and BIM functionalities that need to interact in order to have synergy.
(ii) There are hierarchical relationships between Lean principles that need to be considered. The most abstract ones are at the top of the hierarchy (e.g. reduce variability, pull production), while the most instrumental ones, at the bottom, are the ones that have a direct connection to BIM functionalities.
(iii) An additional BIM functionality was considered to be relevant for site logistics management, namely "visualization of flow activities and temporary objects". This functionality is very relevant for companies involved in the implementation of Lean principles, due to the need of planning and controlling both value-adding and non-value-adding activities.

As suggested by Sacks et al. [26], this research work makes a contribution towards closing some gaps regarding the understanding of the synergies between Lean principles and BIM functionalities. The research work presented in this investigation can be regarded as an example of how this body of knowledge can be expanded, based on empirical studies carried out in specific contexts. Further research should address other processes that could explore other synergies, such as safety management, quality management, collaborative design, among others.

References

[1] G. Jansson, H. Johnsson, D. Engström, Platform use in systems building, Constr. Manag. Econ. 32 (2013) 70–82, https://doi.org/10.1080/01446193.2013.793376.
[2] C. Thuesen, L. Hvam, Efficient on-site construction: learning points from a German platform for housing, Constr. Innov. 11 (2011) 338–355, https://doi.org/10.1108/14714171111149043.
[3] D.T. Matt, P. Dallasega, E. Rauch, Synchronization of the manufacturing process and on-site installation in ETO companies, Procedia CIRP 17 (2014) 457–462, https://doi.org/10.1016/j.procir.2014.01.058.
[4] H. Zabihi, F. Habib, L. Mirsaeedie, Definitions, concepts and new directions in Industrialized Building Systems (IBS), KSCE J. Civ. Eng. 17 (6) (2013) 1199–1205, https://doi.org/10.1007/s12205-013-0020-y.
[5] S.K. Lachimpadi, J.J. Pereira, M.R. Taha, M. Mokhtar, Construction waste minimisation comparing conventional and precast construction (Mixed System and IBS) methods in high-rise buildings: a Malaysia case study, Resour. Conserv. Recycl. 68 (2012) 96–103, https://doi.org/10.1016/j.resconrec.2012.08.011.
[6] Y. Chen, G.E. Okudan, D.R. Riley, Sustainable performance criteria for construction method selection in concrete buildings, Autom. Constr. 19 (2010) 235–244, https://doi.org/10.1016/j.autcon.2009.10.004.
[7] J.W.M. Bertrand, D.R. Muntslag, Production control in engineer-to-order firms, Int. J. Prod. Econ. 30–31 (1993) 3–22, https://doi.org/10.1016/0925-5273(93)90077-X.
[8] J. Gosling, M.M. Naim, Engineer-to-order supply chain management: a literature review and research agenda, Int. J. Prod. Econ. 122 (2009) 741–754, https://doi.org/10.1016/j.ijpe.2009.07.002.
[9] I.D. Tommelein, G. Ballard, P. Kaminsky, Supply Chain Management for Lean Project Delivery, Construction Supply Chain Management Handbook, (2008) 9781420047462, pp. 1–6.
[10] L. Koskela, Application of the New Philosophy to Construction, Center for Integrated Facility Engineering, Salford, 1992 Available at http://www.leanconstruction.org/media/docs/Koskela-TR72.pdf , Accessed date: 12 October 2018.
[11] D.H. Grabenstetter, J.M. Usher, Sequencing jobs in an engineer-to-order engineering environment Douglas, Int. J. Prod. Res. 52 (2015) 6349–6361, https://doi.org/10.1080/00207543.2014.940072.
[12] M. Trebbe, T. Hartmann, A. Dorée, Automation in construction 4D CAD models to support the coordination of construction activities between contractors, Autom. Constr. 49 (2015) 83–91, https://doi.org/10.1016/j.autcon.2014.10.002.
[13] I.D. Tommelein, Process benefits from use of standard products – simulation experiments using the pipe spool model, Proceedings of the 14th Annual Conference of the International Group for Lean Construction, 2006, pp. 177–189. Available at http://iglc.net/Papers/Details/448 , Accessed date: 12 October 2018.
[14] D.D. Viana, I. Bulhoes, C.T. Formoso, Guidelines for integrated planning and control of engineer-to-order, Proceedings of the 21st Annual Meeting of the International Group for Lean Construction, 2013, pp. 549–558. Available at http://iglc.net/Papers/Details/959 , Accessed date: 12 October 2018.
[15] D. Little, R. Rollins, M. Peck, J.K. Porter, Integrated planning and scheduling in the engineer-to-order sector, Int. J. Comput. Integr. Manuf. 13 (2000) 545–554, https://doi.org/10.1080/09511920050195977.
[16] M. Stevenson, L.C. Hendry, B. Kingsman, A review of production planning and control: the applicability of key concepts to the make-to-order industry, Int. J. Prod. Res. 54 (2005), https://doi.org/10.1080/0020754042000298520.
[17] R.B.B. Johnston, M. Brennan, Planning or organizing: the implications of theories of activity for management of operations, Omega 24 (1996) 367–384, https://doi.org/10.1016/0305-0483(96)00016-3.
[18] J.A. Elfving, I.D. Tommelein, G. Ballard, Improving the delivery process for engineered-to-order products - lessons learned from power distribution equipment, Proceedings of the 12th Annual Conference of the International Group for Lean Construction, 2004 Available at http://iglc.net/Papers/Details/295 , Accessed date: 12 October 2018.
[19] I.D. Tommelein, Pull-driven scheduling for pipe-spool installation: simulation of a lean construction technique, J. Constr. Eng. Manag. 124 (1998) 279–288, https://doi.org/10.1061/(ASCE)0733-9364(1998)124:4(279).
[20] C. Hicks, T. McGovern, C.F. Earl, Supply chain management: a strategic issue in engineer to order manufacturing, Int. J. Prod. Econ. 65 (2000) 179–190, https://doi.org/10.1016/S0925-5273(99)00026-2.
[21] A.F. Waly, W.Y. Thabet, A virtual construction environment for preconstruction planning, Autom. Constr. 12 (2003) 139–154, https://doi.org/10.1016/S0926-5805(02)00047-X.
[22] A. Agapiou, L.E. Clausen, R. Flanagan, G. Norman, D. Notman, The role of logistics in the materials flow control process, Constr. Manag. Econ. (1998), https://doi.org/10.1080/014461998372420.
[23] G.H. Briscoe, A.R.J. Dainty, S.J. Millett, R.H. Neale, Client-led strategies for construction supply chain improvement client-led strategies for construction supply chain improvement, Constr. Manag. Econ. 22 (2004) 193–201, https://doi.org/10.1080/0144619042000201394.
[24] I. Tommelein, P. Zouein, Interactive dynamic layout planning, J. Constr. Eng. Manag. 119 (1993) 266–287, https://doi.org/10.1061/(ASCE)0733-9364(1993)119:2(266).
[25] B. Akinci, M. Fischer, T. Zabelle, Proactive approach for reducing non-value adding activities due to time-space conflicts, Proceedings of the 6th Annual Conference of the International Group for Lean Construction, 1998 Available at http://iglc.net/Papers/Details/33 , Accessed date: 12 October 2018.
[26] R. Sacks, L. Koskela, B.A. Dave, R. Owen, Interaction of lean and building information modeling in construction, J. Constr. Eng. Manag. 136 (2010) 968–980, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000203.
[27] J.P. Womack, D.T. Jones, D. Roos, The Machine That Changed the World: The Story of Lean Production, Harper Perennial, New York, NY, 978-0743299794, 1990.
[28] L. Koskela, An Exploration Towards a Production Theory and Its Application to Construction, VTT Technical Research Centre of Finland, 2000 Available at https://www.vtt.fi/inf/pdf/publications/2000/P408.pdf , Accessed date: 12 October 2018.
[29] G. Ballard, G. Howell, Shielding production: essential step in production control, J. Constr. Eng. Manag. 124 (1998) 11–17, https://doi.org/10.1061/(ASCE)0733-9364(1998)124:1(11).
[30] T.M. Williams, The need for new paradigms for complex projects, Int. J. Proj. Manag. 17 (1999) 269–273, https://doi.org/10.1016/S0263-7863(98)00047-7.
[31] F.R. Hamzeh, G. Ballard, I.D. Tommelein, Is the last planner system applicable to design? A case study, Proceedings of the 17th Annual Conference of the International Group for Lean Construction, 2009, pp. 165–176. Available at http://iglc.net/Papers/Details/644 , Accessed date: 12 October 2018.
[32] C. Eastman, P. Teicholz, R. Sacks, K. Liston, BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, (2011) 978-0-470-54137-1.
[33] D. Heesom, L. Mahdjoubi, Trends of 4D CAD applications for construction planning, Constr. Manag. Econ. 22 (2004) 171–182, https://doi.org/10.1080/0144619042000201376.
[34] K.W. Chau, M. Anson, J.P. Zhang, Four-dimensional visualization of construction scheduling and site utilization, J. Constr. Eng. Manag. 130 (2004) 598–606, https://doi.org/10.1061/(ASCE)0733-9364(2004)130:4(598).
[35] T. Hartmann, J. Gao, M. Fischer, Areas of application for 3D and 4D models, J. Constr. Eng. Manag. (2008) 776–785, https://doi.org/10.1061/(ASCE)0733-9364(2008)134:10(776).
[36] B. Akinci, M. Fischer, J. Kunz, Automated generation of work spaces required by construction activities, J. Constr. Eng. Manag. 128 (2002) 306–315, https://doi.org/10.1061/(ASCE)0733-9364(2002)128:4(306).
[37] Z.Z.Z. Hu, J.J.P. Zhang, Z.Z.Z. Hu, BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies, Autom. Constr. 20 (2011) 167–180, https://doi.org/10.1016/j.autcon.2010.09.013.
[38] M. Golparvar-Fard, F. Peña-Mora, C.A. Arboleda, S. Lee, Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs, J. Comput. Civ. Eng. 23 (2009) 391–404, https://doi.org/10.1061/

(ASCE)0887-3801(2009)23:6(391).

[39] Z. Ma, Q. Shen, J. Zhang, Application of 4D for dynamic site layout and management of construction projects, Autom. Constr. 14 (2005) 369–381, https://doi.org/10.1016/j.autcon.2004.08.011.

[40] H. Li, N. Chan, T. Huang, H.L. Guo, W. Lu, M. Skitmore, Optimizing construction planning schedules by virtual prototyping enabled resource analysis, Autom. Constr. 18 (2009) 912–918, https://doi.org/10.1016/j.autcon.2009.04.002.

[41] R. Chavada, N. Dawood, M. Kassem, Construction workspace management: the development and application of a novel nD planning approach and tool, J. Inf. Technol. Constr. 17 (2012) 213–236. Available at http://hdl.handle.net/10149/247112 , Accessed date: 12 October 2018.

[42] R. Jongeling, T. Olofsson, A method for planning of work-flow by combined use of location-based scheduling and 4D CAD, Autom. Constr. 16 (2007) 189–198, https://doi.org/10.1016/j.autcon.2006.04.001.

[43] R. Bortolini, J.S.-I. Shigaki, C.T. Formoso, Site logistics planning and control using 4D modeling: a study in a lean car factory building site, Proceedings of the 23rd Annual Conference of the International Group for Lean Construction, 55 2015, pp. 361–370. Available at http://iglc.net/Papers/Details/1222 , Accessed date: 12 October 2018.

[44] A.L.C. Ciribini, S. Mastrolembo Ventura, M. Paneroni, Implementation of an interoperable process to optimise design and construction phases of a residential building: a BIM Pilot Project, Autom. Constr. 71 ((2016) 62–73, https://doi.org/10.1016/j.autcon.2016.03.005.

[45] R.J. Scherer, S.-E. Schapke, A distributed multi-model-based Management Information System for simulation and decision-making on construction projects, Adv. Eng. Inform. 25 (2011) 582–599, https://doi.org/10.1016/j.aei.2011.08.007.

[46] B. Dave, S. Kubler, K. Främling, L. Koskela, Opportunities for enhanced lean construction management using Internet of Things standards, Autom. Constr. 61 (2016) 86–97, https://doi.org/10.1016/j.autcon.2015.10.009.

[47] A. Bhatla, F. Leite, Integration framework of BIM with the last planner system, Proceedings of the 20th International Group for Lean Construction, 2012 Available at http://iglc.net/Papers/Details/752 , Accessed date: 12 October 2018.

[48] H. Moon, H. Kim, C. Kim, L. Kang, Development of a schedule-workspace interference management system simultaneously considering the overlap level of parallel schedules and workspaces, Autom. Constr. 39 (2014) 93–105, https://doi.org/10.1016/j.autcon.2013.06.001.

[49] H. Said, K. El-Rayes, Automated multi-objective construction logistics optimization system, Autom. Constr. 43 (2014) 110–122, https://doi.org/10.1016/j.autcon.2014.03.017.

[50] S. Chin, S. Yoon, C. Choi, C. Cho, RFID + 4D CAD for Progress Management of Structural Steel Works in High-rise Buildings, (2008), pp. 74–89, https://doi.org/10.1061/(ASCE)0887-3801(2008)22:2(74).

[51] E.P. Karan, J. Irizarry, Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services, Autom. Constr. 53 (2015) 1–12, https://doi.org/10.1016/j.autcon.2015.02.012.

[52] W. Hopp, M. Spearman, Factory Physics: Foundations of Manufacturing Management, Irwin/McGraw-Hill, Boston, 0-256-24795-1, 1996.

[53] V. Gonzalez, L.F. Alarcon, F. Mundaca, Investigating the relationship between planning reliability and project performance, Prod. Plan. Control 19 (2008) 461–474, https://doi.org/10.1080/09537280802059023.

[54] F.R. Hamzeh, I. Saab, I.D. Tommelein, G. Ballard, Understanding the role of “tasks anticipated” in lookahead planning through simulation, Autom. Constr. 49 (2015) 18–26, https://doi.org/10.1016/j.autcon.2014.09.005.

[55] A. Laufer, Simultaneous Management: Managing Projects in a Dynamic Environment, American Management Association, New York, 978-0814403129, 1997.

[56] W. Hopp, M. Spearman, To pull or not to pull: what is the question? Manuf. Serv. Oper. Manag. 6 (2004) 133–148, https://doi.org/10.1287/msom.1030.0028.

[57] C.T. Formoso, A.D.O.S. Santos, J.A. Powel, An exploratory study on the applicability of process transparency in construction sites, J. Constr. Res. 03 (2002) 35–54, https://doi.org/10.1142/S1609945102000102.

[58] A. Tezel, L. Koskela, P. Tzortzopoulos, C.T. Formoso, T. Alves, Visual management in Brazilian construction companies: taxonomy and guidelines for implementation, J. Manag. Eng. 31 (2015) 05015001, , https://doi.org/10.1061/(ASCE)ME.1943-5479.0000354.

[59] D. Viana, C. Formoso, J. Wesz, P. Tzortzopoulos, The role of visual management in collaborative integrated planning and control for engineer-to-order building systems, Proceedings of the 22nd Annual Conference of the International Group for Lean Construction, 2014 IGLC, 2014, pp. 775–786. Available at http://iglc.net/Papers/Details/1074 , Accessed date: 12 October 2018.

[60] J. Holmstrom, M. Ketokivi, Bridging Practice and Theory: A Design Science Approach, 40 (2009), pp. 65–88, https://doi.org/10.1111/j.1540-5915.2008.00221.x.

[61] J.E. Van Aken, Management Research Based on the Paradigm of the Design Sciences: The Quest for Field-tested and Grounded Technological Rules, (2004), https://doi.org/10.1111/j.1467-6486.2004.00430.x.

[62] P. Järvinen, Action research is similar to design science, Qual. Quant. 41 (2007) 37–54, https://doi.org/10.1007/s11135-005-5427-1.

[63] Sein, Henfridsson, Purao, Rossi, Lindgren, Action design research, MIS Q. 35 (2011) 37, https://doi.org/10.2307/23043488.

[64] A.R. Hevner, S.T. March, J. Park, S. Ram, Design science in information systems research, MIS Q. 28 (2004) 75–105, https://doi.org/10.2307/25148625.

[65] S.T. March, G.F. Smith, Design and natural science research on information technology, Decis. Support. Syst. 15 (1995) 251–266, https://doi.org/10.1016/0167-9236(94)00041-2.

[66] F. Leite, A. Akcamete, B. Akinci, G. Atasoy, S. Kiziltas, Analysis of modeling effort and impact of different levels of detail in building information models, Autom. Constr. 20 (2011) 601–609, https://doi.org/10.1016/j.autcon.2010.11.027.

[67] A. dos Santos, Application of Flow Principles in the Production Management of Construction Sites (PhD Thesis). Available at, http://usir.salford.ac.uk/2231/, (1999) , Accessed date: 12 October 2018.