INTEGRATION OF OVERLAPPED DESIGN AND CONSTRUCTION STAGES THROUGH LOCATION-BASED PLANNING TOOLS

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Abstract

The overlap of design and construction stages is a current practice in the construction industry, which aims to shorten the project lead time and cost. Apart from the construction industry fragmentation and its difficulties imposed on project management, this type of project faces some additional challenges, such as difficulties in optimising the design solution in a short period and in keeping the construction activities flowing smoothly. Furthermore, the advantages of this practice may be minimised if the time is badly managed, resulting in over-costs, time delays, and an increase in uncertainty. Although these problems can be avoided through the use of lean management practices, there is a lack of research on the application of lean for managing projects with overlap between design and construction stages. Moreover, the current literature in planning overlapped projects explores traditional methods of planning, such as the Critical Path Method (CPM), which have limited capacity to deal with the construction complexity. Hence, research on the use of lean tools for planning, namely location-based scheduling (LBS) tools, is needed and has a wide field of exploration to improve the performance of overlapped projects.

The aim of this research is to devise a model to design, plan and control the stages of design and construction in the context of projects with overlap between these stages, using LBS tools and other lean practices to pull and align the project production regarding location, sequence and takt-time. The objectives are: (i) Determine how to use location-based tools to structure the work for design, suppliers and construction in alignment with their production sequences and production batches; (ii) Find out how to assemble design packages to meet suppliers' and construction requirements; (iii) Determine the decoupling point of design development in order to apply pull production; (iv) Identify and analyse pros and cons of existing types of pull production systems that better suit the context of overlapped projects; (v) Explore how to measure and manage the work in progress and buffers in an integrated project system; (vi) Identify the best tools to control the production system, and to ensure that downstream information is achieving upstream processes.

The research process contains three studies from the researcher's professional experience: a fourth case study at the new university's building in Norway; a fifth action research study in a highways depot maintenance project in the UK; and a sixth case study in a construction company in a residential project in Norway. The research approach used to develop the studies was the Design Science Research (DSR). The DSR is a mode of producing scientific knowledge through the creation and implementation of a solution (an artefact) for problems that affect the construction management. The production of the artefact is the aim of this research, and it is built throughout the studies.

Findings indicate the use of LBS tools applied in construction to pull production in design and supply. The production control is conducted by an adapted last planner system to confirm and align deliverables with construction. Moreover, the BIM process is designed in connection with procurement and construction activities. The final model of this research can be used in the project management of construction projects with overlapping of design and construction phases, for example fast-track construction, flash-track construction, and complex projects with concurrent development of design and construction.

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List of Abbreviations

ADePT – Analytical Design Planning Technique

AEC – Architectural, Engineering and Construction

AR – Action Research

BO – Boundary Objects

CBA – Choosing by Advantage

CCPM – Critical Chain Project Management

CE – Concurrent Engineering

CONWIP – Constant Work in Progress

CPD – Collaborative Planning in Design

CPC – Collaborative Planning in Construction

CPM – Critical Path Method

CSD – Construction System Design

CSI – Construction System Improvement

CSO – Construction System Operation

DBR – Drum-Buffer-Rope

DP – Decoupling Point

DSD – Design System Design

DSI – Design System Improvement

DSM – Design Structure Matrix

DSO – Design System Operation

DSR – Design Science Research

ECAM – Engineering, Construction and Architectural Management Journal

ETO – Engineering to Order

FL – Flowline

IGLC – International Group for Lean Construction

JIT – Just in Time

LBS – Location Breakdown Structure

LOB – Line of Balance

LPDSa – Lean Product Development System

LPDSb – Lean Project Delivery System

LPS – Last Planner™ System

MC – Mass Customisation

NPD – New Product Development

PCP – Product Creation Process

PERT – Program Evaluation and Review Technique

POLCA – Paired-cell Overlapping Loops of Cards with Authorisation

PPCb – Percentage of Planned Assignments Completed or Percentage of Plan Concluded

PPCa – Production Planning and Control

PPCQ – Percentage of Plan Concluded with Quality

PPCS – Percentage of Plan Concluded with Safety

PS – Phase Scheduling

PSD – Production System Design

SBD – Set-based Design

TFV Theory – Transformation, Flow and Value Theory

TOC – Theory of Constraints

TPS – Toyota Production System

TTP – Takt-Time Planning

TVD – Target Value Design

WIP – Work in Progress

WLC – Workload Control

WS – Work Structuring

1 INTRODUCTION

1.1 BACKGROUND

The construction market demands faster project delivery, higher quality and increasingly complex buildings. Nevertheless, the traditional management of projects no longer meet these demands (Formoso, Tzortzopoulos, & Liedtke, 2002; Moura, 2005). Some reasons for this may be explained by the way the architectural, engineering and construction (AEC) industry is organised and how construction projects are managed.

The AEC industry is characterised by its fragmentation. As design and construction phases are conceived separately (Alarcón & Mardones, 1998), it is more difficult to integrate information in the construction industry (Alshawi & Ingirige, 2003 as cited in Dave, Koskela, Kagioglou, and Bertelsen (2008)).

Typically, construction projects have different organisations working together at the interface between design and construction of a facility (Anumba, Baron, & Duke, 1997). The typical participants are the client, the architect, the structural engineer, the building services engineer, quantity surveyor, main contractor, sub-contractors, material suppliers, marketing consultant, project manager and other specialists (Alarcón & Mardones, 1998; Anumba et al., 1997). Participants in a construction project develop their work using their own plans and make decisions, which sometimes are disconnected from other stakeholders.

As a result of this fragmentation, construction projects face several problems at the interface of design-construction, such as poor design quality, lack of constructability, suboptimal design solutions (Alarcón & Mardones, 1998; Bertelsen, 2004), lack of design standards, waste of manpower capacity (Alarcón & Mardones, 1998), change orders, reworks in design and construction, design and construction delays (Alarcón & Mardones, 1998; Ballard, 2002), high cost and low value delivered for clients (Ballard, 2002).

Therefore, to overcome the low performance of traditional projects which are executed in a rigid and linear sequence of design-construction activities (Alarcón & Mardones, 1998), the AEC industry is adopting the **overlap between design and construction stages**. This strategy intends to reduce the construction project’s duration, but also may be used to increase the product’s flexibility (Formoso et al., 2002; Formoso, Tzotzopoulos, Jobim, & Liedtke, 1998) and to launch “the product to the market as quickly as possible” (Deshpande, Salem, & Miller, 2012).

Regarding the overlapping, “the downstream activity starts before the completion of its upstream (predecessor) activities” (Khoueiry, Srour, & Yassine, 2013). In the context of this research, a project with overlap means a **project in which the construction stage starts before the design completion**. In the literature, there are three conceptualisations about this type of project models, such as phased construction, fast-tracking and flash-tracking. In the first model, the phased construction (Fazio, Moselhi, Théberge, & Revay, 1988), there is the overlap between design and construction stages, but the construction work package only starts after the completion of the respective design work package. In the fast-tracking model, the construction work package starts before the completion of its design (Fazio et al., 1988); in the flash-tracking, however, there is an overlapping of 80% of the time of the design and construction phases (Austin, 2016).

In overlapped projects, the new product development process is not necessarily executed with the participation of constructors, suppliers and contractors in the design process. In other words, when there is an overlap between design and construction stages, it does not mean that there is a concurrent engineering process or integrated design. However, it means that there is a higher number of interdependent stakeholders working concurrently and who need to be coordinated.

When compared to traditional construction projects, the management of overlapped projects faces other challenges; for instance, the iterative design process is now driven to keep the construction work flowing smoothly, while at the same time it needs to optimise the design solution (Deshpande et al., 2012). Another challenge imposed by the management of this type of construction model is the lack of time between the completion of the design solution and its implementation on-site, which makes the time a "valuable commodity" in projects with overlap between design and construction stages (Deshpande et al., 2012). Therefore, overlapped projects have higher risks than traditional ones (Deshpande et al., 2012), and require precise alignment between design and construction plans.

As a consequence, the advantages of projects with overlap between design and construction activities are still polemic in the literature review. Although this model of project development presents the reduction of a project's lead time as the main advantage (Huovila, Koskela, & Lautanala, 1997), many authors highlight possible disadvantages. Whether badly managed, these construction projects can:

- Cost more than the traditional construction due to the fact that the production rate is above the optimum level (Tighe, 1991) (Kwake 1991 as cited in (Koskela, Ballard, & Tanhuanpää, 1997);
- Have unexpected costs (Fazio et al., 1988);
- Have longer project lead time (Fazio et al., 1988);
- Design sub-optimal solutions (Tighe, 1991);
- Increase uncertainty and decrease value (Huovila et al., 1997).

Furthermore, the construction models that propose the overlap between design and construction are based on the traditional conceptualisation of production (conversion model), which means that the flow activities and value are neglected by the project management (Huovila et al., 1997). As part of a solution to project low management performance, Koskela and Howell (2001) proposed a production-based approach to project management. In this approach, projects are conceptualised as temporary production systems. Hence, project management is equal production management (Koskela & Ballard, 2006). The conceptualisation of a production-based approach for project management is based on the TFV (transformation, flow and value) theory (Koskela, 2000), and its intrinsic goal is to get the facility produced, eliminating waste while increasing value (Koskela & Ballard, 2006).

The TFV theory is the conceptual basis of research in lean construction management. The Lean Construction is the adaptation of the Lean Production (lean applied in the manufacturing industry) paradigm in the construction environment. The Lean Production is based on the Toyota Production System (TPS), which overcame the mass production model.

This thesis explores the use of lean construction philosophy in the management of projects with overlap between the design and construction stages, focusing on the alignment of planning and control activities to integrate people, tools and process. The overlapped projects occur frequently in the construction industry practice and require further studies in order to assure their success.

This research adopts a design science research (DSR) or constructive research approach. Design sciences, such as architecture, medicine and engineering, aim to develop a valid and reliable knowledge to devise solutions to problems (van Aken, 2004). The DSR approach aims to devise and evaluate human-made artefacts to solve real-world problems. The research process proposed for DSR has different stages, and these stages vary according to the author. However, according to Kasanen, Lukka, and Siitonen (1993), the constructive research process can be addressed in six phases: (a) find a relevant practical problem; (b) obtain an understanding of the topic; (c) construct a solution idea; (d) demonstrate that the solution works; (e) present the theoretical contributions of the solution; and (f) examine the practical functioning of the solution.

In this context, as the researcher studied a practical problem which had research potential, this thesis starts with the first phase of the constructive research approach: the recognition of this real problem with theoretical problem correlation. For this reason, the next section describes a practical problem recurrently seen in construction project management, which is a consequence of the misalignment between design and construction management of overlapped projects. This practical problem was also the researcher's motivation for the investigation in the PhD programme. Further, the research problem is presented, followed by the research aim and objectives, a summary of the research method and structure of the thesis.

1.2 PRACTICAL PROBLEM

Between the years 2012 and 2015, the researcher worked as a lean consultant in Brazil. During these years, she implemented lean in 21 construction sites in six companies in four different cities. The lean construction implementation[1] was based on the collaborative development of: 1) The production system design using Schramm's model (2004), which includes developing the line of balance (LOB) as a master schedule of the construction project; 2) Last Planner™ System (LPS)[2] (Ballard, 1994) implementations with weekly and lookahead planning, and, less often, with phase scheduling; 3) Lean tools like *kanban*, *andon* and *heijunka* on-site.

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[1] Papers about the implementations were published in different conferences. To read them, access www.sippro.eng.br/artigos.asp

[2] Last Planner System is a trademark from the Lean Construction Institute.

Although the use of lean practices on-site promoted the production workflow stability and planning reliability, some common disruptions were observed throughout the projects. Most of the projects were conceived in overlapped between design and construction stages; and, due to the misalignment between design and construction schedules, detailed design was not delivered on time for construction, or was even lacking information.

This widespread problem was reported in a medium-sized[3] construction company which implemented lean construction in 13 sites. This company builds residential buildings in four capital cities and is responsible for the plot purchase, financial funding, designers' contracting and design coordination, construction and building maintenance. The company is part of a very competitive market, and, for this reason, it launches its projects on the market while still in the early design development, in order to speed up the apartment sales and capitalise the project.

Since 2012, the company implements lean construction practices, such as the LPS on its construction sites. The LPS is a planning and control system that deals with the construction uncertainty and variability, promoting a more reliable production workflow. It is composed of many hierarchical levels of plans, varying the planning horizon and degree of detail.

In this company, construction was planned by project managers who use the LOB technique to structure the work: define production batch size, sequence of activities, level of vertical integration, manpower capacity, construction sequence strategy, workflow, buffers, handoffs, and other essential information to be used in the LPS. On the other hand, the design is planned by the design manager using Ms Project software to define the milestones of design delivery.

On the construction sites, managers apply three levels of the LPS: master plan (long-term), lookahead plan (medium-term) and commitment plan (short-term). During the use of LPS, it was possible to visualise in the lookahead and commitment plans many problems in design quality and delayed delivery. Problems related to the lack of detailed design for material purchase and labour contracting were detected in the lookahead plan, and poor quality of detailed design for construction in the commitment plan. For instance, a project was impacted by design problems which affected the brickwork activity and delayed the construction for 20 working days.

Due to constant design problems in most of its projects, the board of the construction company decided to implement lean in the administrative departments so as to integrate all sectors and to minimise the wastes. The lean implementation started with an analysis of the Design department's processes, which used some sources to identify wastes, such as interviews, flowchart, data flow diagram and value stream maps. All flows of information, documents and data among designers, company's areas and construction sites were tracked. By the end of data collection, problems in the interface were found between design and construction, such as:

- Delay in design delivery by designers (do not meet the deadlines);

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[3] Around 1000 employees.

- Design has errors that cause rework both for construction and designers;
- Design does not follow the company's standards of construction;
- Late change order by the construction board, generating rework for design and construction;
- Lack of metrics to represent the Design sector's and partners' performances;
- Difficulty to produce as-built in construction sites.

Most of the problems detected were consequences of badly designed management. Despite being in-house departments, design and construction were often segregated, and both were not exchanging enough information about their schedules, processes and standards. Further, the design schedule did not consider the construction plan, irrespectively of any overlap. As a result, the design department often delivered unnecessary drawings to construction, whereas the necessary ones were delayed, representing a poorly managed designers' production capacity and a non-integrated process.

Generally, the design process has a production sequence and logic that is completely different from the construction; and, because the construction sequence, priorities and standards are not considered in the production of design drawings, there is a clash in the interface. Typical problems are the delay in delivering design documentation for suppliers, many times not yet hired, which creates work in progress[4] (WIP) between their processes; when suppliers receive design information, they do not have enough time to produce and deliver the products, causing delays on construction. In addition, the production batch size for the participants (designers, suppliers and constructors) is currently large, which increases the waits throughout the project and inventories of completed work. Figure 1 represents the WIP and delays among the interfaces' design-supply-construction.

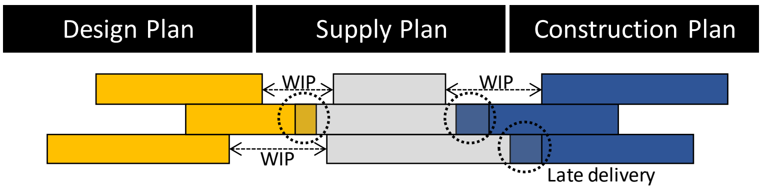


Figure 1: Typical problems in the interface design-construction.

These problems described are also highlighted by Sivaraman and Varghese (2016). The authors faced problems in a project due to the lack of construction priorities control which had caused the release of drawings not required by the construction team, while the drawings that were a priority had critically delayed the construction or had constructability issues (Sivaraman & Varghese, 2016). Another problem described by the authors (Sivaraman & Varghese, 2016) is the priority for procurement based on the lead time: material with longer lead time had priority of production and was released at once on-site, i.e. in large batches, even not being required at the initial phase of construction. Whereas, the required material at the initial phase went unnoticed. The delivery of large batches of material increased the inventories, limiting the storage space. The authors believed that these problems were consequences of "engineering

[4] WIP: work in progress. It is "items of work between processing steps" (Marchwinski & Shook, 2003). In this research, it is defined as the amount of time that location units have unfinished work.

for structural and civil components were not sequenced appropriately due to lack of information on construction sequence and priority” (Sivaraman & Varghese, 2016).

Dave, Hämäläinen, Kemmer, Koskela, and Koskenvesa (2015) corroborate that disconnections are commonly reported in the literature and practice as a problem in the interface design-construction. To be able to develop a detailed construction schedule, the major input is the design information; and that, due to this disconnection in the interface, “the design information is not released in time for the development of a detailed production schedule” (Dave et al., 2015). Therefore, “a better interface between production and design schedule should lead to the release of design information with a pull from the master schedule” (Dave et al., 2015).

To avoid these problems, the project manager should consider the alignment of production planning and control in both design and construction phases. As pointed out by Koskela (1992), the project management needs to focus control on the whole process in order to avoid sub-optimisation. Ballard (2002) corroborates this when he affirms that the essential feature of the new approach for the project management is “its focus on the system rather than component processes”. Then, as well as in the lean manufacturing industry, the design and production should be conceived as a unique process because the production system is seen as an extension of the product development philosophy and not the reverse (Cleveland, 2006).

Besides this, to control a process, it is necessary to exist a plan. The plan has the objective to present what must be done and how, followed by its control to keep the execution more effective (Laufer & Tucker, 1987). Hence, plans play the role as a prescriptive plan, “a target plan against which process is measured, and a record of the process” (Eckert & Clarkson, 2010).

Many different companies involved in the design and construction stages of a construction project do not have a “full understanding of the process that they need to go through”, which increases the importance of have a unified and aligned plan for people to interact, divide and coordinate the work (Eckert & Clarkson, 2010).

These practical examples presented in this section were the main motivation for the researcher to begin her doctorate journey to discover how these frequent problems in construction projects with overlap between design and construction phases could be avoided using integrated production management using lean construction philosophy.

1.3 RESEARCH PROBLEM

The building output of a construction project is a product. As a product, it has its phases of development from the moment of the product conception, design and launch on the market (Ulrich & Eppinger, 2016). The product development process also includes the feedback from production and users (Ulrich & Eppinger, 2016). A lean product development necessarily integrates disciplines, departments and suppliers, namely processes from sales, marketing, design, manufacturing, product planning, purchasing, engineering, finance and human resources (Morgan & Liker, 2006).

The Lean Product Development System (LPDSa) is based on the integration of three main subsystems: people, process, and tools and technologies (Liker, 2004). Their integration is necessary to combat the high fragmentation and specialisation of the AEC professionals, which is resulting in a sub-optimal project delivery process (Parrish, Wong, Tommelein, & Stojadinovic, 2007).

There is an intrinsic difference between the manufacturing production systems and the construction production systems: while the manufacturing systems need to prepare all the product information before starting production, in the construction scenario, the building production starts without the complete product information, including its design. Then, as opposed to the manufacturing product development, the construction product development has overlapped phases, namely the design and construction.

The TPS, or the LPDSa, always highlighted the importance of integrating the product development stage processes and information to guarantee the success of the new product. In the construction scene, even when there is a sequential stage of design and construction, information about product drawings, specifications, and other data are required during the construction. This proves that the design activities are still occurring in parallel with the building construction, even when it was supposed to be completed before.

This characteristic is what makes the new product development in construction challenging. For this reason, it is important to improve the existent overlap between design and construction in delivering construction projects and, in particular, through the lean construction perspective.

This research focuses on the integration of people, process and tools in the interface between design and construction stages in construction projects with overlap between these stages. Luiten (1994) explained this interface by considering the building process in three sub-activities: **design building**, which represents the design knowledge; **manage construction**, representing the planning knowledge; and **construct building**, which represents the constructability knowledge. To manage the interface, it is necessary to control six interactions between designers and constructors (Luiten, 1994):

1. Forward exchange of the building design.
2. Feedback on the building design from construction.
3. Backwards exchange of constructors' information.
4. Backwards exchange of general constructability knowledge.
5. Upstream shift of construction management tasks.
6. Downstream shift of design tasks.

The Design building process should receive design, planning and construction knowledge; product information; client's requirements; and construction resource information. The Manage construction process should receive building design; design, planning and construction knowledge; building site information; building method information; construction progress information; and requirements of the client. The construct building process should receive design, planning and construction knowledge; building design; building method, schedule and resource plan.

The information and knowledge produced by different stakeholders who work in different stages of the product development process are exchanged concurrently in projects with overlap between design and construction. As a result, higher attention to the information flow is necessary.

According to Koskela and Ballard (2003), there are three managerial activities in construction projects: (a) **design** of product and production system; (b) **operation** of the production system, of which production planning and control is part; and (c) production system **improvement**. These activities can be distinguished based on their temporal relationship with the productive act. The design stage must occur previously to the production; the operation during the production; and improvement after the productive act (Koskela & Ballard, 2003).

The success of a project with overlap between design and construction stages relies on the success of managing the information and knowledge exchanged by the stakeholders during the design, operation and improvement of the production system. These three managerial activities should occur at all stages of the product development process.

Visualising the actual practice of overlapping dependent activities in the construction industry, some researchers explored how to reduce the risk of delays and over costs in construction projects (Austin, 2016; Hossain & Chua, 2014; Srour, Abdul-Malak, Yassine, & Ramadan, 2013). To define the level of overlap between dependent activities, concepts of sensitivity and evolution were developed for the new product development in the manufacturing industry (Krishnan, Eppinger, & Whitney, 1997), then studied in design activities in the AEC industry (Bogus et al., 2011; Bogus, Molenaar, & Diekmann, 2005; Bogus, Molenaar, & Diekmann, 2006; Srour et al., 2013) and, more recently, studied in design and construction activities overlapping (Blacud, Bogus, Diekmann, & Molenaar, 2009; Hossain & Chua, 2014; Pena-Mora & Li, 2001; Srour et al., 2013).

For the overlapping between design and construction activities, Blacud et al. (2009) studied the factors that contribute to the sensitivity of construction activities under design changes. The definition of sensitivity of construction activities to design changes is: “the amount of physical rework caused by upstream design changes” (Blacud et al., 2009). They found four factors that influence the sensitivity of design activities: the level of transformation, lead time, modularity, and interaction with other building components. The authors assumed that the degree of overlap between design and construction activities is related to the nature of information exchanged between them (Blacud et al., 2009). The ideal overlap is when the initial design assumptions are equal to the final ones, which avoid reworks in downstream construction activity. Whether changes occur in the final design, the consequences for construction may counteract the gains produced by overlapping and even increase the lead time and cost of the construction compared to the traditional sequential and linear approach (Blacud et al., 2009).

These researches that explore the overlap of dependent activities are very limited through the lean construction perspective. These researches use the conventional model of production, i.e. they consider production only by the aspect of transformation activities, neglecting the flow and value aspects highlighted by the TFV theory. Adding to this, these researches predict the rework activities in the construction stage according to changes in design (Hossain & Chua, 2014) which, for the Lean Construction paradigm, waste is an activity to be reduced or eliminated from the production processes.

Moreover, the iterative process of design is intrinsic to the construction projects. Some design iterations are considered positive when generating value for the client, or negative when consuming resources without adding value (Ballard, 2000d). Besides this, the design process contains many stages of development, from the conceptual to technical drawings; along with them, different stakeholders interact, and their processes must be considered in the production planning.

To support the plan of design and construction stages, other conventional tools are used in the AEC industry, for example Work Breakdown Structure (WBS), Critical Path Method (CPM), PERT and Gantt diagram. These tools use, as the conceptualisation of project management, the conventional model of process, i.e. they focus on transformation activities neglecting the flow and value generation perspectives. They need the support of other tools to visualise the flow and value aspects of production.

Considering the researches that use TFV theory as a conceptual basis, there are in the literature review many techniques, tools and methods to plan and control design and construction activities. However, few of them focus on construction projects with overlap between design and construction stages.

The LPS is applied for design and construction and has the TFV theory as the conceptual basis of project management. The LPS aims to stabilise the workflow through controlling the variability and increasing the reliability of plans (Ballard & Koskela, 1998b). The implementation of LPS in construction is much wider than its application in the design stage. According to Ballard (2002), the use of the LPS in design makes the design flow more reliable.

Another method to control the design product development in the AEC industry is the Agile (Demir & Theis, 2016; Hass, 2007; Owen, Koskela, Henrich, & Codinhoto, 2006). The Agile began to be used in new software development, but recently it has been used with the Stage Gate approach in the manufacturing industry (Cooper, 2016; Cooper & Sommer, 2016). The main aim of Agile is to insert the user's requirements along the product development, in order to increase its value (Hass, 2007). The method uses sprints to define the period of product development and its goals, and scrums, which are daily meetings to keep tracking of the process with designers. When combined with Stage-Gate, the sprints take place between gates of the new product development (Cooper, 2014; Cooper & Sommer, 2016).

There is also described in the literature review the use of design structure matrix (DSM) for design processes planning (Koskela et al., 1997; Rosas, 2013; Smith & Eppinger, 1998). DSM is used to identify the dependency among design activities and support the optimal sequence of design tasks (Koskela et al., 1997). Due to focus on information flow among the designers, DSM uses the TFV theory as conceptual project management, and it was specially developed for design activities.

Analytical Design Planning Technique (ADePT) is a planning tool for design which focuses on the flow of information between design tasks, i.e., uses the TFV theory as project management conceptualisation (Hammond, Choo, Austin, Tommelein, & Ballard, 2000). ADePT combines the design process model with the DSM analysis to create a project and discipline design programmes (Austin, Baldwin, Li, & Waskett, 1999).

A more effective way to plan and control construction projects is using location-based schedules (LBS). They are applied for construction planning since the 1970’s as linear scheduling methods for repetitive processes (Carr & Meyer, 1974; Kleinfeld, 1976; O'Brien, 1975; Peer, 1974b; Schoderbek & Digman, 1967). These tools are used in construction to plan high rise buildings (Carr & Meyer, 1974; Lucko, Alves, & Angelim, 2014; Mendez & Heineck, 1998; O'Brien, Kreitzberg, & Mikes, 1985), roads (Arditi & Albulak, 1986), resource levelling (Damci, Arditi, & Polat, 2013, 2016), non-repetitive areas (Valente, Montenegro, Brito, Biotto, & Mota, 2014), and so on.

The most famous LBS in construction is the Line of Balance (LOB), Flowline and the Takt-Time Planning (TTP). LBS tools allow the reduction of production batch size and cycle times, insertion of buffers between activities, adjustment of production pace, and visualisation of the workflow (Valente et al., 2014). For that reason, it is TFV theory-based.

However, there is not an application of location-based tools for planning design stage. Previously described, the techniques for planning the design process have focused only on the design stage of the project management; and the LOB, flowline and TTP, only for construction stage. A summarised table of the main tools, techniques and methods to plan and control processes in project management and the context of use can be seen in Table 1.

Table 1: Summary of tools, techniques and methods to plan and control design and construction phases.

Tool, Technique, Method	Project Management Conceptualisation	Context Of Use
Work Breakdown Structure	Conventional	Design and Construction
CPM	Conventional	Design and Construction
PERT	Conventional	Design and Construction
Gantt Diagram	Conventional	Design and Construction
Last Planner System	Lean Thinking	Design and Construction
Stage-Gate	Conventional	Design and Construction
Agile	Value perspective	Design
Design Structure Matrix	Lean Thinking	Design
ADePT	Lean Thinking	Design
Line of Balance	Lean Thinking	Construction and ETO company
Flowline	Lean Thinking	Construction
Takt-time Planning	Lean Thinking	Construction

Focusing on integration between various stages of project development, Bolviken, Gullbrekken, and Nyseth (2010) developed an adaptation from the LPS called Collaborative Design Management, in which new levels of planning are used to manage the design, such as, crew plan, dialogue matrix and decision plan. The authors created three phases to manage design: the design creation process; design production process; and, decision-making process. In this collaborative planning, the integration design-construction occurs through the LPS: the last planner from construction is interconnected with the LPS used by designers, namely, the lookahead plan from construction pulls the weekly plan in design. However, it is necessary to understand better the relationship between the distinct levels of design and production plans, what are the planning techniques used to design the construction system, how the production batch size is defined for design and construction, and how the design process adapts its task sequence to meet the construction sequence.

Another researcher, Viana (2015), implemented the LPS in engineering-to-order (ETO) companies to integrate the departments of design/engineering, plant, and site assembly in a holistic production management system. In Viana's work, the researcher implemented many lean production system elements, and she focused on controlling the WIP to optimise companies' production capacity while reducing wastes of overproducing unnecessary items to be assembled on-site. In this research, the interfaces among the departments were connected and the workflow planned using a LOB. However, the development of this system occurred inside vertically integrated companies that are suppliers of prefabricated building systems to simultaneous projects. This fact increases the complexity of planning their production system due to a high level of variability in demands. Adding to it, the ETO companies' clients (projects) already established the assembly deadlines and detailed design; then, these companies do not participate in most of the production system design of their clients' projects.

The idea of applying construction pulling production of downstream activities is also seen in (Sivaraman & Varghese, 2016). The researchers worked in the interface engineering-procurement-construction of a construction project with overlap between engineering and construction phases. The authors focused on an ETO company of piping, after the installation onsite be delayed due to a cascade delay caused by the foundation design. The authors developed an information technology platform to enable updated information on construction to pull engineering and procurement processes in order to align their sequences of production. The components of the pipeline received a mark number based on their location in a grid and elevation. A dependence net of material, information and construction flows was drawn previously to set the relationships among participants. This solution proposed by (Sivaraman & Varghese, 2016) is the first exploration of a pull system to control the changes in the sequence of upstream activities according to the construction requirements. Although it was applied in only one process (pipes) and involved one ETO company, this solution already proposed the identification of components using the building location. The solution focused more on controlling the system operation, rather than planning it using location-based tools.

A public company in Norway applied lean design management in the National Academy of the Arts project (Holm, 2014). The company had the rules of the client and owner of the project. The use of lean design was a practical experimentation promoted by the project manager, and it is not documented by the academia. The design management had some steps from the design system design, passing through its operation until its improvement (Holm, 2014): 1. Prepare the lean construction strategy; 2. Product creation process; 3. Establish the takt-time; 4. Develop and improve the lean design process; 5. Extend the use of lean takt planning and construction with contractors; and 6. Lessons learned. Throughout these steps, all the participants (designers and engineers) established the same goal and process to accomplish the project. This case applies the concept of takt-time for design, and other lean practices, such as co-location of designers and engineers, and collaborative planning. Although the use of takt-time in construction long-term plan, the team did not use location-based tools to plan the design stage.

Through these four examples, it seems that both academia and industry are addressing the fragmentation of planning and control of design, contractors and construction. The studies used the concept of pull production to reduce work in progress and lead time and increase the quality of design and construction. However, as Hopp and Spearman (2011) point out, pull production systems require a smooth master production schedule that specifies the system predicted demand. In the construction sector, the demand for construction is determined by the design which represents part of client/user requirements.

The examples presented focused more on the system operation, and less on the system design, which is responsible for minimising the effects of variability on the production system. Adding to it, although researches contributed connecting various stages of the project development through the planning, none of them had explored the production design and planning of design, contractors and construction in projects with overlap using location-based tools. Table 2 presents the principal works previously described, the main tools applied and the context.

Table 2: Researches and cases using pull production system for integrating diverse stages of product development.

Authors	Pull System Integrating Different Participants	Main Tools Used	Context
Bolviken et al. (2010)	Integration of design and construction production using a Collaborative Design Management that uses LPS in both stages.	• BIM • Last Planner System + Decision Plan (design) + Two weeks work and crew plans	• Construction company • Overlapped Design and Construction
Viana (2015)	Integration of different sectors of ETO companies through a unique production planning and control system.	• Last Planner System • Line of Balance	• ETO companies
Sivaraman and Varghese (2016)	Integration of engineering design, ETO company and construction by an information technology platform to participants update the information status of their production, and mainly, the construction requires what they need for upstream activities.	• IT Platform • Net of information, material and workflows • Components code based on grid location	• ETO company • Overlapped Design and Construction
Holm (2014)	Design management that integrates architects, constructors and engineering designers by means of a collaborative plan that uses the concept of takt-time (2 weeks) for all the participants' activities.	• Co-location • BIM • Takt-time • Hierarchical levels of collaborative plans	• Construction project • Overlapped Design and Construction

When considering that design should be managed as production (Ballard & Koskela, 2009), it is possible to design its system and align it with suppliers and construction systems. So, if the design is a production system, then the principles of pull production can be implemented, and location-based tools used for planning construction as well.

Concluding, with the highlighted necessity to align the designers, suppliers and construction plans in overlapped projects, this research intends to fill this gap in designing a pull production system from construction to upstream stages applying location-based tools. There is a gap of researching the pull production besides the context of ETO companies; experimenting location-based tools for design planning; and more efforts in designing an aligned production system, then controlling it.

As pointed out by Dave et al. (2015), there is the necessity for “a robust theory of planning and scheduling”, and a more suitable approach to address “critical aspects of planning and scheduling function”. As the authors suggested by integrating LOB with LPS (Dave et al., 2015) for example, it is possible to plan and control the construction stage. However, the same it is needed when considering the design stage and its overlap with construction.

1.4 RESEARCH AIM AND OBJECTIVES

This research aims to devise a model to design, plan and control the stages of design and construction in overlap, using location-based planning tools to pull and align the project production.

The objectives are:

- (i) Determine how to use location-based scheduling tools to structure the work for design, supply and construction;
- (ii) Find out how to assemble design packages to meet suppliers’ and builders’ requirements;
- (iii) Determine the decoupling point of design development in order to apply pull production;
- (iv) Identify and analyse pros and cons of existing types of pull production systems that suit better to the context of overlapped projects;
- (v) Explore how to measure and manage the work in progress and buffers in an integrated project system;
- (vi) Identify the best tools to control the production system in the interface design-construction.

1.5 RESEARCH CONTRIBUTION TO KNOWLEDGE AND CLAIM OF ORIGINALITY

The thesis fills a theoretical gap in construction project management literature by means of a model for integrating design, plan and control activities between design and construction stages in construction projects with overlapped between these stages. Moreover, the theoretical contributions achieved are:

1. Contextualize the use of lean tools into the NPD stages and management activities for the design and construction integration purposes;
2. Use the location-based scheduling tools to pull production, reduce the production batch size, the work in progress and align the production sequence in the D-C interface;
3. Articulate the production planning and control system to integrate decisions and information between participants at the interface D-C. The plans are connected vertically and horizontally;
4. Explore a new perspective to overlap design and construction stages: breaking down the activities based on location breakdown structures of construction master plan, and then applying pull flow towards design.

Moreover, the artefact of this research, i.e., the model, is also a practical contribution, due to its application on construction project management context. It congregates the concepts surrounding the overlap between design and construction, and shed light on its use for informed clients, project managers, design managers and construction managers. The model directs how projects with overlap of stages should be managed regarding its planning and control activities, processes and tools.

1.6 RESEARCH METHOD

The research process for this investigation is based on the DSR, which is presented in Chapter 3. The DSR is a third mode to produce knowledge differently from the natural and social sciences. DSR aims to create something new to the world or improve part of it (Lukka, 2003; March & Smith, 1995; van Aken, 2004). According to van Aken (2004), the DSR is in the middle ground between descriptive theories and practice and typically involves a social and technical system.

In design sciences, understanding a problem is only halfway to solve it, and much knowledge is produced by practitioners (Vaishnavi & Kuechler, 2015). Moreover, DSR is a mode of producing scientific knowledge through the creation and implementation of an artefact (a solution) able to alter a particular phenomenon or problem (Vaishnavi & Kuechler, 2015).

DSR is used in lean construction, specifically for construction management (Rocha, Formoso, Tzortzopoulos-Fazenda, Koskela, & Tezel, 2012). It is a research strategy able to connect research and practice, by solving problems that affect the construction management (Koskela, 2008).

This research adopts a DSR because the researcher found a practical problem along with her experience in lean construction implementation in Brazil (presented in the previous chapter), which is also the motivation of this PhD work. With a practical problem which also has a research potential due to its gap in the literature review (presented in the research problem), the DSR is a suitable research approach to be used in this investigation in order to develop an artefact to solve the problem, at the same time, it contributes to the theory.

Then, the thesis was based on the DSR steps. The research method, described in Chapter 3, was adapted to the uncertainties surrounding the empirical studies availability, and it was tailored according to the researcher's experience in construction project management. It was used reflections upon the practice to understand the problem, develop the solution and evaluate it.

The practical aspect of the research was achieved by deploying three different types of empirical studies: retrospective practitioner studies, case studies and action research study. It started by identifying the practical problem in the retrospective studies conducted when the researcher was a lean consultant professional. The connection between the practical problem and the theoretical problem was accomplished through the literature review developed in Chapter 2. The theoretical knowledge obtained was then applied in the development of the artefact using the empirical studies. Along with their conduction, the model was being developed and improved through cycles of evaluation.

Chapter 4 represents the first solution output from the retrospective studies. Chapter 5 describes the case study 4 and its contributions to the second version of the model, which was then improved in Chapter 6 at the end of the action research study 5 and case study 6.

All the theoretical and practical knowledge acquired throughout the thesis development was transformed in contributions in Chapter 7. Herein, the final version of the model is presented as the main contribution to construction management, and the discussion section demonstrates the advances in the theoretical knowledge. Chapter 8 concludes the work developed, presenting the main findings and opportunities for future research.

Figure 2 outlines the research method and the chapters of the research.

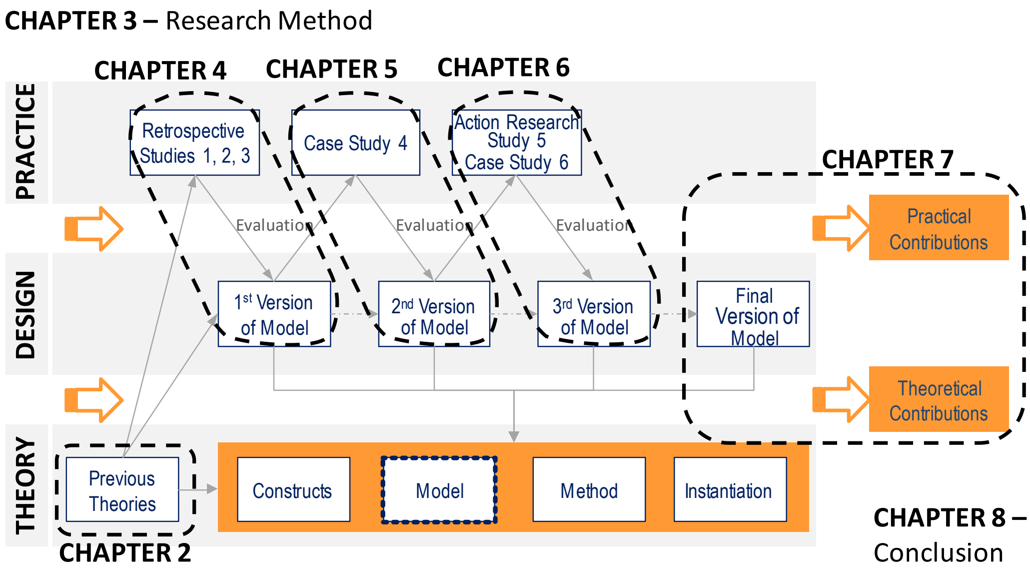


Figure 2: Outline research method and chapters.

1.7 STRUCTURE OF THE THESIS

The thesis is structured in a sequence of chapters that makes easier the understanding of the research process and the outputs of the studies which progressively contributed to the model development.

Chapter 1 introduces the context of the thesis investigation, the practical problem identified by the researcher that justified the use of the DSR as the main approach for the research method. It also presents the research problem connected to the practical one and its unfolding into the research aim and objectives. The chapter is closed by the presentation of the research method outline and research structure.

Chapter 2 describes the literature review in the fundamental concepts about Lean Product Development Process, Lean Design Management, Lean Construction Management and BIM. It also justifies the theoretical gap as well as criticises the state of art in the field of the study.

Chapter 3 presents the research methods employed in this thesis, from explaining the context of the research in construction management and the practical basis of the knowledge that justifies the adoption of the DSR. The methodological choices are presented and justified, such as the research approach, methods, strategies, and data collection techniques used. The chapter also provides the research design with the main phases of development of the thesis, followed by the studies descriptions and the procedures to evaluate the artefacts.

Chapter 4 demonstrates through three retrospective practitioner studies the practical problem detected by the researcher. Study 1 was developed in a public aquarium project, in Brazil, in which the LOB was used for designing the production system, pull suppliers' and designers' activities. Study 2 occurred in the customisation department of a construction company and deployed the LOB and LPS in construction to pull the customisation process, reducing its batch size. Study 3 took place at a construction company and explored the integration of main departments' processes through the Stage Gate approach. The output of the three studies was the first version of the model presented at the end of the chapter which was evaluated afterwards.

Chapter 5 explains the case study 4 in the Fine Art, Music and Design Faculty, in Norway. In this study, the BIM was aligned with procurement, which was aligned with construction Takt-Time Plan (TTP). It results in the improvement of the artefact to its second version, followed by its evaluation.

Chapter 6 contains the action research study 5 deployed at the Maintenance Depot, in England. In this study, it was implemented collaboratively with the construction company staff the construction system design using LOB and the reverse plan for procurement and design. The chapter also presents the case study 6 in a residential building project, in Norway, where a collaborative and integrated planning and control system was studied in both design and construction stages. The result of both studies was the third version of the model which was evaluated by the case study participants.

Chapter 7 extends the model development into its final version. The discussion section of the chapter sums up the findings, learnings and reflections throughout the studies and the model development, by comparing the contexts, outputs, practices and findings among the studies.

Chapter 8 summarises the overall context of the problem, learning and research findings of this investigation. It also identifies the contributions of this thesis to the theory and practice of construction management, the limitations of the research, followed by the future research suggestions.

The introduction chapter presented the context of this investigation work, the practical and theoretical problems of the topic, the research aim and objectives, the research method and the research structure. The chapter that follows presents and criticises the state of art of the relevant topics that based this research, such as the lean product development process, lean design and lean construction management, and BIM.

2 LITERATURE REVIEW

The most common reason why the companies in AEC industry work in overlap between the design and construction stages is to shorten the new product development (NPD) process. The NPD is composed of a set of stages which are intrinsically connected by people and information.

This thesis investigates the overlap of two stages of the NPD: design and construction. For this reason, the literature review presents an overall view of NPD in section 1, followed by the discussions of the interface between design and construction in section 2. In the following sections 3 and 4, Design and Construction Management are described respectively. BIM is presented in section 5 because it is a particular technology that supports the design and construction processes. Figure 3 outlines the chapter's sections.

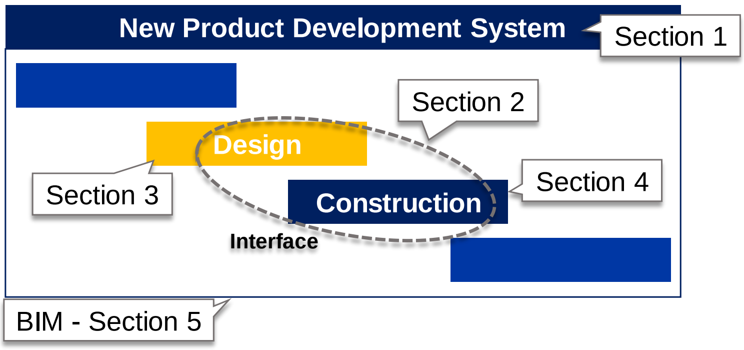


Figure 3: Scheme of the literature review.

2.1 NEW PRODUCT DEVELOPMENT

> *"The advantages that come from cutting time-to-market in half and consistently developing better products are so significant that the competitive balance in some industries is changing in favour of companies that can achieve these goals first. Companies introducing more new products, reacting faster to market and technology changes, and developing superior products are winning the battle over competitors" (McGrath, 2012).*

This section presents the literature review surrounding the NPD in the manufacturing and construction industries. The NPD is a process carried out within companies to translate customers' requirements into finished products (Kagioglou, Cooper, Aouad, Sexton, & Sheath, 1998). A process is a sequence of steps that transform inputs into outputs (Ulrich & Eppinger, 2016). The NPD process comprehends the activities that companies undertake throughout the lifecycle of a product (Kagioglou et al., 1998) from the conception and design to the commercialisation of a product (Ulrich & Eppinger, 2016).

The motivation to study the process of NPD relies on the fact that companies are trying to shorten the product development time in order to deliver it earlier to the market. According to Smith and Reinertsen (1998), faster product development is necessary to increase sales, beat the competition to market, adapt to changing markets, styles and technologies, and maintain a leadership position. The later authors point out that enterprises must develop a balanced and integrated product development process by integrating disciplines and considering their boundaries carefully.

2.1.1 New Product Development Activities

In the NPD process, the number of stages varies among enterprises and field. Whether or not the stages are formalised, frequently the companies omit, intentionally or accidentally, some activities of NPD (Dwyer & Mellor, 1991). However, independently of the number of stages, the NPD activities can be divided into three categories (Cooper et al., 2008; Kagioglou et al., 1998): pre-development activities; development activities; and post-development activities.

The NPD process can be agile. This means it is able to be flexible to make changes to the product without being too disruptive. The changes are based on customer needs, market competitors' response, new technologies, or the manufacturing process (Trott, 2016). According to Smith (2007), the software industry uses the agile NPD process to enable the firms to adapt to the changing markets. The concept is spreading to other industries.

What the agile concept implies is to maintain the flexibility in the product development. The less disruptive a change is in the NPD, mainly in the later stages of it, the more flexible is the system. However, it is worth noting that, along the NPD, the level of uncertainty and complexity varies (Figure 4). At the beginning of the process, the flexibility to change the product is higher, while there are high levels of uncertainty around the new product and low complexity (herein, complexity is understood as the product detail – the number of parts) due to a small development team (Smith, 2007). The opposite occurs at the end of the NPD when there is a high level of complexity in the system, but less uncertainty in the developed product (Smith, 2007). At the later stages of development, the flexibility is usually lower, and the process is already structured.

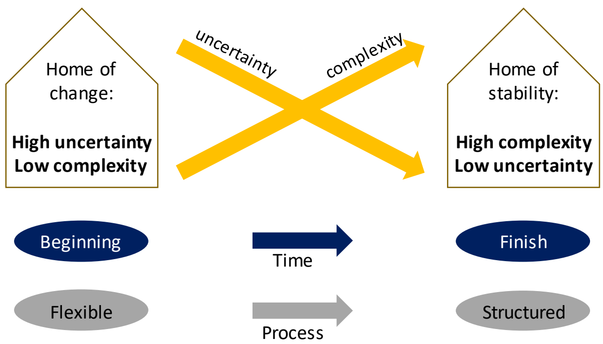


Figure 4: Process shift over time (Smith, 2007).

2.1.1.1 Pre-Development Activities or Fuzzy Front End

The pre-development activities or the ones that occur at the "fuzzy front end" are those that are necessary at the beginning of the NPD process, or the front end period. In this phase, companies decide about the concept of the product, the necessary financial investment of the idea, and the new opportunities (Trott, 2016). At the front end, the organisations judge when the new concept is ready to enter into the structured development process (Stevens, 2014).

At this phase, it is crucial to capture information about the customer's needs and requirements (Kagioglou et al., 1998). The pre-development activities are essential to strategically study a new opportunity for a product in the market. Although it is not an expensive financial phase, it is complex and risky and determines the potential rewards (Brentani & Reid, 2012).

2.1.1.2 Development Activities

The activities to develop the new product physically include its design and manufacturing process. Usually, the products are tested (in-house and customer tests) and validated according to their performance and functionality (Cooper et al., 2008). Included in the development activities is the test in the manufacturing process in order to check the production capability, costs, throughput time, and so on. Herein, a precise data about product's viability is analysed front the expected market revenues and cost (Cooper, 2011).

2.1.1.3 Post-Development Activities

At the later stages of the NPD, the post-development activities occur such as: launch of the new product into the market; marketing; after-sales support; and review of the NPD process performance (Cooper et al., 2008). In the latter, there is the opportunity to improve the product, process, manufacturing and all the related activities. Capturing the feedback of the NPD is crucial to avoid repeating the same mistakes in future projects (Cooper et al., 2008; Kagioglou et al., 1998).

2.1.2 Models of New Product Development

Several models describe the stages and activities of the NPD. The most relevant models to be described in this section are: 1) Departmental-stage models; 2) Activity-stage models; 3) Cross-functional models; 4) Decision-stage models; and 5) The Development funnel models.

2.1.2.1 Departmental-stage models

The departmental-stage models are a linear and sequential model of NPD, in which departments are responsible for specific activities. They are also known as "over the wall" models because the departments throw the project over the wall to the next department to conduct their tasks (Trott, 2016) (Figure 5).

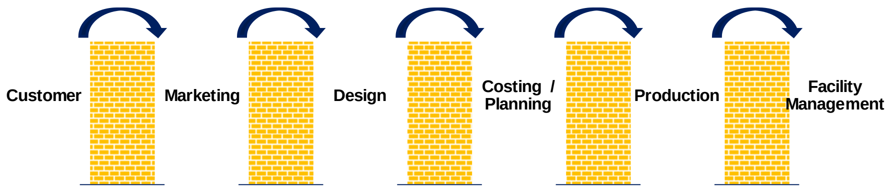


Figure 5: "Over the wall" model for NPD.

In departmental-stage models, the product development occurs almost exclusively in one department or stage at a time. When concluded and all requirements are checked, the product development starts in the following department or stage. Few concurrent and interdepartmental interactions occur in the NPD, which creates issues in the later development activities, causing rework and consultation between functions (Trott, 2016).

2.1.2.2 *Activity-stage models and Concurrent Engineering*

Activity-stage models are similar to departmental-stage models, however their focus is on the activity (Trott, 2016). In order to adopt an activity-stage model, it is necessary that "a major change in philosophy from functional orientation to project orientation" (Trott, 2016) takes place.

One example of an activity-stage model is the Concurrent Engineering (CE). This has emerged as an "integrated design" and an alternative for the "over the wall" models. CE is also known as Simultaneous Engineering or Parallel Engineering (Anumba & Evbuomwan, 1997). One of the first CE definitions is dated from 1992 by Carter and Baker cited in Koskela and Huovila (2000):

> *"Concurrent Engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from concept through disposal, including quality, cost, schedule, and user requirements."*

An example of how the organisation's departments continue to be involved across the CE NPD process is shown in Figure 6, in which the level of involvement varies from heavy to low.

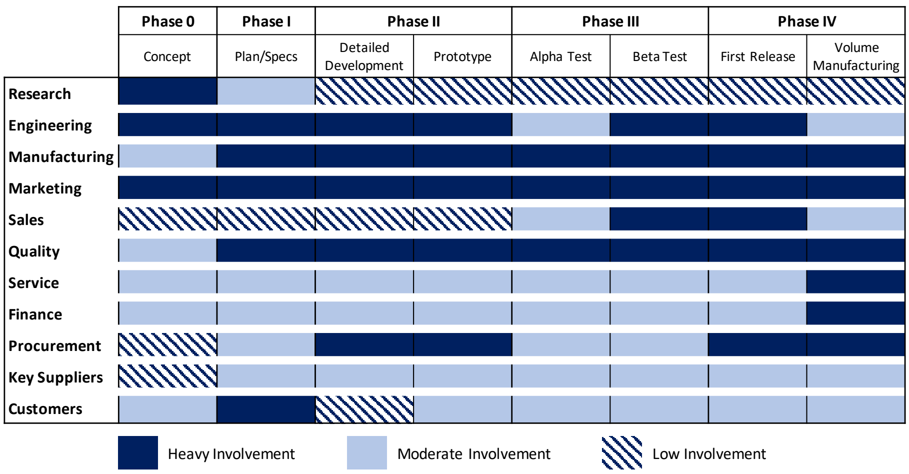


Figure 6: Concurrent engineering integrates all functions during the development process (McGrath, 2012).

Due to its success in reducing costs and time, the practice was widely adopted by the manufacturing industry in the 1980s (Forgues & Koskela, 2009). In the construction industry, CE reduces the uncertainty, focusing on constructability of design and planning of production activities, while it is based on the TFV theory (Huovila et al., 1997). In order to improve the project delivery, stakeholders from the supply chain must be involved from the beginning of the project in order to explore the product design and its production processes (Parrish et al., 2007). The CE is considered as an approach that establishes design as a common thread linking organisations together (Austin et al. 2001).

2.1.2.3 *Cross-functional models (teams)*

The cross-functional models deploy a dedicated project team representing people from a variety of functions. It requires changes in the organisation structure, project management approach and interdisciplinary teams (Trott, 2016). The NPD appears as a simultaneous and concurrent process with cross-functional interaction (Barczak, Griffin, & Kahn, 2009).

In companies with a functional organisation, the authority rests with the functional manager (Smith & Reinertsen, 1998). In companies driven by project or business, the use of a matrix structure clarifies the management structure of multiple departments, i.e. cross-functional teams (Trott, 2016). In this tool, communication and authority are depicted by lines (horizontal and/or vertical) (Smith & Reinertsen, 1998). The two organisational structures are shown in Figure 7.

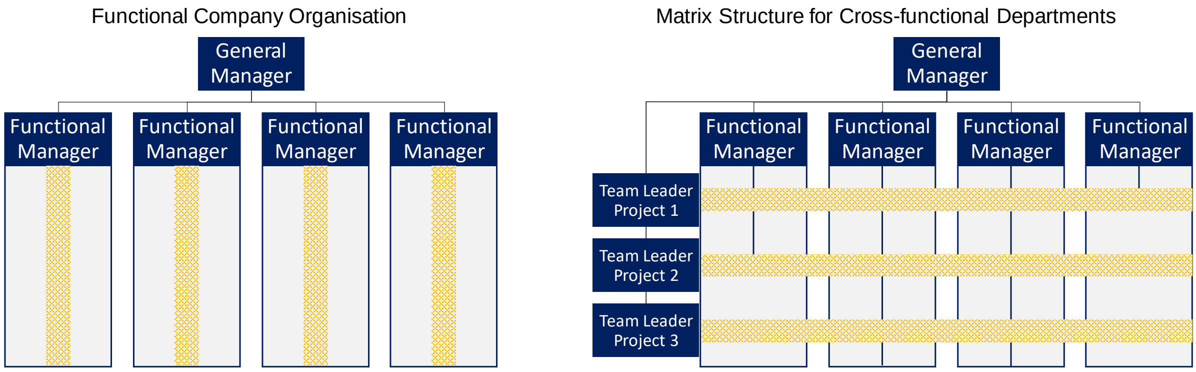


Figure 7: Organisation's structure based on function and project. Adapted from Smith and Reinertsen (1998) and Trott (2016).

2.1.2.4 Decision-stage models: Stage-Gate

The stage-gate system was developed by Cooper (1990) to NPD process with "a positive impact on the conception, development and launch of new products" (Cooper, 2014). The traditional stage-gate is composed of five stages: 1) Idea scoping; 2) Build a business case; 3) Development; 4) Testing & validation; 5) Launch. There are five gates between each stage (Cooper, 1990).

A third generation of the stage-gate model was created to overcome some deficiencies in the system, such as slow development, does not prioritise projects in a portfolio, bureaucratic process (Cooper, 1994). The new model proposes the overlapped activities in the same stage, or even between stages (Cooper, 1994). Also, the Go/Kill decisions are delayed to promote flexibility and speed, plus the "hard" gates become "fuzzy" gates, in which the "go" decisions are analysed according to the information critical for the project (Kagioglou et al., 1998). In the third generation of stage-gate, there is yet the sequential and consecutive stages which cannot be eliminated or bypassed (Kagioglou et al., 1998).

Practitioners of the stage-gate criticise its linearity, rigidity, bureaucracy, low incentive to innovation, low dynamism and flexibility to adapt to a faster-paced world, more competitive and global, and less predictable (Cooper, 2014). As a consequence, companies have adapted the stage-gate to their different types of NPD, i.e. overlapping the activities within phases and/or between phases, or reducing the number of stages and gates in order to make the system more adaptive, flexible, agile and accelerated (Cooper, 2014) (Figure 8). This new approach is called Agile-Stage-Gate Hybrid Model.

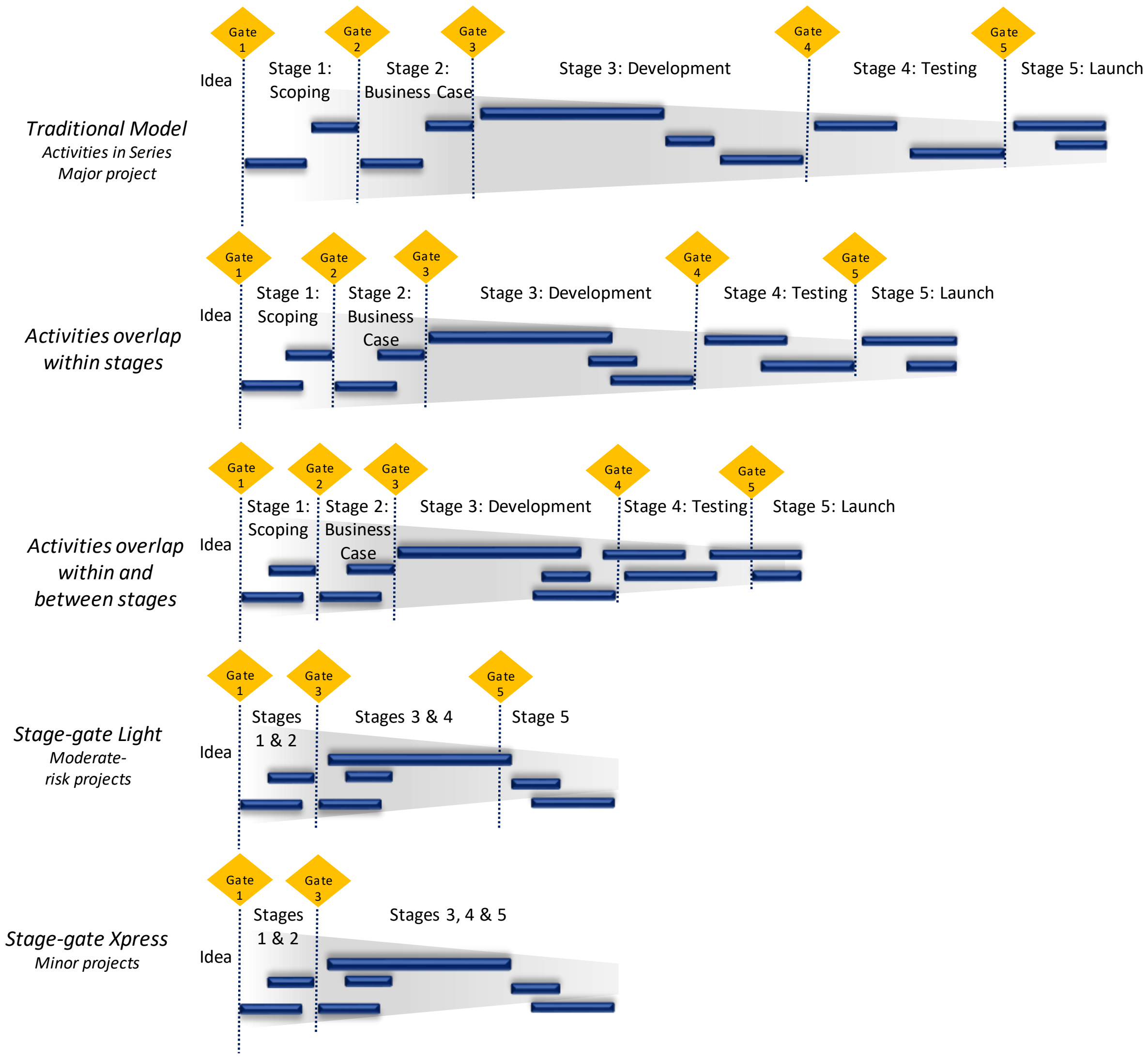


Figure 8: Stage-Gate models comparison in traditional and overlapping in the stage and between stages; scalable to different contexts of project size and risk (adapted from Cooper (2014)).

1.1.1.1.1 Agile-Stage-Gate

The Agile-Stage-Gate is a new project management method used by industries, in which the stages remain, and Agile is applied within some stages, such as development and testing (Cooper & Sommer, 2016). According to Cooper and Sommer (2016), the Agile-Stage-Gate uses nine elements from Agile, from the artefacts (sprint, scrum, etc.), tools and people roles, in order to create the project heartbeat, prioritise development, visual management and adaptation to changes, support sharing and team learning.

Changes in the product are considered at the beginning of each sprint; as a result, the team can work without disruption, with high productivity and with product specifications fixed. The aim of each sprint is to develop a deliverable to present to the client and receive feedback; then, it needs to be something tangible, concrete and be able to measure progress (Cooper & Sommer, 2016). The authors suggest the use of product versions, between product concept, and a ready-to-trial prototype for physical products. It can be 3D drawings, or virtual models, which the authors call protocepts, and must be used to reduce technical uncertainties (Cooper & Sommer, 2016).

Agile is applied in typical IT projects and uses a dedicated and collocated project team. However, when applied by companies that develop physical products, some adjustments must be made, as most of the companies do not have a dedicated team for only one project and the designers are from different companies.

2.1.2.5 The Development Funnel

Wheelwright and Clark (1992) proposed the development funnel model, in which a range of new ideas/projects are conceptualised and progressively selected throughout the product development phases until the selection of only one project that is to be focused on and developed. The criteria for selection are based on reviews about the product and process. Customer and market requirements drive the development phase.

McGrath (1996) developed a similar Funnel model with more phase reviews (Figure 9). According to McGrath, between each phase of the product development process must exist the phase review. “Phase review should be decision-making sessions,” and the actual performance of the product and process should be compared to the plan (McGrath, 1996).

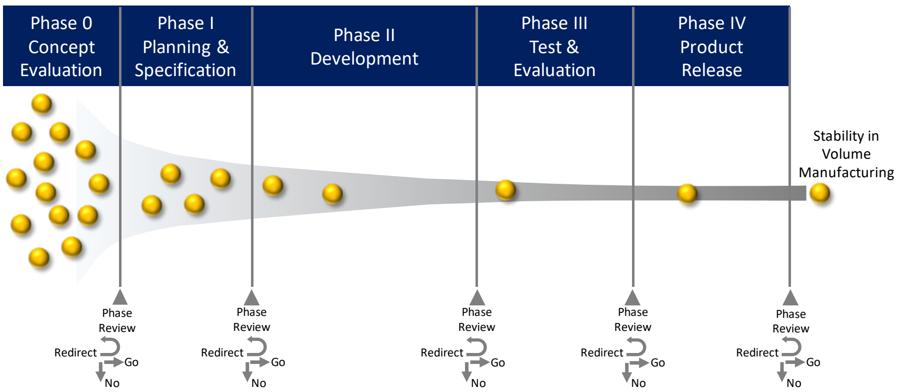


Figure 9: Phase review process funnel (McGrath, 1996).

One major criticism of funnel models of NPD is the limitation of companies’ resource capability in allocating efforts in the conceptual development of a large number of projects (Cooper et al., 2008).

2.1.3 Lean Product Development System

The Lean Product Development System (LPDSa)[5] is based on the Toyota Product Development System, known worldwide by producing “higher quality vehicles faster, for less cost, and at a greater profit than its competitors” (Morgan & Liker, 2006). Toyota’s success is not only a result of its manufacturing system; rather, its success starts in the **product development system** that enables Toyota to bring excellent products to the market (Liker, 2004).

In an LPDSa, it is necessary to link disciplines, departments and suppliers; in other words, processes from sales, marketing, design, manufacturing, product planning, purchasing, engineering, finance and

[5] LPDSa refers to Lean Product Development System. LPDSb refers to Lean Project Delivery System.

human resources must be integrated (Morgan & Liker, 2006). The LPDSa is based on three primary subsystems: people, process, and tools & technologies (Liker, 2004).

Thirteen principles are pointed by Morgan and Liker (2006) as essential practices to occur in these systems. In the **process** subsystem, the tasks and their sequence are studied from the product concept to start of production. The principles in this subsystem are (Morgan & Liker, 2006):

- **Principle 1:** Establish customer-defined value to separate value-added from waste.

An LPDSa starts with the customer; then, it is necessary to identify product requirements, define value, communicate value, and align objectives throughout the organisation (Morgan & Liker, 2006).

- **Principle 2:** Front-load the product development process to explore thoroughly alternative solutions while there is maximum design space.

Front-loading the NPD system enables cross-functional teams to study alternatives of design that have a high impact on the success of the product for the lowest cost (Morgan & Liker, 2006). Toyota uses Set-Based Concurrent Engineering (SBCE) to create and examine multiple alternatives and systematically narrows the set to a final choice, usually the superior one.

- **Principle 3:** Create a levelled product development process flow.

The view of the NPD as a process is very powerful (Morgan & Liker, 2006). The authors point out several characteristics that a lean product development process must have to avoid wastes. Table 3 presents the seven wastes (Ohno, 1988) in the context of product development.

Table 3: Seven wastes applied to the product development (Morgan & Liker, 2006)

Seven Wastes	What is it?	Product Development Examples
Overproducing	Producing more or earlier than the next process needs	Batching, unsynchronised concurrent tasks
Waiting	Waiting for materials, information, or decisions	Waiting for decisions, information distribution
Conveyance	Moving material or information from place to place	Handoffs/excessive information distribution
Processing	Doing unnecessary processing on a task or an unnecessary task	Stop-and-go tasks, redundant tasks, reinvention, process variation – lack of standardisation
Inventory	A build-up of material or information that is not being used	Batching, system over utilisation, arrival variation
Motion	Excess motion or activity during task execution	Long travel distances/ redundant meetings/ superficial reviews
Correction	Inspection to catch quality problems or to fix an error already made	External quality enforcement, correction and rework

Principle 4: Utilise rigorous standardisation to reduce variation, and create flexibility and predictable outcomes.

The LPDSa standardised products, processes and professional competence to enable flexibility and speed in the system. For this reason, the design, the processes and the skills are also standardised.

The **people** subsystem comprises how companies develop their culture, covering from selecting and training engineers, leadership style to organisational structure and learning patterns. The principles related with this subsystem are (Morgan & Liker, 2006):

- **Principle 5:** Develop a chief engineer system to integrate development from start to finish.

The chief engineer in an LPDSa is not only a project manager. He/she is the one who focuses on the integration, is a personal influence, with know-how and authority, and represents the customer's voice.

- **Principle 6:** Organise to balance functional expertise and cross-functional integration.

The LPDSa requires coordination across functions to stay focused on the customer's needs. It uses the organisational matrix to balance the functional organisation and the product organisation. It uses big room to support simultaneous engineering.

- **Principle 7:** Develop towering technical competence in all engineers.

Hiring, training and retaining people is crucial to the LPDSa. The rigorous selection process of the professional is followed by a technical mentoring system with regular evaluations of performance. The Toyota's culture values technical capability.

- **Principle 8:** Fully integrate suppliers into the product development system.

The suppliers must have the same level of high quality in engineering and manufacturing capability that Toyota has. The suppliers must be compatible with the product development system. They should be engaged at the very early stages of the NPD in order to contribute to the simultaneous engineering.

- **Principle 9:** Build in learning and continuous improvement.

The management of tacit knowledge is the most powerful and challenging to manage. It is necessary to transfer and apply it, but also to learn how to improve the work quickly. Reflection on the practice (*hansei*), mentoring, PDCA cycles and excellence in problem-solving are important practices to improve the product development system.

- **Principle 10:** Build a culture to support excellence and relentless improvement.

Lean tools require a supportive culture to be effective. The Toyota DNA includes the "go to the source", set-based thinking, reflection on work, and 'putting the customer first' spirit. The culture also builds the sense of responsibility, daily *kaizen* (continuous improvement), discipline, ethics, value of professionals, leaders as example, and mistakes are seen as learning opportunities.

In the **tools and technology** subsystem, all the "soft" and "hard" tools are covered to support people in executing better processes. The principles are (Morgan & Liker, 2006):

- **Principle 11:** Adapt technology to fit people and process.

Technology must be integrated into the system; support the process, not drive it; enhance people, not replace them; and have the right size.

- **Principle 12:** Align your organisation through simple, visual communication.

"Alignment means you harmoniously bring together all the individual inputs from various people at the right time to achieve the desired objective." It should occur in the individual, team, system and subsystem levels, plus horizontally. To achieve the alignment throughout the product development process, communication is vital. Toyota uses the CE, big room (*obeya*) for cross-functional design communication, and A3 process for improvement and, mainly, problem-solving. Toyota also aligns the organisation's goals and objectives of policy development (*hoshin*). The *hoshin* is composed of the strategic planning, its deployment, controlling metrics, and checks and acts to keep the LPDSa effective.

- **Principle 13:** Use powerful tools for standardisation and organisational learning.

Toyota has some specific and simple tools and methods to leverage the organisational learning and standardisation. All of them should be clear, owned, maintained, validated and updated.

2.1.4 New Product Development in Construction

The NPD process in construction has some peculiarities, such as:

- Difficult to retain trained professionals for future projects, due to the temporary character of projects;
- Traditional contracts hamper the early involvement of downstream stages professionals, making the NPD disintegrated and disconnected;
- Contractual arrangements incentive the culture of "pointing to the guilty" company when a mistake or problem occurs throughout the NPD;
- The time pressure over designers hampers the possibility of professionals' reflection on the practice to improve the NPD process;
- Extensive variety of software and technology used by the AEC industry that is not always compatible, causing duplicated data, rework, and loss of information across the project participants;
- Informal adoption of NPD stages, lacking clarity of detail, responsibilities and goals.

Although there is a chaotic organisation of projects in AEC industry, there are some NPD models available for construction that enhance the transparency, communication and coordination, as well as reduce the variabilities intrinsic to the NPD process. These models were developed by scholars and architects for construction projects, such as the Generic Design and Construction Process Protocol (Kagioglou et al., 1998), the RIBA Plan of Work 2013 (RIBA, 2013), the Lean Project Delivery System (Ballard, 2000b) and the Integrated Project Delivery (AIA, 2007).

An important feature of NPD in construction is the endeavour to achieve a right balance in product flexibility through the mass customisation. This concept is also discussed at the end of this section.

2.1.4.1 The Generic Design and Construction Process Protocol

The generic design and construction process protocol (GDCPP) was developed towards the end of the 1990s and beginning of the 2000s by the University of Salford and Loughborough University and a large number of companies representing the whole construction supply chain (Kagioglou et al., 1998). The process protocol map (Figure 10) illustrates the design and construction process through its phases of development, the main participants and the deliverables in the process, added to the management of the phases and gates.

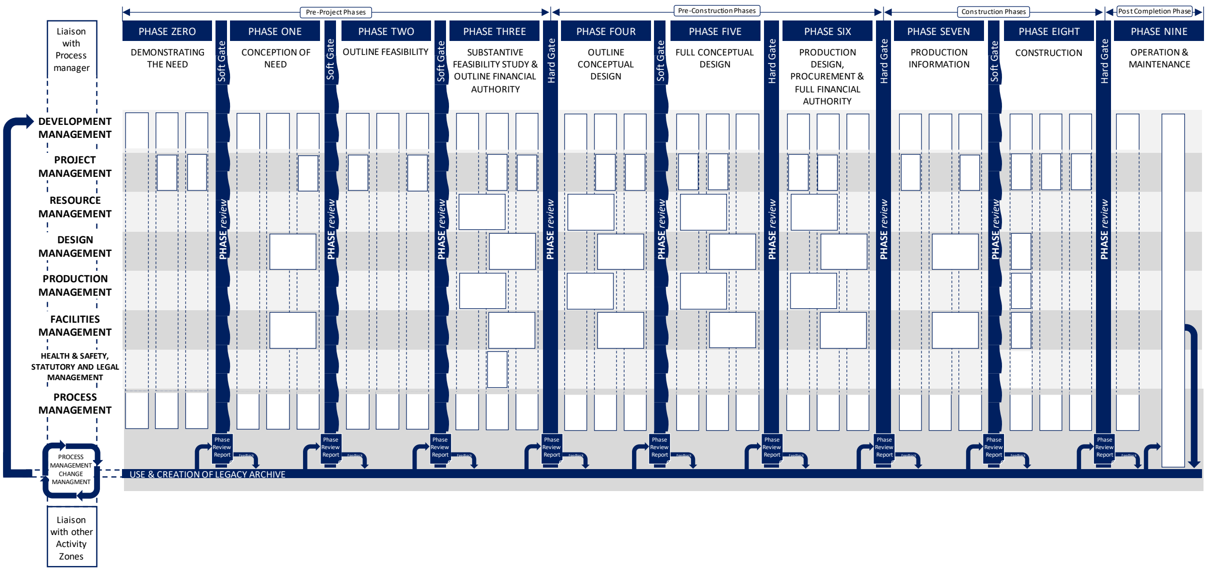


Figure 10: Generic Design and Construction Process Protocol (GDCPP) (Kagioglou et al., 1998).

The process protocol is based on the stage-gate and cross-functional teams' models, mixing soft and hard gates between ten phases of the construction product lifecycle. In each phase, the teams produce the deliverables in "activity zones" that later will pass through the gate, i.e. phase review. The phases are distributed in four major phases (Kagioglou et al., 1998):

- **Pre-project phase:** 0. Demonstrating the need; 1. Conception of need; 2. Outline feasibility; 3. Substantive feasibility study and outline financial authority;
- **Pre-construction phase:** 4. Outline conceptual design; 5. Full conceptual design; 6. Production design, procurement and full financial authority;
- **Construction phase:** 7. Production information; 8. Construction;
- **Post construction phase:** 9. Operation and maintenance.

The protocol relies on six principles (Kagioglou, Cooper, Aouad, & Sexton, 2000):

1. Whole Project View: the process must cover the whole life cycle of the product development in order to guarantee downstream requirements that may be considered at the front-end of the process.
2. A Consistent Process: together with performance measurement, evaluation and control, facilitates the continuous improvement of design and construction.
3. Progressive Design Fixity: at the gates, the design information is fixed, and the terminology and content of deliverables agreed, which ensures the reduction of costs and rework during construction.
4. Co-ordination: the Process Manager, appointed by the client, is responsible to “co-ordinate the participants and activities of each phase throughout the process”.
5. Stakeholder Involvement/Teamwork: “project success relies upon the right people, having the right information at the right time and doing the ‘right’ things” (Kagioglou et al., 1998). Proactive resourcing of phases and earlier involvement of stakeholders to incentive timely communication and decision-making.
6. Feedback: lessons learnt about failures and successes are important for the improvement of future projects. For this reason, they need to be captured and distributed for later phases through the Legacy Archive to ensure the continuous improvement of design and construction.

The GDCPP provides the main concepts for an NPD system in the AEC industry using a structured framework. It intends to integrate the supply chain, increase transparency, communication and shared understanding among participants in order to produce and deliver the right information at the right time. Any stakeholder can use it from the supply chain, namely client, contractors, subcontractors, architects, consultants and suppliers.

2.1.4.2 RIBA Plan of Work

The AEC industry also adopts the idea of stages in the UK. The Royal Institute of British Architects (RIBA) defined eight stages of the product lifecycle which defines the main objectives of each stage, activities and outputs (RIBA, 2013):

- Stage 0 – Strategic definition: identify client’s business case and strategic brief;
- Stage 1 – Preparation and Brief: develop project objectives as quality, sustainability, budget; develop initial project brief and undertake feasibility studies and review site information;
- Stage 2 – Concept Design: prepare the concept design and preliminary cost information;
- Stage 3 – Developed Design: develop the design, cost information and project strategies;
- Stage 4 – Technical Design: develop technical design;
- Stage 5 – Construction: off-site manufacturing and on-site construction, as-constructed information;

- Stage 6 – Handover and Close Out: handover of building and conclusion of building contract;
- Stage 7 – In Use: undertake in use services, post-occupancy evaluation, review project performance and outcomes.

The RIBA Plan of Work 2013 also has eight taskbars with specific content for each stage. They are: core objectives; procurement; programme; town planning; suggested key support tasks; sustainability checkpoints; information exchanges; and UK government information exchanges.

2.1.4.3 Lean Project Delivery System

The Lean Project Delivery System (LPDSb) (Figure 11) describes a set of core production management concepts and principles, in addition to computer modelling and relational contracts, that are applied in four interconnected phases of a project: project definition; lean design; lean supply; and, lean assembly (Ballard, 2000b). The LPDSb also includes modules of production control and work structuring (described in section 2.4.2.5) which extends throughout the project life cycle (Ballard, 2000b). Each phase is composed of a set of interconnecting triads, where there are downstream activities from the subsequent phase (Khanzode, Fischer, & Reed, 2005).

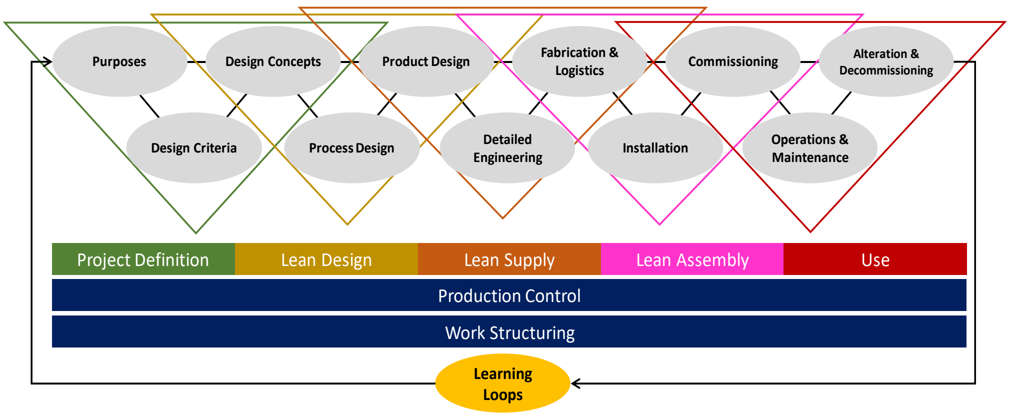


Figure 11: Lean Project Delivery System (LPDSb) (Ballard, 2000b).

In the phases, namely Lean Design, Lean Supply and Lean Assembly of LPDSb, is where the interface design-construction exists. The LPDSb combines many techniques, managerial methods and tools (e.g. target value design, set-based design, team co-location, choosing by advantages, building information modelling and LPS) to minimise wastes and improve the value generation.

Together, these practices provide support for collaboration among designers, builders, client and key members of the supply chain. They enable early engagement, alignment of commercial interests and integrated decision-making (Lichtig, 2005).

2.1.4.4 Integrated Project Delivery

Integrated Project Delivery (IPD) is a collaborative approach that promotes the alignment of project stakeholders' goals and incentives, sharing risks and rewards in a multiparty agreement (Kent & Becerik-Gerber, 2010).

IPD is described as a "project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to reduce waste and optimise efficiency through all phases of design, fabrication and construction" (AIA, 2007). The IPD business model promotes the early involvement of key participants, appropriate risks and profits sharing among stakeholders, a precise definition of responsibilities and use of management structures to promote decision-making (AIA, 2007).

The financial success of the project team relies on the success of the entire project. As a consequence, IPD promotes the innovation, collaboration, communication and information sharing among participants, which needs an environment of mutual respect and trust (AIA, 2007, 2010). A summary of IPD practices and its comparison with the traditional project delivery can be seen in Table 4.

Table 4: Differences between traditional and integrated project delivery (AIA, 2010).

Traditional Project Delivery		**Integrated Project Delivery**
Fragmented, assembled on "just-as-needed" or "minimum-necessary" basis, strongly hierarchical, controlled	**Teams**	An integrated team entity composed of key project stakeholders, assembled early in the process, open, collaborative
Linear, distinct, segregated; knowledge gathered "just-as-needed;" information hoarded; silos of knowledge and expertise	**Process**	Concurrent and multi-level; early contributions of knowledge and expertise; information openly shared; stakeholder trust and respect
Individually managed, transferred to the greatest extent possible	**Risk**	Collectively managed, appropriately shared
Individually pursued; minimum effort for maximum return; (usually) first-cost based	**Compensation / Reward**	Team success tied to project success; value based
Paper-based, 2-dimensional; analogue	**Communications / Technology**	Digitally based, virtual; Building Information Modelling (3, 4 and 5-dimensional)
Encourage unilateral effort; allocate and transfer risk; no sharing	**Agreements**	Encourage, foster, promote and support multi-lateral open sharing and collaboration; risk sharing

IPD is a form of project delivery that focuses on fostering the collaboration of project stakeholders through their interest alignments using relational contracts. These types of contracts, e.g. IFOA, AIA agreements, ConsensusDOCS 300 agreement, are used to develop a trust-based relationship and CE among participants from the early stages of the project, until the facility management (Kent & Becerik-Gerber, 2010).

Pishdad-Bozorgi and Beliveau (2016) point out that the "IPD is effective promoting trust" but that, due to the team members' personal characteristics, added to the quality of an IPD agreement, "it does not warrant trust-based relationships". For this reason, the authors (Pishdad-Bozorgi & Beliveau, 2016) suggest that IPD must be viewed as an execution guideline and not just an agreement for "when things go wrong". The keys for a successful IPD are developing an equitable alignment of efforts and rewards among the project participants and selecting the collaborative partners committed to the IPD principles, and who have a trust-based relationship (Pishdad-Bozorgi & Beliveau, 2016).

2.1.4.5 Mass Customisation

The Mass Customisation (MC), among many definitions of the term, is defined as a new paradigm of product development in which goods and services meet clients' requirements while keeping the efficiencies of the mass production (Jiao, Ma, & Tseng, 2003). Namely, the MC increases the value of products by offering a higher degree of customisation while it enjoys the mass production economies of scale (Rocha, 2011b).

When applied in construction, the MC introduces variability to the product related to the client's inputs (Rocha, Kemmer, & Meneses, 2016). The client's decisions influence the design drawings and specifications and their availability for downstream processes, including construction (Rocha, Anzanello, & Gerchman, 2018). For this reason, customisation in construction product is perceived as causing a negative effect on production (Rocha et al., 2018).

In order to increase the value generated for clients, the organisations need to identify the product attributes to differentiate based on a client's requirements (MacCarthy & Brabazon, 2003). Then, they need to present the options clearly to support the client's decision. Usually, companies use software to configure the product variants, or toolkits, such as catalogues showing the particular attributes of colour, size and shape (MacCarthy & Brabazon, 2003).

One concept applied in MC in construction is the Decoupling Point (DP). It refers to the first construction work package influenced by the MC (Rocha, 2011b; Rocha & Kemmer, 2013). The identification of DP in the construction sequence enables the delaying of the product differentiation by postponing DP as much as possible (Rocha & Kemmer, 2013). The DP, when recognised in the Line of Balance (LOB) (discussed in section 2.4.3.2), provides the deadlines for the MC process. Based on the LOB, a reverse plan can be devised including milestones for material deliveries, client's desired design options, client's decision, and kits of customisation options distributed for clients (Rocha, 2011b; Rocha et al., 2018) (see Figure 12).

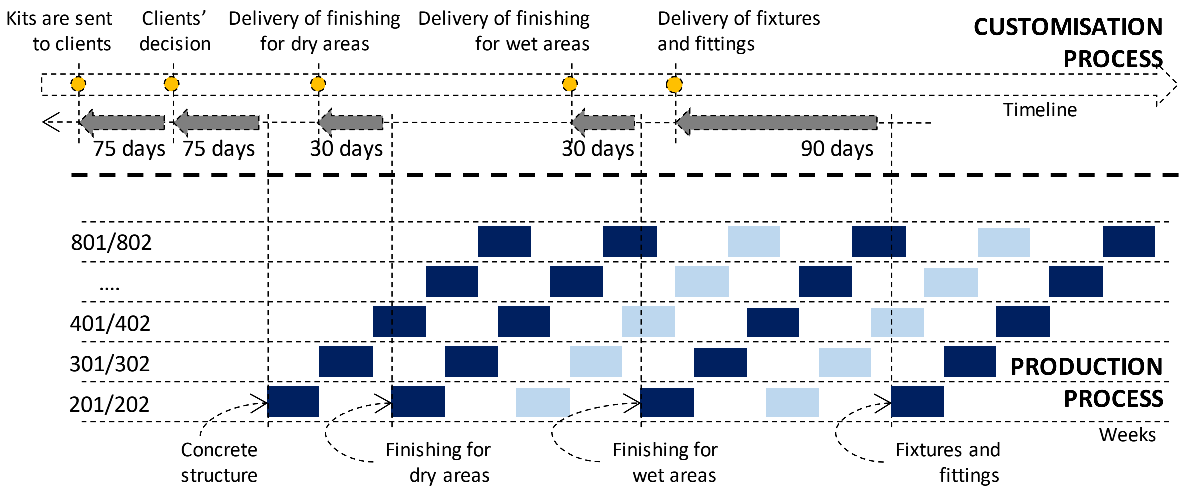


Figure 12: Key dates of the customisation process and their relationship with the line of balance (Rocha, 2011b).

Rocha and Kemmer (2013) elaborated a method to delay the product differentiation in high-rise apartment building projects. The method is composed of eight steps (Rocha & Kemmer, 2013): (a) Elicit scope of customisation; (b) Identify work packages influenced by customisation in initial plan; (c) Identify DP position in initial plan; (d) Divide work packages influenced by customisation into two work packages; (e) Reorganise work packages creating an alternative plan where work packages influenced by customisation are postponed as much as possible; (f) Identify DP position in alternative plan; (g) Compare DP position in initial and alternative plans and assess benefits and constraints; (h) Redefine alternative plan.

2.1.5 Conclusive Discussion on New Product Development

Section 2.1 of the literature review pinpointed the main state of the art of NPD in general and, in particular, in the construction industry. It presented the NPD activities (pre-development, development and post-development); the different models commonly adopted (departmental-stage, activity-stage, cross-functional teams, decision-stage and the development funnel); the LPDSa; and the NPD in construction.

As time is a valuable resource to overlap stages, the product development should integrate information of different stages and include the client when making decisions. It promotes a smoother workflow, and reduces the unexpected problems on construction sites. In the first part of this section, it was realised that specific NPD models are suitable for the context of overlap projects, such as the CE, the cross-functional teams, and the decision-stage model, in particular the agile stage-gate approach:

- **Concurrent Engineering:** the organisation's departments are organised per NPD activity and project, and have different levels of involvement across the NPD stages;
- **Cross-functional teams:** can exist in the CE model. It guarantees the integration of information from different stakeholders across the NPD stages, and delivers a better product;
- **Agile stage-gate model:** allows the overlap of activities within a phase and between phases. Mixing concepts from the scrum method, it could make the NPD in construction more flexible according to the client's changes through short-cycles of design increments and revisions with the client.

However, to apply the models above in construction, there are some challenges. For instance, to use CE, it is necessary to understand the level of involvement of each department in the product lifecycle stages. Added to that, the cross-functional teams require a clearly defined process flow where the teams can interact with defined authority and communication channels. Moreover, to use stage-gates, a clear definition of the phases' content and level of detail must be stated to the project teams. The agile aspect is only conceivable if the client can be involved in the product development on a regular basis.

The literature review has also shed light on the LPDSa. The LPDSa, through a series of principles in people, process and technology, depicted a path for organisations to implement a lean NPD process to minimise wastes while enhancing value. Although herein the focus is on the organisational level, several principles may be applied in the project context, where many different organisations work together towards the product delivery. The challenge in construction projects is to keep all the developed lean knowledge for future projects, in which different teams are gathered as a temporary organisation.

The NPD was investigated in the context of construction projects. The GDCPP mixes the activity-stage model, represented in the process protocol as activity zones, with the stage-gate model. Although the GDCPP exposes the linear and sequential stages of the project, it represents the holistic view for project management, installing the necessary concepts in management to maintain an integrated and concise NPD. The GDCPP can easily be applied in projects with overlap activities between different project phases as soon as it clarifies the workflow among stakeholders. It can be seen as the primary managerial tool to be developed in an NPD process, outlining the phases, the stakeholders, deliverables, knowledge management, phases review criteria, and so on.

Following the same idea of dividing the construction NPD into phases, the RIBA's Work Plan 2013 set the main stages objectives and activities in a very rigid sequence of stages, directing the readers to tools and supplementary documents. Because the phases are extensive, to use RIBA's model in the context of overlap stages between design and construction, it is necessary to break down the stages in minor phases and prepare a map for overlapping activities, clearly define the deliverables and exchange information among project participants.

Showing the project development from a Lean perspective, the LPDSb uses the CE approach across five phases of project development. It is based on the TFV theory (described in section 2.4.2.1) to improve the performance of project delivery. It works better if there is the support of IPD, but the LPDSb does not necessarily promote the overlapping of design and construction stages. The use of CE in LPDSb is to promote the collaboration and integration of professionals' knowledge from the product life cycle in the stages of project definition, lean design, lean supply, lean assembly and use.

The IPD brings contractual support to project stakeholders' share profits and risks. When this happens, it is expected to integrate professionals, project goals, knowledge, information and process. IPD can be applied to any type of project since the key stakeholders are available and engaged in the collaboration. A very transparent structure of project accountancy is necessary to keep the relationship trustful.

IPD is an excellent procurement route compared to the most adopted by the construction industry organisations. Similarly, the procurement route of the project is a strategical decision, as the choice is to adopt the MC. The MC requires a deep understanding of clients' requirements in order to develop the desired options. It entails the alignment between the product and production design to make the workflow as smooth as possible, and guarantees a profit by offering clients more features options.

In order to adopt MC in a construction project, the definition of the moment when the client input (CI) the order of modification is vital to manage the overlap between its design and construction activities. Namely, if the CI occurs at the moment of the product purchase, the project team can adopt the traditional procurement route and designers can send complete design information to the construction team. As a consequence, an early decision may become outdated at the moment of its construction. On the other hand, if the overlap between design and construction exists, the CI can be closer to the construction period, providing more time for clients to make decisions related to the desired modifications in their residential units.

2.2 INTERFACE DESIGN-CONSTRUCTION

Section 2 of the literature review explores the interface between the design and construction stages. Namely, what exists in both stages, how and what is communicated between each other, what changes are made in case of overlap between the design and construction stages. To answer these questions, a brief description of the interface and the conditions for overlapping dependent activities are described, followed by the concept of boundary objects and complexity of production systems. The section is concluded by way of the presentation of the project managerial activities.

2.2.1 Interface Design-Construction

The interface between design and construction in AEC industry has been studied in the academic literature in many different aspects. Luiten (1994) explained this interface by considering the building process in three sub-activities: **design building**, which represents the design knowledge; **manage construction**, representing the planning knowledge; and **construct building**, which represents the constructability knowledge. To manage the design and construction interface, it is necessary to control six interactions between designers and constructors (see Figure 13) (Luiten, 1994):

1. Forward exchange of the building design.
2. Feedback on the building design from construction.
3. Backward exchange of constructors' information.
4. Backward exchange of general constructability knowledge.
5. Upstream shift of construction management tasks.
6. Downstream shift of design tasks.

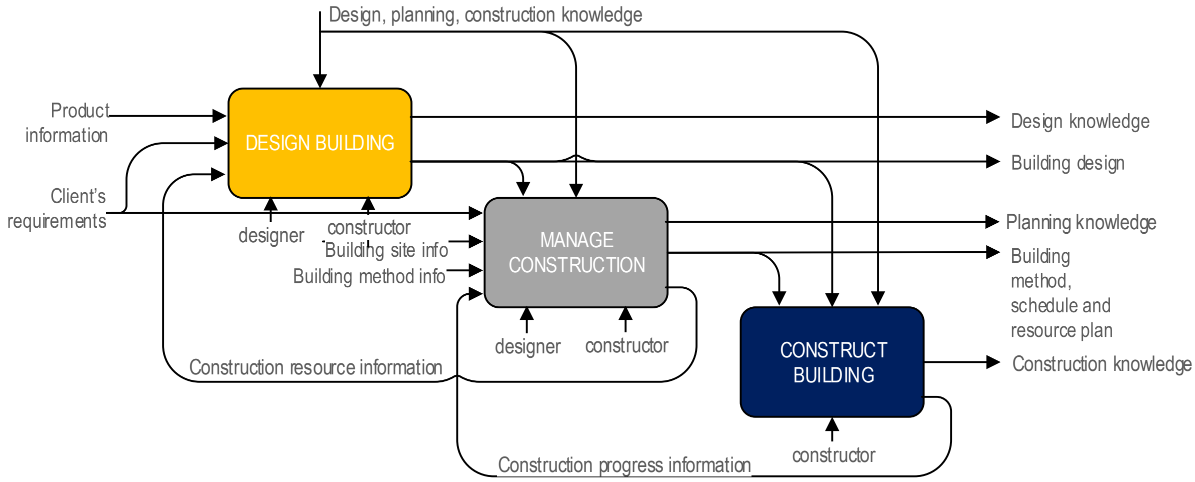


Figure 13: Activities and information or knowledge flows in the realisation of a building (Luiten, 1994).

In summary, in the interface between design and construction there exist the following flows (Luiten & Fischer, 1998): product information; client's requirements; design knowledge; planning knowledge; construction knowledge; building design; building method, schedule and resource plan; building site information; construction progress information; construction resource information designers; clients and users; constructors; and planners.

Austin, Newton, Steele, and Waskett (2002) depicted a construction project model focusing on design and construction stages, from information to material exchanges flows. They broke down the design stage into scheme design and detailed design, and the construction stage into construction management and construction activity. In between the design and construction stages there are production information, on-site fabrication and off-site fabrication (Austin et al., 2002).

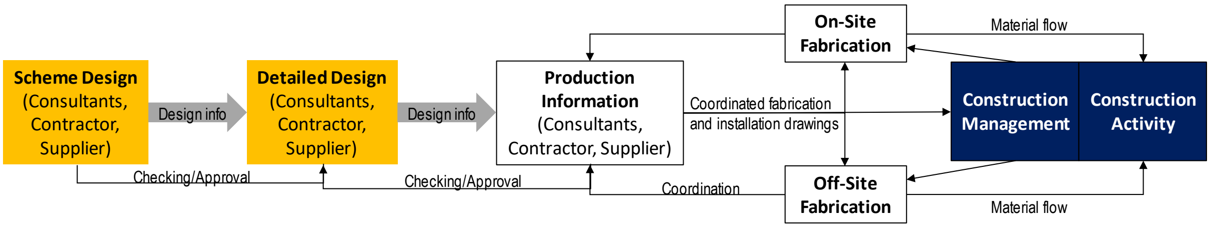


Figure 14: Model of the changing nature (from information to material) of exchanges (Austin et al., 2002).

Luiten (1994) explains that, for each of the interactions in the interface, the technical and organisational barriers can hamper the integration of design and construction. The author exposes an approach to integrate them through the sharing of information, knowledge and goals. In Luiten’s (1994) research, the integration must occur in three related levels: (a) Integration of knowledge and information; (b) integration of computer applications; and, (c) Integration of building process at an organisational level. He believes that, to integrate computer applications, both information and knowledge must be shared among the stakeholders, and that, for this reason, their formalisation and exchange must follow a standardised agreement.

Dave et al. (2008) point out that the majority of research addressed specific areas in construction rather than looking at it as a whole process. The authors proposed a framework of three important aspects of an integrated view of the construction process, similar to the LPDSa, namely people, process, and information technology, where each supports each other. When any research tries to address one specific aspect while ignoring the other, it may not achieve the desired impact (Dave et al., 2008).

2.2.1.1 Boundary Objects

At the interface Design-Construction, the communication and collaboration between stakeholders can be promoted through the use of Boundary Objects (BO). BO have been used in a mediatory role to improve the collaboration and shared understanding among different social worlds. The concept of BO has been applied in different research areas, e.g. collaborative information systems, organisation science, and information science (Lee, 2007), ever since the introduction of the term in 1989 by Star and Griesemer.

BO are used to describe objects that “inhabit several intersecting social worlds and satisfy the informational requirements of each of them” (Star & Griesemer, 1989). Boundary is used to mean a “shared space, where exactly that sense of here and there are confounded” (Star, 2010). A boundary can be seen as a space where two or more worlds are “relevant to one another in a particular way” (Akkerman & Bakker, 2011), or even “a sociocultural difference leading to discontinuity in action or interaction” (Akkerman & Bakker, 2011).

The concept of BO is seen as a useful “theoretical construct with which to understand the coordinative role of artefacts in practice” (Lee, 2007). A single object can be used to explore activities in information or a workflow for different purposes by different people, between communities of practice (Lee, 2007). Therefore, BO may have different meanings in different social worlds, but their structure can be shared between more than one world, as a means of translation, the stuff of action (Star & Griesmer, 1989; Star, 2010).

BO can also be used as management tools to integrate teams and organisations in order to break the cognitive inertia that hinders value generation, making it possible to transform practices in construction (Forgues, Koskela, & Lejeune, 2008).

2.2.2 Overlap Between Design and Construction

The overlapping of sequential and dependent phases increases the complexity of the project management. The overlapping between design and construction is a common strategy used by the construction industry in order to reduce the project lead time. Traditionally, the construction starts when the design is complete. When there is overlap, the construction activities start before the design completion.

In the literature, there are three conceptualisations about projects with overlapping between the design and construction stages (Figure 15):

- **Phased construction model:** includes the overlapping between design and construction activities. However, the work package of construction only starts after the completion of the respective design work package (Fazio et al., 1988);
- **Fast-tracking model:** occurs when the construction work package starts before the completion of its design (Fazio et al., 1988);
- **Flash-tracking model:** occurs when existing an overlap of 80% of the time of the design and construction phases (Austin, 2016).

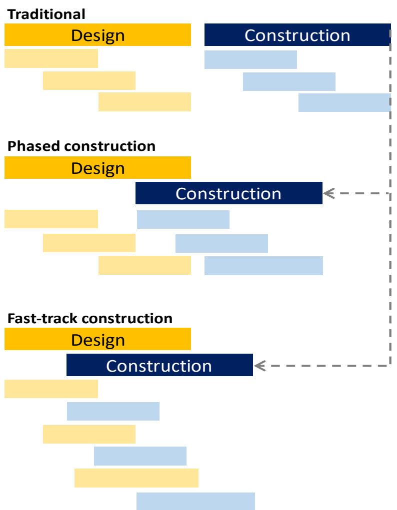


Figure 15: Comparison between traditional and overlap construction projects (based on Fazio et al. (1988)).

The CE, described in section 2.1.2.2, is also a strategy explored in manufacturing industry in the NPD process. In CE, there is the integration of key project members responsible for different stages of the whole product life cycle to develop an optimal design solution suitable for all the stages, called integrated design.

The abovementioned models of project development (phased construction, fast and flash-track) do not necessarily use the CE process, i.e. the design may not be conceived as integrated with other project stages. The most significant difference between these models of overlapping design and construction and CE approach is that the first ones are based on the traditional (conversion) conceptualisation of production (Huovila et al., 1997). Whereas, the CE approach aims to reduce the uncertainty, focusing on constructability of design and planning of production activities, while it is based in the TFV theory (Huovila et al., 1997).

To study the overlap between activities, it is necessary to identify the activity relationships. The four types of possible relationships between activities are: (a) dependent activities; (b) semi-independent activities; (c) independent activities; and (d) interdependent activities (Prasad, 1996) (Figure 16).

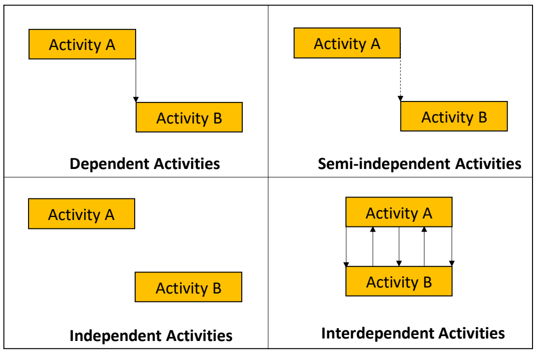


Figure 16: Four types of activity relationships (Prasad, 1996).

In order to reduce the risk in overlapping dependent activities, concepts of sensitivity and evolution were developed for the NPD in the manufacturing industry (Krishnan et al., 1997), then studied in design activities in the AEC industry (Bogus et al., 2011; Bogus et al., 2005; Bogus et al., 2006; Srour et al., 2013) and, more recently, studied in design and construction activities overlapping (Blacud et al., 2009; Hossain & Chua, 2014; Pena-Mora & Li, 2001; Srour et al., 2013).

Krishnan et al. (1997) specify the types of overlapping between dependent activities according to their evolution and sensitivity (Figure 17). These concepts were the basis for other researches regarding overlapping strategies in manufacturing and construction.

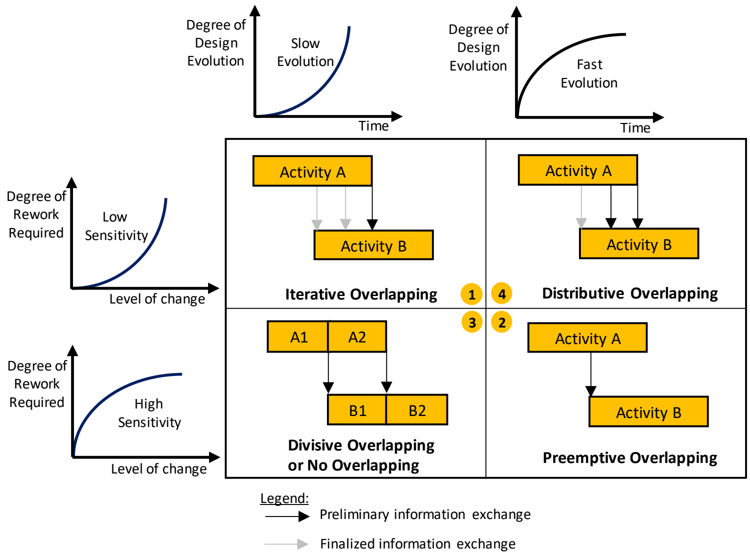


Figure 17: Types of overlapping based on Evolution and Sensitivity (Krishnan et al., 1997).

For design activities, evolution is described as “the rate at which design information is generated from the start of an activity through the completion of the activity” (Bogus et al., 2005), while sensitivity is described as “how much rework (measured in additional time) is required on the downstream activity if upstream information changes” (Bogus et al., 2005). In their work, Bogus et al. (2005) developed a framework to enable project managers to analyse dependent design activities using the concepts of evolution and sensitivity to evaluate and plan their degree of overlapping. Upstream design activities can be classified as **slow** or **fast evolution**, while downstream activities are **low** or **high sensitivity**.

The ideal situation to overlap sequential design activities is to achieve fast evolution of upstream activity and low sensitivity of downstream activity (Bogus et al., 2005). However, according to activity characteristics, some strategies in design can be selected in order to reduce sensitivity and speed up the design evolution (Bogus et al., 2006) (Table 5).

Table 5: Overlapping strategy framework (Bogus et al., 2006).

		Evolution	
		Slow	Fast
Sensitivity	Low	Overdesign Early release of prelim info Prototyping No iteration/optimisation Standardisation Set-based design	Early freezing of design Overdesign Early release of prelim info Prototyping
	High	Overdesign No iteration/optimisation Standardisation Set-based design Decomposition	Early freezing of design Overdesign

For the overlapping between design and construction activities, Blacud et al. (2009) studied the factors that contribute to the sensitivity of construction activities under design changes. The definition of the sensitivity of construction activities to design changes is: “the amount of physical rework caused by upstream design changes” (Blacud et al., 2009). They found four factors that influence the sensitivity of design activities: the level of transformation, lead time, modularity, and interaction with other building components.

The authors assume that the degree of overlap between design and construction activities is related to the nature of information exchanged between them (Blacud et al., 2009). The ideal overlap is when the initial design assumptions are equal to the final ones, which avoid reworks in downstream construction activity (Figure 18). Whether changes occur in the final design, the consequences for construction may counteract the gains produced by overlapping and even increase the lead time and cost of the construction compared to the traditional sequential and linear approach (Blacud et al., 2009).

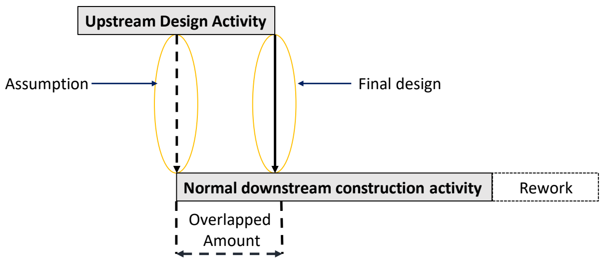


Figure 18: Consequences of overlapping in construction activity (Blacud et al., 2009).

Srour et al. (2013) developed a process of four steps to schedule the design stage in overlapping projects. They used design activities dependency tables, or Design Structure Matrix (DSM) (described in section 2.3.2.6), to achieve the optimum sequence and visualise the activities dependencies. Then, they designed an algorithm to optimise and shorten the schedule. The result is the project schedule in a Gantt chart. In Srour et al. (2013), the optimisation of design sequence and its overlapping do not consider either the resources or the construction sequence. The optimisation only focuses on transformation activities neglecting the flow, the production batch sizes, and so on.

The overlapping of dependent and sequential activities using simulations and algorithms is not an easy task. The researches must consider the dependent activities that exist in the interface between design and construction. Usually, the construction sequence network involves a high level of interdependencies, and a large amount of information flow from planning, safety, procurement, and so on, needs to be considered as well. The aforementioned studies cannot solve the problem of overlapping design and construction activities, but only focus on transformation activities and do not consider the interface activities.

2.2.3 Complexity in Production Systems in Construction

Just as most systems in the world are complex, so too is construction (Bertelsen, 2004). Complexity is a concept that has evolved through time. Back in the 1990s, it focused only on structural complexity with low attention for uncertainty (Austin et al., 2002; Baccarini, 1996). Throughout the years, new definitions regarding complex projects emerged (Bakhshi, Ireland, & Gorod, 2016), including uncertainty (Williams, 1999), emergence (Beckerman, 2000), autonomy, connectivity (Bell & Kozlowski, 2002), diversity, socio-political, and elements of context (Vidal & Marle, 2008). Figure 19 mixes the team task complexity proposed by Bell and Kozlowski (2002) with the compilation of interpretations of complexity in project management (Bakhshi et al., 2016).

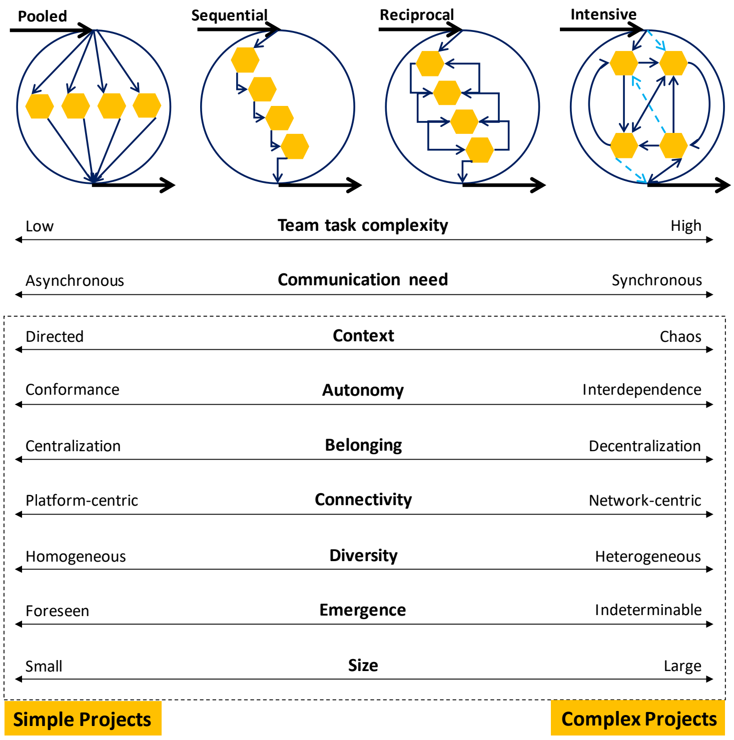


Figure 19: Team task complexity and project complexity. Adapted from Bell and Kozlowski (2002) and Bakhshi et al. (2016).

Complexity can be interpreted and operationalised regarding differentiation; it means the number of varied elements and interdependencies, or the degree of interrelatedness between these elements (Baccarini, 1996). For Williams (1999), complexity can be explained according to **structural complexity** (following Bacarini, 1996), and **uncertainty** in goals and methods.

The complexity in construction is not only a result of technological complexity, but it is also a result of the interactions between many different disciplines that belong to different specialised firms (Gray & Hughes, 2001). Complexity increases by increasing subcontracting in construction: “As work becomes more complex, so more diverse skills are needed to accomplish it” (Lawrence and Lorsch, 1967 cited in (Gray & Hughes, 2001).

The structural complexity in AEC projects is seen as the number of participants with a high level of interdependence: general contracting, quantity surveying, town planning, accountancy, structural engineering, services engineering, project management, construction management and contract adjudication (Gray & Hughes, 2001). As complexity is increasing in the construction industry, the ability to bring projects to a successful completion on time as regards budget and quality dramatically decreases (Dalcher, 1993 cited in Williams (1999)). Moreover, the uncertainty in the construction stage increases due to subcontractors having several other projects, and disturbances in one project can affect other projects (O’Brien, 1998 cited in Bertelsen & Koskela, 2004). The same phenomenon occurs at the design stage (Bertelsen & Koskela, 2004).

Baccarini (1996) states that the construction industry has experienced great difficulty in coping with the increasing complexity of construction projects. The consequence of high structural complexity is the increasing demand for **managing** and **coordinating**, but also for **integration** (Lawrence & Lorsch, 1967 cited in Gray and Hughes (2001). Baccarini (1996) adds that complexity must be managed by integration, i.e. coordination, communication and control.

The project success is achieved through a balance between planning and control effort and project complexity (Gidado, 1996). The project complexity is measured according to the difficulty in achieving adherence to a planned production workflow (Gidado, 1996). “An efficient implementation of managerial functions (planning through to controlling) can influence the effect of project complexity on project success” (Gidado, 1996). For this reason, it is important to understand the different managerial focus that the NPD process requires from the managers. The project management has different levels of complexity throughout its development. At the early stages, during the conceptual and scheme design, negotiation and agreement between a few stakeholders are trivial to achieve a common project goal, and decisions at this point have a high impact on the project performance (Austin et al., 2002). At the same time, decisions are made by new entrants in the project. So, the level of interdependence increases due to the high number of people involved, which requires more coordination of information flows (see Figure 20).

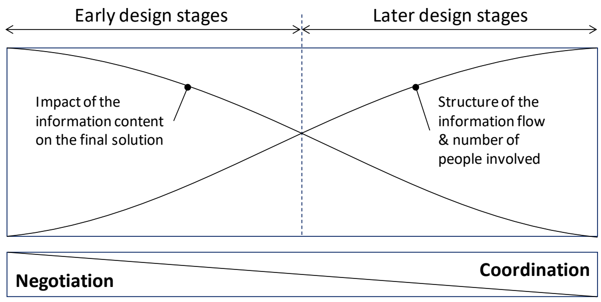


Figure 20: The changing nature of the project process (Austin et al., 2002).

Bertelsen (2004) corroborates this idea by claiming that, as construction is a one-of-a-kind production, consequently it is necessary to **integrate the design and production processes**. Integration is concerned with unifying the diverse contributions into a cohesive team effort (Gray & Hughes, 2001). Following the idea of managing complex projects through a holistic view, Young et al. (2001 cited in Young (2008)) expanded Bruce Archer’s model of levels of design (design at the level of decision, product and project) to a new model of levels of design, which combined ideas of different design models for managing complexity of projects:

- Design at the level of product configuration and detail – **design within a context**;
- Design at the level of systems thinking – **designing context**;
- Design at the level of policy formation and ideology – **design of context**.

Young (2008) states that, to deal with “complex and emergent social and business contexts”, it is crucial “to design the context rather than to design within the context”. Correspondingly, by applying the same idea of the need to change the managerial view front of project complexity, traditional project management methods proved to be inadequate to deal with construction complexity, and, for this reason, new methods of management are needed (Baccarini, 1996; Williams, 1999).

2.2.4 Managerial Activities

The lean thinking is a new paradigm which improves the project management and overcomes the limitations of traditional methods by changing how to view the production. Through the perspective of lean construction, Koskela and Ballard (2003) explain that there are three generic actions when managing a construction project: (a) design of product and production system; (b) operation of the production system, which can be divided in the production planning and control; and (c) production system improvements (Figure 21). These activities can be distinguished based on their temporal relationship with the productive act. The design stage must occur previously in the production, the operation during the production, and improvements forward to the productive act (Koskela & Ballard, 2003). The design stage can be divided into product design and production system design.

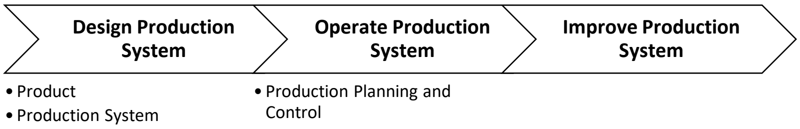


Figure 21: Generic activities of the production management (based on Slack, Chambers, and Johnston (2010) and Koskela and Ballard (2003).

These three actions (design-operate-improve) are used throughout the whole thesis as a basis to categorise and understand the managerial activities in the development studies and discussion of this investigation.

2.2.5 Conclusive Discussion on Interface Design-Construction

In the interface between design and construction, there are people from different companies, with different responsibilities, from different social worlds that must share information and knowledge in order to develop better products. In order to 'populate' this interface, two models were presented (Austin et al., 2002; Luiten & Fischer, 1998), and the three cores for integrated management of people, process and information technology were discussed (Dave et al., 2008).

Through the subsection of overlap between the design and construction stages, it was realised that there is much research going on around how, and how much dependent activities can be overlapped. However, most parts of these researches do not consider the complex interface design-construction. Moreover, these researches have a limitation in their production management view. Namely, they focus only on transformation activities, neglecting the value and flow.

The study of complexity has brought exciting insights about the variable level of complexity throughout the NPD. At the early stages of the NPD, in conceptual and scheme design, the project management should emphasise the negotiation aspect between parties; whereas, at the final stages of design, it should concentrate on the coordination of already structured information flow among a high number of participants.

The managerial activities were presented to support the categorisation and understanding of the studies of this investigation. Design, operate and improve the production system can also be applied to the project perspective when using the lean thinking.

From the first two sections of the literature review, a model was devised (Figure 22) that mixes the activities of the NPD process as pointed out by Kagioglou et al. (2000) with the project managed as production activities (Koskela & Ballard, 2003), plus the changing nature of the complexity in construction projects.

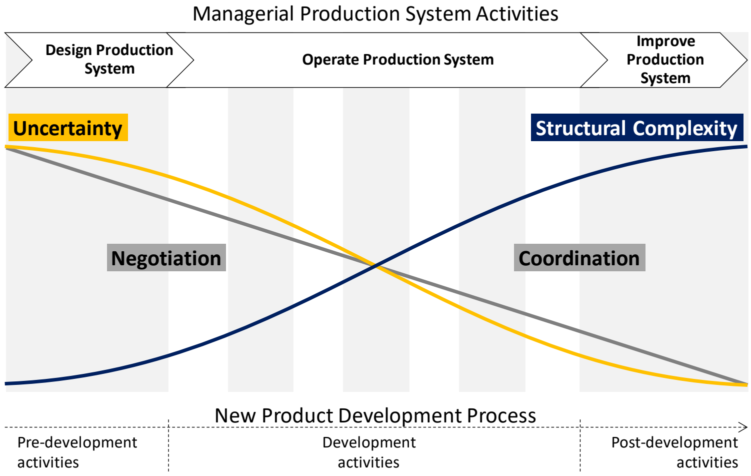


Figure 22: Model that combines the NPD activities with the production management activities over the changing nature of construction project complexity.

The next two sections of the literature review describe what are the most recent practices adopted by the AEC industry to promote the integration of people, process and information technology. Some methods and tools have the role of BO to connect designers, constructors, suppliers, clients, users, and other participants in a construction project. The following section presents the foundations of lean design management and the practices adopted by the AEC industry to promote the integration between design and construction phases based on the lean paradigm.

2.3 LEAN DESIGN MANAGEMENT

In AEC projects, the design management is viewed as problematic (Ballard & Koskela, 1998a; Emmitt, Sander, & Christoffersen, 2004). The construction projects are “unaffordable, unconstructable, off-target” and delivered late (Macomber, Howell, & Barberio, 2012). Due to the negligence of the nature of design process and construction production systems, the construction industry faces high levels of rework, re-pricing, change of orders and re-value of engineering (Macomber et al., 2012).

The quality of design is considered a critical component for the quality of the project as it is through it that the product characteristics can determine the degree of satisfaction of customer expectations (Picchi, 2003).

In the design phase, the customer’s requirements are identified, and the constructive aspects, procedures, drawings and quality are defined (Alarcón & Mardones, 1998). The design effort is complex, with numerous interdependencies, singularly uncertain, with erratic decision-making by clients and authorities, and often carried out under time pressure (Koskela et al., 1997). Due to the lack of integrated planning among different disciplines, the informal planning of activities and the lack of control of information flow are the main causes of the design low performance (Tzortzopoulos, Formoso, & Betts, 2001).

The lean thinking is applied to design management in order to overcome deficiencies of management by focusing on value generation for customers and to reduce wastes in the process. This section about lean design management presents the conceptual foundations of lean design management, as well as the main processes and tools used by industry and academia.

2.3.1 Lean Design Foundations

The lean design management is based on the TFV theory (Koskela, 2000), as is the lean construction. While the traditional view of project management neglects flow and value management, the lean design management has emerged with the basic idea to focus on value-adding activities to generate value for users, reduce or eliminate the flow activities, and manage the conversion activities (Ballard & Koskela, 1998a). The lean design management uses three views (value, flow and conversion) to produce and deliver products, as described in Table 6.

Table 6: Comparison of conversion, flow and value generation views (Ballard & Koskela, 1998a).

Item	Conversion	Flow	Value Generation
Conceptualisation of engineering	As a conversion of requirements into product design	As a flow of information, composed of conversion, inspection, moving and waiting	As a process where value for the customer is created through the fulfilment of his/her requirements
Main principles	Hierarchical decomposition, control and optimisation of decomposed activities	Elimination of waste (no conversion activities), time reduction	Elimination of value loss (achieved value in relation to best possible value)
Methods and practices	Work breakdown structure, critical path method, organisational and responsibility chart	Rapid reduction of uncertainty, team approach, tool integration, partnering	Rigorous requirement analysis, systematised management of flow down requirements, optimisation

Practical contribution	Taking care of what has to be done	Taking care that what is unnecessary is done as little as possible	Taking care that customer requirements are met in the best possible manner
Suggested name for practical application of view	Task Management	Flow management	Value management

One concept that is also important for the design management is the **Design in Process (DIP) inventory** (Reinertsen, 1997). The DIP is equivalent to the Work in Process (WIP) in manufacturing factories. However, DIP can be much larger and more expensive to hold than WIP (Reinertsen, 1997). The DIP is incomplete design information which is not generating profit. It is a sign of the health of the design process (Reinertsen, 1997).

In order to manage the design, it can be considered similar to the production process (Ballard, 2002; Ballard & Koskela, 1998a), in which detailed design process transforms requirements and ideas into product design documents (Tribelsky & Sacks, 2011). Tribelsky and Sacks (2011) shed light on another view of design management: reduce waste and improve value through measuring the design information flow. The latter authors point out a set of indices to be measured in information flow: action rate, package size, WIP, batch size, development velocity, bottlenecks and rework. Some are based on the flow view of major design problems (Hopp & Spearman, 2011; Koskela, 2000).

Ballard and Zabelle (2000) advise the use of some tools and techniques for managing and producing a design in the LPDSb (LPDSb – section 2.1.4.3). They are: cross-functional teams (discussed in section 2.1.2.3), pull scheduling or phase scheduling (in section 2.4.2.6), reduce design batch sizes, use Design Structure Matrix (DSM – section 2.3.2.6), use Set-based Design (in section 2.3.2.2), share incomplete information, use Work Structuring (in section 2.4.2.5), simultaneous product and process design, share geometry and unify modelling, and use Last Planner System (LPS) (in sections 2.3.2.5 and 2.4.3.5).

Whether considering the design as a physical process, Ballard and Koskela (2009) point out that the design should be managed in a similar way as the production system, i.e. through the three managerial actions of designing, operating and improving the design system.

2.3.1.1 Design System Design

The Design System Design (DSD) is the first managerial activity before starting the design development. In this managerial activity, it should be decided how to structure the system to produce the necessary work, i.e. how it will be divided into pieces, allocated to specialists, and assembled to create value (Ballard, Koskela, Howell, & Zabelle, 2001a). In the case of design, decisions may be related to (Ballard & Koskela, 2009):

- The physical layout of designers, especially when co-located;
- Information, technology and communication tools;
- Standards for data exchange;
- Design representation (BIM or drawings);

- Contractual relations and incentives;
- Decision-making structure;
- Validation and verification structure;
- Targets (target value design/cost);
- Methods and tools (set-based design, choosing by advantages, collaborative planning, LPS, agile).

These decisions are crucial to keeping the design development flowing smoothly. Although it is composed of a set of important decisions, the DSD is frequently neglected by the AEC industry, and decisions are made informally along the design execution.

2.3.1.2 Design System Operation

In the Design System Operation (DSO), the predominant activities that should occur are planning, controlling and correcting (Ballard & Koskela, 2009). In planning, the structure and sequence of design tasks must be devised in different levels of detail. A recommended tool to develop it is the DSM, which breaks down the design phases into tasks and deliverables, but also optimises the sequence and interdependence of design tasks (Ballard & Koskela, 2009).

In order to achieve better planning, those who do the work should plan how to do it, and an effective way to produce the network of design tasks is using the collaborative planning (Ballard & Koskela, 2009). Herein, the specialists define a logic network using sticky notes on a wall, working backwards from the target milestone, and rearranging the sequence and relating the task's dependencies (Figure 23). Then, the specialists assign the tasks and provide an average duration to complete them. However, through the DSM analysis, the work plan can be tested and improved (Ballard & Koskela, 2009). Buffers must be considered in the planning to assure the completion of the network of tasks. Buffers need to be defined according to type, size and location (Ballard & Koskela, 2009).

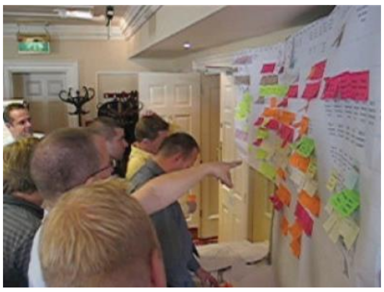


Figure 23: Collaborative planning (Ballard & Koskela, 2009).

The next activity of DSO is control. The activities in the design system must be steered towards targets in the scope, quality, schedule and cost (Ballard & Koskela, 2009). The control is a necessary activity to assure the plan execution. To prepare for this, it is necessary to identify and remove the constraints, such as resources, information from other designers, design and test work methods (Ballard & Koskela, 2009).

The six typical constraints to execute a design task (Figure 24) used in a collaborative planning process in design are (Bolviken et al., 2010):

- Design basis: this is the previous design activity completed in the required quality;
- Expectations and requirements: compliance with contractual requirements, client's expectations, design constructability, government rules and regulations;
- Team: definition of consultants and designers, and decision-making authority for them;
- Methods and tools: an adaptation of method and tools according to scope, the complexity of design and participants;
- Decisions: decision necessaries to develop a design solution;
- Dialogue: establish communication form and forum.

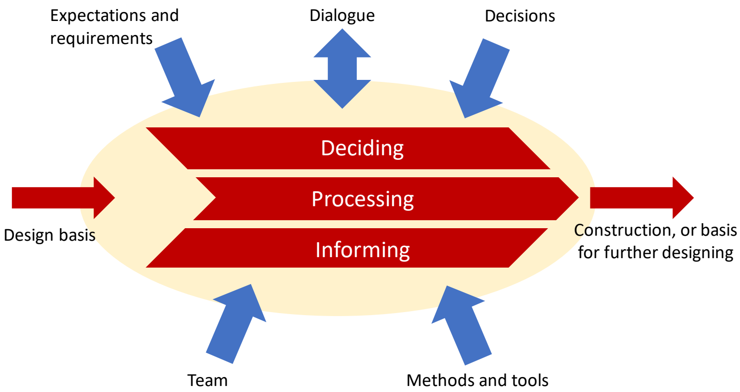


Figure 24: Six conditions for a sound design activity (Bolviken et al., 2010).

According to Ballard and Koskela (2009), in order to release the work from one designer to another, the best way to do this is pulling it, i.e. designing in response to a signal from the immediate customer.

The third activity in DSO is the correction. Correction is necessary when there is a deviation between the target and the executed. To avoid the propagation of a detected error, it is necessary to understand its effects, identifying and correcting the errors along the connected work (Ballard & Koskela, 2009).

Kiiras and Kruus (2005) understand the design operation as a combination between push and pull techniques (pull systems are discussed in sections 2.4.1.2 and 2.4.2.2). From the beginning, the design is pushed up to the completion to become the design package. The latter comprises design documents and procurement of the respective contractor. From this point, the production of detail design and specification is pulled by the construction site management. The site team, using the LPS, should secure the "status of the design documents for 4-6 weeks ahead". This view, represented in Figure 25, is part of the FinSUKE model from Finland that aims to overcome the poor performance of traditional project management and traditional procurement route.

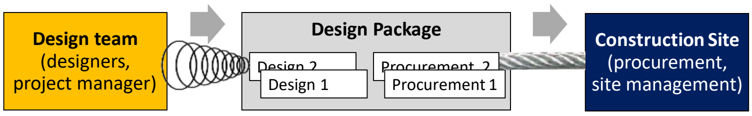


Figure 25: Building design management as a combination of push and pull techniques (adapted from Kiiras and Kruus (2005).

In order to plan the workflow of design, Tiwari and Sarathy (2012) used "chunking" which is a process through whereby the building is broken down into smaller areas, namely the "chunks". Chunking helped to maximise the concurrent work between the team members, avoided rework and streamlined the workflow. To define the chunks, it is necessary to consider three aspects of the space (Tiwari & Sarathy, 2012): 1) The function and complexity; 2) The optimal area to hand over between upstream and the downstream design disciplines in two weeks; 3) The optimal area for construction modelling work in two weeks. Then, the building is chunked to fit into a two-week period of work, not only according to how it should be designed, but also how the design freeze should be handed over to downstream activities (construction modelling and coordination) (Tiwari & Sarathy, 2012).

To facilitate the visualisation and coordination of the chunks and design fixity, a matrix is used to represent and track the process that a chunk should go through. The use of pull planning supported the system, i.e. the team used "I get-I give" cards on the wall to signalise what the team members needed from others, what they could deliver and the required work time. The participants realised that cards with no customer meant production of waste (Tiwari & Sarathy, 2012).

A public company in Norway applied lean design management in the project of a new university building (Holm, 2014). The company had the rules of the client and owner of the project. The use of lean design was a practical experimentation promoted by the Head of the project, and the academia did not document it. Some steps of the design management are the DSD, passing through its operation until its improvement (Holm, 2014): 1) Prepare the lean construction strategy; 2) Product creation process; 3) Establish the takt time; 4) Develop and improve the lean design process; 5) Extend the use of lean takt planning and construction with contractors; and 6) Lessons learnt. Throughout these steps, all the participants (designers and engineers) established the same goal and process to accomplish the project. This case is the first that applies the concept of takt time for design, and other lean practices, such as co-location of designers and engineers, and collaborative planning. Although the use of takt time in construction was included in the long-term plan, the team did not use location-based tools to plan the design stage. This project was investigated in detail in the Case Study 4, Chapter 6 of this thesis.

2.3.1.3 Design System Improvement

In the Design System Improvement (DSI), the prevention of breakdown reoccurrences must be done in order to improve the performance of the design system (Ballard & Koskela, 2009). The improvements are necessary because design organisations cause 50% of the disturbances in design, and not the design process (Sverlinger, 1996 cited in Ballard and Koskela (2009). A design system can be improved by finding the root causes of deviations from target outcomes and taking action to correct them (Ballard & Koskela, 2009).

2.3.2 Lean Design Processes and Tools

In this subsection are presented the processes and tools adopted by the lean design to create value and minimise flows and wastes throughout the design, operation and improvement activities of the design system management.

2.3.2.1 Target Value Design

Target Value Design (TVD) is a project management approach that aims to maximise value through the adaptation of Target Costing practices for construction industry peculiarities (Macomber et al., 2012; Zimina, Ballard, & Pasquire, 2012). The idea of TVD emerged in order to avoid some consequences of the AEC fragmentation industry. This practice aims to use the customer's requirements as drivers for design generates and delivers value; at the same time, it promotes the continuous improvement and waste reduction (Ballard, 2011). TVD is known to reduce the contingency funding, project cost and lead time; increase project members' profitability, and deliver value to customers (Ballard, 2011).

TVD is used in the project definition phase and lean design phase (Lee, 2012). The "design to cost" strategy includes assessing the project's feasibility through the concurrent and inter-organisational collaboration in the design, especially early design stage, and estimating processes (Lee, 2012).

The TVD process (Figure 26) starts with the development of project business planning; then, the client participates in the project definition process with other project team members and validates the business case (Zimina et al., 2012). The project team begins the design development by presenting the detailed budget to the client. The client must decide about funding the project or not. The construction will only start once the client's permission is given.

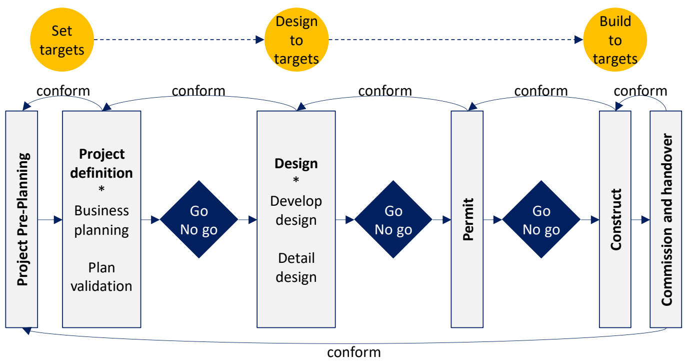


Figure 26: Target value design process scheme (Zimina et al., 2012).

TVD is not appropriate for some types of projects, such as a pre-designed solution; when project team members are not capable of using TVD techniques; or when organisational integration is not allowed.

Although Zimina et al. (2012) compared TVD practices with the traditional cost and contract management practices, the results did not point out the most important practice by which to achieve the project's success. However, TVD is considered a successful project management approach, its success being a consequence of a set of tools and techniques (e.g. Last Planner System, Set-based design, BIM models, co-location, etc.) and procurement routes (IPD and relational contracts) rather than only defining costs and values targets from the client's requirements. Moreover, the use of all these practices together creates a favourable environment for stakeholders' collaboration, innovation, learning, and project information transparency.

Notwithstanding this, TVD still lacks mechanisms to allow designers to evaluate design against budget and values of the client in real time, i.e. it relies on fast creation, and the updating and sharing of information among participants. Adding to this, it is still unanswered on how to define the batch size of the design, and how to reduce them.

Furthermore, the literature review is not clear on how to capture the client's values to develop design solutions and estimate cost. Miron, Kaushik, and Koskela (2015) investigated the value generation in TVD projects under the lean construction concept of value. The authors found that the main focus of TVD implementations was in the target cost. They suggested having a project consensus on the use of the concept of value, better documentation of the value captured, and evolution along the whole life cycle of the project.

2.3.2.2 Set-Based Design

Set-based design (SBD) is a methodology where designers are encouraged to develop integrated design solutions for different relevant criteria when considering schedule and budget (Lee, 2012). It is an entire design space that is opened as far as possible, and is narrowed collectively until a globally satisfactory design solution is achieved (Parrish et al., 2007). A set of feasible design solutions is maintained until the 'last responsible moment' to make a decision (Lane & Woodman, 2000, cited in Lee (2012).

The traditional SBD, known as "point-based concurrent engineering", focuses on developing sets of design solutions in the very early design phase, while the downstream functions analyse and critique the design from their perspective (Sobek, Ward, & Liker, 1999; Ward, Liker, Cristiano, & Sobek, 1995). The SBCE occurs when both design engineering and manufacturing engineering develop their sets of feasible solutions in parallel, sharing information and constraints to refine the design (Lee, Bae, & Cho, 2012). The advantage of SBCE is the development of an optimal solution for the system performance, rather than focusing on an individual subsystem (Lee et al., 2012), because sometimes the optimal solution for design is not the same for manufacturing.

The SBD was explored in the AEC industry in some design disciplines. The SBD method requires more effort in the front-end of the project, and requires "the needs of multiple project participants" in order to develop better outcomes and savings for the overall project (Parrish et al., 2007).

Due to the opportunity to interact with builders to generate design solutions, the SBD methodology is suitable for projects where there can be an overlapping of the design and construction stages. However, it is known that designers do not have exclusivity to develop different design alternatives, which is a barrier to SBD implementation. Adding to this, the literature review still lacks further studies about how to define the 'last responsible moment' to make a design decision, especially when it is applied in overlapped construction projects.

2.3.2.3 Choosing by Advantage

Choosing By Advantages (CBA) is a system for decision-making which uses a defined vocabulary to promote transparency in the decision-making process and ensures that every participant is “speaking the same language” (Parrish & Tommelein, 2009). It was developed by Suhr (1999) to consider the advantages of alternatives and to compare them when choosing the most suitable one. It is a method used in the SBD process.

The CBA tabular method was adapted for construction by Arroyo, Tommelein, Ballard, and Rumsey (2016). Their method is made up of seven steps: 1) Identify alternatives; 2) Define factors; 3) Define must have/want to have criteria for each factor; 4) Describe the attributes of each alternative; 5) Decide the advantages of each alternative; 6) Decide the importance of each advantage; and 7) Evaluate cost data.

Arroyo, Tommelein, and Ballard (2012) compared two methods for decision-making: value-based methods (Analytical Hierarchical Process - AHP) versus CBA. The authors found that CBA is a superior method because it values the importance of advantages between alternatives. The authors recommend incorporating CBA in the lean construction body of knowledge, due to the fact that it increases the transparency, promote consensus among participants, delivers value to stakeholders, and reduces the uncertainty in the decision-making process (Arroyo, Tommelein, & Ballard, 2015).

The CBA used in the AEC industry does not consider attributes from the construction stage, as the set-based CE does. More research is needed to integrate and develop CBA between designers and constructors. As the complexity of the decision-making process increases, it becomes more difficult for the tabular method of CBA to be structured. As a result, it is necessary to evaluate this method by considering more information from construction. More answers are needed with regard to how to include construction information in the CBA: will it be used in another tabular sheet, or integrated as an attribute or criteria in the tabular sheet of design alternatives? How many different alternatives of the production system can be incorporated for the same design alternative CBA process? How do designers perceive the advantages of a construction alternative?

2.3.2.4 Agile Design Management

A recent adaptation of Agile to design management was developed by Demir and Theis (2016), in which the authors used a multi-scrum approach systematically to adjust the project organisation and structure. The Agile is agile because (Demir & Theis, 2016):

- it embraces changes, which add value (Hass, 2007);
- has feedback loops (iterations), which allow flexibility and responsiveness to change in a systematic and structured fashion (Wysocki, 2006 and Hunt, 2006 cited in Demir and Theis (2016);
- assumes that the variability cannot be reduced;

- does not intend to reduce or eliminate changes (Highsmith & Cockburn, 2001 cited in Demir and Theis (2016);
- focus on the team as an expertise factor (Hunt, 2006 cited in Demir and Theis (2016).

There are challenges for adapting Agile to the design stage of construction projects (Demir & Theis, 2016). In construction projects, it is difficult to define who the product owner is, e.g. whether it is the client or the user, and how to prioritise its requirements. The levels of detail of deliverables in the backlog, work packages and tasks are unclear. Usually, agile is recommended for a maximum of 20 team members; however, in construction projects, this number of members can easily be exceeded. Adding to this, the team members are not co-located to meet for the daily scrum. Plus, the traditional design approaches avoid change orders.

2.3.2.5 Last Planner System in Design Stage

The LPS is used as a planning and control system to deal with the uncertainty in construction projects in the phases of design and construction. The use of LPS in the design process can be seen in many works in the literature review. The implementations took place in different types of projects, such as office building (Koskela et al., 1997), small high-tech facility (Miles, 1998), residential condominium (Tzortzopoulos et al., 2001), theatre (Ballard, 1999a), hospital (Hamzeh, Ballard, & Tommelein, 2009), factory (Viana, Tillmann, Sargent, Tommelein, & Formoso, 2015; Wesz, Formoso, & Tzotzopoulos, 2013), and so on. The LPS was also implemented in different contractual agreements, for instance in traditional design-build (Koskela et al., 1997), design-bid-build (Bolviken et al., 2010; Khan & Tzortzopoulos, 2015), integrated form of agreement (IFOA) (Hamzeh et al., 2009) and sharing risks and gains (Ballard, 1999a).

The LPS benefits have more impact in the construction phase of projects than in the design stage itself (Ballard, 2002): "*When constructors can take action in advance of receiving design information that coordinates the flow of labour and equipment, material deliveries, and completion of prerequisite work, the project runs more smoothly and efficiently.*"

Although there are different contexts of LPS implementation, some benefits have been verified in these researches, such as the increase in design process transparency, an increase of designers' collaboration and communication, and the use of project performance measurement. On the other hand, the authors reported difficulties in executing the lookahead plan, change orders, or delays in the client's decisions, analysing the root causes of non-compliance tasks, and improvement in the process of design planning.

According to Ballard (2002), first it is necessary to establish more effective methods for production control in general, and then to extend production control techniques to design. Ballard (1999a) presents some obstacles to pull the design process. First, the author points the nature of design process itself; second, design tasks cannot be fully understood in advance of their execution and the inputs necessary to their completion cannot be identified before accepting and initiating the assignment. This can be avoided by estimating the duration based on the professional experiences in previous tasks (Ballard, 1999a). Adding to this, the type of control appropriate to design is not the same from construction, and the obstacles to applying pull techniques in design management must be overcome (Ballard, 1999a).

In Bolviken et al. (2010), the authors presented the application of LPS in both stages of design and construction, calling it Collaborative Planning in Design. In this system, there are two levels of planning (Figure 27): **strategic**, composed by master, purchasing and delivery schedules, and phase schedules for design and production; and **operational**, composed of decision schedule for design, lookahead plan for design and production, weekly plan for design and production, and team plan for production (Bolviken et al., 2010). The scheduling system for design is coordinated with the scheduling system for production. Through the connection between the lookahead schedule from construction and the weekly work plan from design, the construction is pulling the detail engineering design (Bolviken et al., 2010). Figure 27 depicts the collaborative planning.

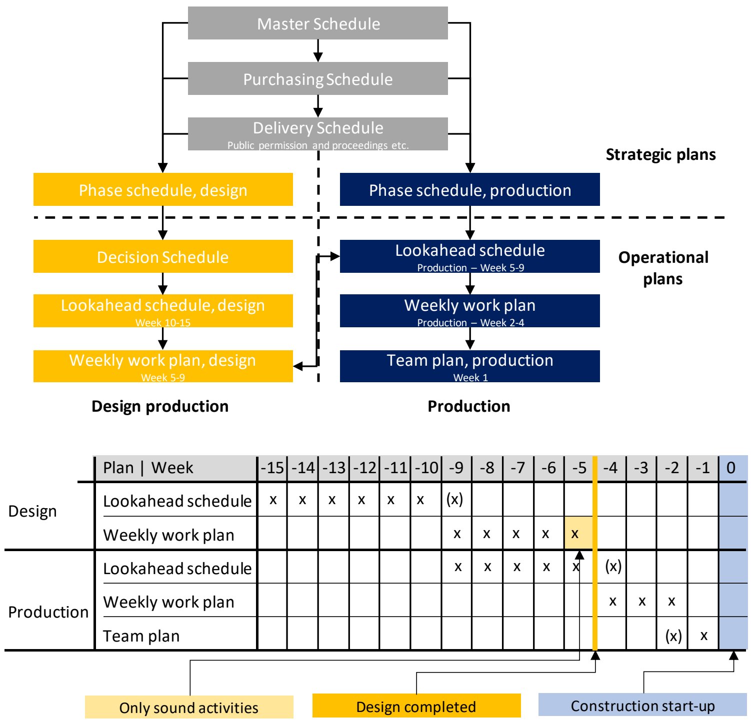


Figure 27: Strategical and operational plans in the Collaborative Planning which connects operational plans in design and construction (Bolviken et al., 2010).

The LPS applied in the design stage of the AEC industry has partial success in its implementation, mainly because the lookahead plan is the most critical and challenging horizon of planning to be executed by designers (Ballard, 2002; Miles, 1998; Tzortzopoulos et al., 2001). Although it promotes transparency, it still lacks more tools to control the change orders, including the client in the process, and to support designers to estimate the duration of design tasks in the weekly plans. More adaptation is necessary for the LPS to become more flexible (Hamzeh et al., 2009) and promote short project learning cycles as it is the Agile.

2.3.2.6 *Design Structure Matrix*

The lean design uses the DSM to support the flow view in design management. It was presented as a lean design management tool by Koskela et al. (1997).

The DSM is a network modelling tool for visually representing elements of a system and their interactions, and supports its decomposition and integration problems (Browning, 2001; Eppinger & Browning, 2012). DSM can be applied in different contexts, for example “product development, project planning, project management, systems engineering and organization design”, i.e. for the product, or process by aggregating individual interactions among components, people, activities, or parameters (Browning, 2001; Eppinger & Browning, 2012).

Koskela et al. (1997) argue that there is an optimal sequence of design tasks, but “uncertainties tend to push the design process away from the optimal sequence” and decrease the productivity, prolonging the duration and decreasing value. Through measurements and managerial control, it is possible to achieve the optimal, or near the optimal, sequence (Koskela et al., 1997). Other researchers applied the DSM as a lean design tool to find an optimal sequence of design tasks (Choo, Hammond, Tommelein, Austin, & Ballard, 2004; Hammond et al., 2000; Tuholski & Tommelein, 2008).

The DSM is being used as a complementary tool in different methods and techniques to plan the design tasks. One example is the Analytical Design Planning Technique.

2.3.2.7 *Conclusive Discussion on Lean Design Management*

Although the tools, techniques and methods aforementioned in this section are based on lean design concepts of value, flow and transformation, few of them were applied in the whole project, particularly in both design and construction stages. Most parts of the practices are used only for planning and control the design tasks. A possible reason for this phenomenon is the use of these tools in the traditional project development model, i.e. sequential and linear, where the construction stage only starts after the design completion. Other reasons may be the unavailability of the construction plan at the moment of the development of design activities, or even the lack of collaboration between the design manager and construction manager.

However, these tools have a great potential to be applied in an integrated planning and control system in projects with overlap between the design and construction stages. The limitations to manage the design system in overlap with construction are described in Table 7.

The abovementioned tools and practices are advocated by the lean community to manage the design process. Nevertheless, the tools are not reported to be integrated for both design and construction stages, with the exception of the Bolviken et al. (2010) work. Due to this lack of holistic use of the tools, the use of the Collaborative Design Planning is one of the case studies of this thesis and is reported in Chapter 6.

Table 7: Main processes and tools of lean design management.

Tool/Practice	***Description***	***Limitations for overlap D-C stages***
Target Value Design (TVD) (Ballard, 2011; Lee, 2012; Macomber et al., 2012; Zimina et al., 2012)	It uses the client's requirements to generate value by design, while continuously improve and reduce wastes in project development.	TVD must front-load design with accurate project cost estimation. To enable this, the earlier involvement of key contractors is desirable. Traditional contract is not recommended to apply TVD. Overlap D-C can benefit from TVD.
Set-based design (SBD) (Lee et al., 2012; Parrish et al., 2007; Sobek et al., 1999; Ward et al., 1995)	Designers develop integrated design solutions for different criteria considering schedule and budget that will be narrowed collectively until a satisfactory solution.	The use of SBD in construction projects faces the challenge of resources capacity. Usually, the AEC companies are engaged in more than one project, which hampers the development of complete design solutions. The certainty of the "last responsible moment" to make a design decision is still vague.
Choosing by Advantage (CBA) (Arroyo et al., 2015; Arroyo, Tommelein, & Ballard, 2016; Parrish & Tommelein, 2009; Suhr, 1999)	Improves the decision-making process, aligning criteria to evaluate design alternatives, promoting consensus.	From the lean perspective, it is an advocated method to promote shared understanding and transparency. However, more research is needed to integrate and develop CBA between designers and constructors. There are still limitations in the tabular method to embrace construction organisation alternatives.
Agile Design Management (Demir & Theis, 2016)	Agile applied in the design management to embrace changes and add value for designers and client.	Agile is recommended in case there are full-time dedicated professionals in the project working co-located with other stakeholders. This is a challenge for the fragmented AEC organisations. Is it possible to use the same takt time in both design and construction?
Design Structure Matrix (DSM) (Browning, 2001; Eppinger & Browning, 2012; Koskela et al., 1997; Tuholski & Tommelein, 2008)	It is a network modelling tool that visually represents elements of a system and their interactions, and it supports its decomposition and integration of problems.	DSM requires certainty in the activities definition to set an optimal sequence among them. The tool in a complex project may need refinements and revision across the NPD according to increases in the level of detail. How to devise a DSM for both design and construction activities is still a research question with potential benefits for both planning.
Last Planner System in Design (Ballard, 1999a; Bolviken et al., 2010; Khan & Tzortzopoulos, 2015; Koskela et al., 1997; Tzortzopoulos et al., 2001; Wesz et al., 2013)	LPS applied in the design stage to increase the design process transparency, designers' collaboration and communication. It improves workflow stability and reliability.	LPS in design already faces partial success in its implementation, mainly in the lookahead planning. It needs more control tools to change orders, including the client in the design process and support designers, estimate tasks duration. The Collaborative Planning explained by Bolviken et al. (2010) already outlines how to use LPS in both design and construction stages, and the adaptations necessary for the project context.

2.4 LEAN CONSTRUCTION MANAGEMENT

Lean construction is a new production management philosophy that uses adapted concepts, tools and techniques from the lean manufacturing in order to design, plan, control and improve construction production systems.

The lean thinking is applied to construction management in order to overcome deficiencies by focusing on value generation for customers and reduce wastes in the process. This section about Lean Construction Management presents the conceptual foundations of lean construction management, as well as the main processes and tools used by industry and academia.

2.4.1 Lean Production Foundations

Lean production is a term coined by Womack, Jones, and Roos (1990) in the book *The Machine That Changed the World*, as result of five years of research on the Toyota Production System (TPS). The MIT researchers noticed that the TPS is much more effective and efficient than the traditional mass production, and for this reason it is a new paradigm of manufacturing.

The TPS was developed during World War II by the Toyota Motor Corporation in order to make their production system achieve the highest quality, lowest cost and shortest lead time through the elimination of waste (Marchwinski & Shook, 2003). These goal achievements were necessary for the company's survival in the post-war Japanese market, which was suffering from inflation, and small and fragmented demand (Liker, 2004). Then, Toyota began its journey to equal its productivity with Ford throughout the 1950s and 1960s, led by Taiichi Ohno (Liker, 2004; Marchwinski & Shook, 2003). Further development of the lean production system was made with the supply base through the 1960s and 1970s (Marchwinski & Shook, 2003).

Through years of study on the consolidated TPS, Womack and Jones (2003) outlined five principles of lean production: Value, Value Stream, Flow, Pull and Perfection. These five lean principles are entirely applied by the manufacturing industries, and its base, the TPS, is briefly described in the next subsection.

2.4.1.1 Toyota Production System

The TPS can be explained by the "Toyota House" in Figure 28.

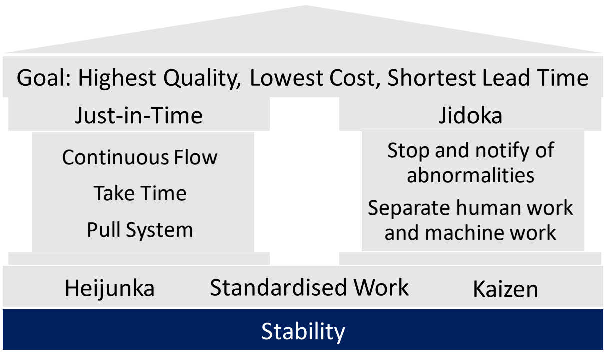


Figure 28: Toyota Production System House (Marchwinski & Shook, 2003).

The Toyota House's foundation is based on stability and, in order to support it, concepts such as *heijunka*, standardised work and *kaizen* must be applied. A stabilised production system is one with low variability and uncertainty. Below are the definitions of the central concepts of the TPS (Marchwinski & Shook, 2003):

- *Heijunka*: means levelling the type and quantity of production in a fixed period of time. It is used to meet the customers' demands while reducing the batch size, inventories, costs, workforce and lead time.

- Standardised work: establishes the precise procedure for each operator in a process. It is based on 1) Takt time; 2) Precise work sequence; and 3) Standard inventory. It is the baseline for improvements.
- *Kaizen*: is the continuous improvement in the overall value stream or process to increase the value and reduce the wastes in the production system.

The two pillars of the house are the just-in-time (JIT) and *jidoka*. The first one is composed of the continuous flow, takt time and pull system. On the other hand, *jidoka* is composed of two elements, the stop and notify abnormalities, and separate human and machine work.

JIT, which is a production system that “makes and delivers just what is needed, just when it is needed, and just in the amount needed”, is based on three operating elements (Marchwinski & Shook, 2003):

- Continuous flow: also known as one-piece flow, it is the production and moving of “one item at a time through a series of processes”, at which each process makes just what is requested by the next one as continuously as possible.
- Takt time: is the rate at which products are made in a process to meet customer demand or “the available production time divided by the customer demand”.
- Pull system: is a production system where the downstream process signals its needs to upstream process, eliminating overproduction.

Jidoka, or autonomation, is the second pillar of TPS which provides to machines and operators the ability to stop the work after detecting any abnormal conditions in the production system (Marchwinski & Shook, 2003). It is known as the “automation with human intelligence”. It improves the quality of products because, when the work stops, the root causes of the problem must be found and eliminated.

2.4.1.2 Pull Production System in Manufacturing

In the TPS, the tool used to pull the production system is the ***kanban***, which triggers a production according to the demand (Hopp & Spearman, 2011). It can be used to move or produce items. When used for production, it signalises, usually by a card, to an upstream station to produce the necessary products for the downstream process (Marchwinski & Shook, 2003).

The difference between a push and pull system is that the first one schedules the release of work upon demand, while the second authorises the release of the work based on the system status (Hopp & Spearman, 2011).

In order to understand better the pull systems, it is important to clarify two concepts: the **work in progress (WIP)** and the **buffer**. The WIP can be defined as “items of work between processing steps” (Marchwinski & Shook, 2003). The importance of visualisation and control of WIP has increased in construction due to the popularity of location-based tools (Faloughi, Linnik, Murphy, & Frandson, 2015). In this context, WIP is defined as the amount of time that location units contain unfinished work, i.e. do not receive any transformation activity.

Moreover, buffer is used to protect a production system against the variability. It can be a buffer of inventory, capacity and time (Hopp & Spearman, 2011). In the LBS tools, such as LOB and flowline, it is possible to visualise the **time buffers** (time gap between the tasks) and the inventory buffers, or **work buffers**, as described by Lucko and Gattei (2016) (location/unit gap between the tasks). A type of buffer commonly explored by the TTP is the **production capacity buffer** (Frandson, Seppänen, & Tommelein, 2015) which is under loading the crews' capacity to perform an activity.

Other methods may be used in pull systems in manufacturing (see Figure 29), such as:

- **CONWIP** (CONstant Work-In-Progress) (Hopp & Spearman, 2011) where the pull signal to release items are sent in a production line from the downstream stock point to the upstream stock point, limiting the WIP to a constant level. The production between stock points is pushed (Hopp & Spearman, 2011);
- **POLCA** (Paired-cell Overlapping Loops of Cards with Authorization) (Krishnamurthy & Suri, 2009) is a hybrid push and pull system used in environments with high variety and/or custom products. It uses cards to pull production in a pair of cells, but not pull to a specific product or batch of products as *kanban* or CONWIP do;
- **WLC** (WorkLoad Control) (Hendry, Huang, & Stevenson, 2013) plans and controls the inputs of work to a shop floor in accordance with workload limits. The order release depends on customer enquiry (Silva, Stevenson, & Thurer, 2015). It enables the customer to confirm jobs and review the production capacity to meet the demand (Viana, 2015). The "level of WIP is controlled by doing the right parts" (Viana, 2015);
- **DBR** (Drum-Buffer-Rope) (Goldratt, 2013): "the production process is scheduled to run in accordance with the needs of the bottleneck(s), as the bottleneck (constraint resource) determines the performance of the whole production system" (Stevenson, Hendry, & Kingsman, 2005). The process flow constraint is the Drum, which dictates the production pace. The Rope is the mechanism to pull the production based on the constraint (drum). The length of the rope and the release of material in a fixed amount of time ensures a constant buffer at the constraint. The DBR is under the Theory of Constraints (TOC)[6] philosophy (Goldratt & Cox, 2016).

[6] The Theory of Constraints is a management philosophy and set of tools for organisations improve their profits by managing the constraints. While lean focuses on identify and remove wastes to improve the flow of value, the TOC focuses on identify and manage the constraints to improve throughput (Marchwinski & Shook, 2003) .

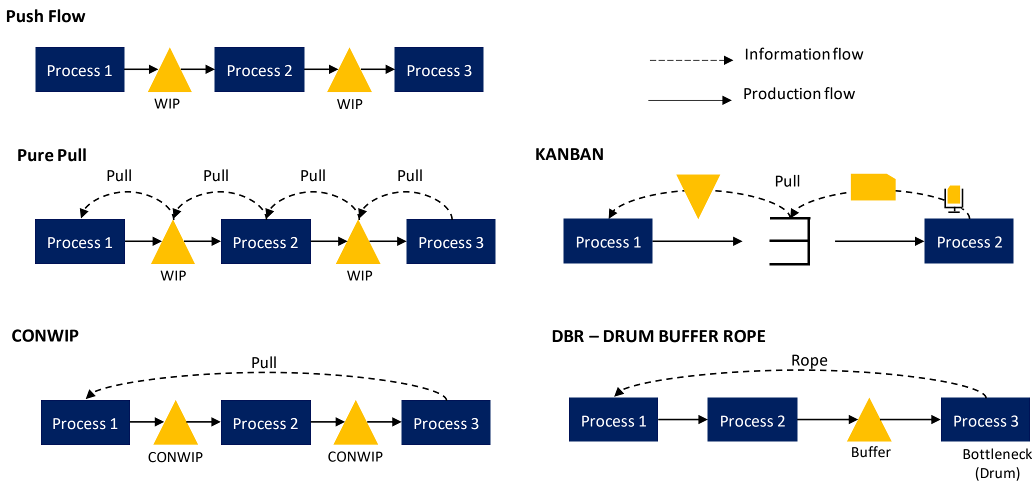


Figure 29: Examples of different pull systems used in the manufacturing industry.

2.4.2 Lean Construction Management Concepts

The Lean Construction relies on a major theory and a set of essential concepts brought from the manufacturing industry. For this investigation, the Transformation, Flow and Value (TFV) Theory is presented followed by the different types of pull systems. The management activities of design, operate and improve the construction system is also described.

2.4.2.1 TFV Theory

According to Slack et al. (2010), all operations produce goods and services by transforming inputs – materials, information and customers' requirements – on products or services (outputs). This conceptual model is defined as (Koskela, 1992):

- The production process is a conversion of inputs into outputs;
- The conversion process can be subdivided into sub-processes, which are also conversion processes;
- The total cost of the process can be minimised by minimising the costs of each sub-process;
- The process output value is associated with cost (or value) of the inputs in the process.

Figure 30: Conventional model of process, based on Koskela (1992).

According to Koskela (1992), the conversion model does not consider the physical flow activities, such as the flow of materials and labour. These activities do not add value and contain most of the work costs. Moreover, the traditional model seeks to make improvements in a sub-process individually, not seeing the production system as a whole.

The new production theory, entitled TFV, conceptualises the production from three points of view: transformation, flow and value (Koskela, 2000). The production is seen as the flow of materials and information through a network of experts, and the production design regarding creating value for the customer.

Throughout the process, the material is processed (converted) and inspected; then, after inspection, if a defect is detected, the material may be rejected or reworked. Otherwise, it will be transported or be waiting for the next process, and so on (Koskela, 1992).

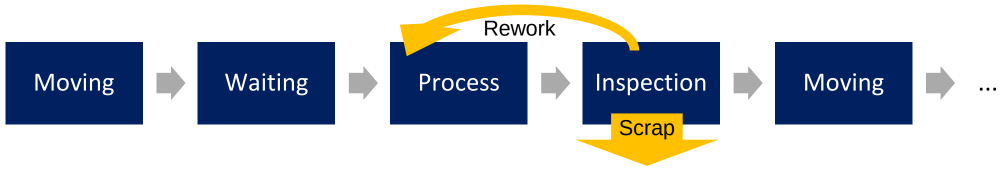


Figure 31: TFV process model: production as a flow, based on Koskela (1992).

According to Koskela (1992), the process, which is the aspect of conversion of production, is an activity that adds value when converting materials and/or information towards what is required by the customer. Otherwise, moving, wait, and inspection represent the aspect of production flow, and are activities that do not add value; they are also called waste, as they consume time, resources or space but do not add value. This theory has been applied to this work in the management of the production system.

2.4.2.2 Pull Production System in Construction

The first work on construction management approaching the use of pull system is presented by Tommelein (1998). The author focused on different simulate schedules for pipe-spool installation using discrete event simulation models. Tommelein (1998) claims that delay and uncertainty in supplying materials for specific locations can decrease field productivity. The author used a “model of material-management process with a matching problem that typifies fast-track process-plant projects”. She prepared several scenarios, changing elements in the supply chain such as variability in activities duration and execution quality, that allowed different sequences of material delivery and work area completion. The first scenario represents a total lack of coordination between the material delivery and work area; the second one is perfect coordination; and the third one uses pull-driven scheduling. As a result, Tommelein (1998) found that the lean construction technique of pull production, i.e. the downstream process (site) sends real-time progress status to upstream process, in this case to the fabricators of pipes off-site, allowed the opportunity for resequencing the production, reducing buffers, enabled time for project completion, and increased the productivity.

Viana, Bulhões, and Formoso (2013) implemented pull production in an integrated planning and control system in an ETO company which is responsible for designing, prefabricating components and assembling on-site. The author used the assembly process on-site to pull the prefabrication of components. Also, (Viana et al., 2013) presented some guidelines to support the pull production in ETO environment:

- **Implement collaborative and decentralised planning and control:** each department should have short and medium-term planning and control processes, which could be the LPS with some adaptations, and people from the operational level should participate to transparent the problems that hinder production. Collaborative planning is required for the environment with high variability in demand. It is also required to control WIP and confirm the need for execution in control points along the product development process;

- **Establish integrated planning and control meetings:** these meetings are confirmation points of the orders programmed in the master schedule. They aim to adjust plans according to the current demand, avoiding WIP on the plant and construction sites;
- **Make use of the information from assembly systematically:** create effective initiatives to ensure the information from the assembly is used in manufacturing and design. The authors suggest regular meetings to update the status of the sites and resequencing upstream processes;
- **Make use of short-term planning information as a confirmation point:** use confirmation points between the monthly targets and the actual production short-term goals. For instance, weekly meetings with the head of departments should discuss what they have done and should do;
- **Use visual management tools:** create visual boards to expose the status of each department and control their activities. Visual boards can present the components that are urgent, feasible, backlogs, and the one that should not be produced. The boards provide information for the lookahead planning that focuses on the downstream information form assembly;
- **Develop people capabilities:** people should be capable of understanding the concepts behind the procedures. The authors suggest workshops and training about production management.

The authors (Viana et al., 2013) concluded that, to support a pull production system for a complex ETO environment, it is necessary to have **reliable information from the construction sites, rigid control of WIP and confirmation points** as a means to deal with uncertainty and update upstream processes

2.4.2.3 Production System

Before exploring the theme of the production system, it is necessary to understand the concept of the system. According to Ackoff (1970), a system is a whole that cannot be separated without incurring losses in its essential characteristics.

The production system is an intentional gathering of people, objects and procedures to operate in an environment (Meredith & Shafer, 2009). Defining the limits of a system is essential because, if it is defined very narrowly, it can omit important relationships between the components thereof. On the other hand, extending its limits increases the complexity and costs associated with their development and use (Meredith & Shafer, 2009).

In a production system, there are several parts that comprise a whole, as the inputs (raw materials, people, equipment, buildings, technology, money, information, etc.) are processed by a transformation subsystem into outputs (products and services) (Gaither & Frazier, 1999).

The objectives of the production systems are delivering products with desired functions, aesthetics and quality to customers at the right time and the right cost (Askin & Goldberg, 2002). Meredith and Shafer (2009) corroborate with this statement and add that organisations are responsible for creating value, and the production sector has a key role in the construction of that value.

Because the environment is dynamic in nature, it is necessary to monitor and control it, and if the system is not achieving its goal, it must undergo corrective actions (Meredith & Shafer, 2009). The product is also monitored in the control subsystem to determine if it is acceptable regarding quality, quantity and cost (Gaither & Frazier, 1999).

2.4.2.4 Construction System Design

The meaning of design is to design the appearance, layout and operation of something before it is built (Slack et al., 2010). Design of the production system involves planning the processes, products or services, technology and market, in order to develop a detailed plan to produce goods and services (Gaither & Frazier, 1999).

The CSD fulfils a goal at the beginning of any productive effort, to discuss and translate the desired production strategy in some decisions on the production system, thus forming a structure that will manage the different activities (Schramm, 2004). Therefore, the CSD extends from the global organisation of the company until the project operations, defining who should be involved in the roles for the decision-making process as to how the physical work will be performed (Ballard et al., 2001a).

During the preparation of the production system, it must consider the organisation of production alternatives in order to choose the most appropriate strategy to achieve the desired results (Meredith & Shafer, 2009). Decisions made at this stage are interdependent and, if one is changed, the others will be affected (Meredith & Shafer, 2009).

Three primary goals of the design of the production systems are (Koskela, 2000): 1) deliver the project; 2) maximise value; and 3) minimise waste. CSD represents the most basic form of minimising the effect of variability, contributing to achieving the major project goals (Ballard et al., 2001a). It considers alternatives to production organisation to develop the most appropriate strategy for the project and the construction company (Schramm, Costa, & Formoso, 2004).

2.4.2.5 Work Structuring

The term Work Structuring was introduced in the construction industry by Ballard (1999b) and Tsao, Tommelein, Swanlund, and Howell (2000) to designate the production system design. However, there are some differences in focus between both researches. Work structuring can be defined as process design (Ballard, 1999b). It is “the development of operation and process design in alignment with product design, the structure of supply chains, the allocation of resources, and design-for-assembly efforts” with the goal of making "workflow more reliable and quick while delivering value to the customer" (Ballard, 1999b).

Work structuring is used before the production stage, but it can be used any time during the construction (Ballard, 1999b). It breaks down the product and the process in parts, sequences and assignments to do the workflow with less variability, to reduce waste while increasing the value (Milberg, 2007). To achieve this goal, the work structuring deals with three central concepts (Figure 32):

- Production unit: “a group of direct production workers that do or share responsibility for similar work, drawing on the same skills and techniques” (LCI, 2004 cited in (Tsao, 2005);
- Work chunk: “A unit of work that can be handed off from one production unit to the next” (Tsao, 2005);
- Handoff: “The combined (1) completion of a work chunk by a production unit that allows a subsequent production unit to further transform the work chunk or execute a different work chunk as planned, (2) declaration of completion of the work chunk by the production unit and release to the subsequent production unit, and (3) acceptance of the released work by the subsequent production unit” (Tsao, 2005).

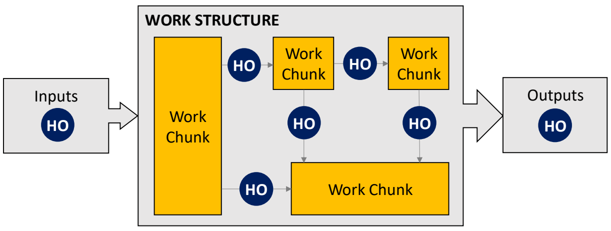


Figure 32: Relationship between work chunks and handoffs (Tsao, 2005).

2.4.2.6 Phase Scheduling or Pull Planning

The term Phase Scheduling (PS) emerged in the lean construction literature in Ballard's white paper (Ballard, 2000c). PS is also known as pull planning or reverse PS. It is a collaborative production design activity to structure the work of a project phase (Ballard, 2008). PS occurs during the production system operation due to information becoming available and accurate for planning when the subcontractors are hired.

It was incorporated into the LPS (Ballard, 2000a) to bridge the gap between the master plan and the lookahead plan. For that, the PS participants use a mix of push and pull flows for planning the work. The construction phase's milestones that were set up at the project's master plan are pushed to the phase planning. Next, the phase's activities are broken down into tasks and handoffs. A network and duration of tasks are defined by the contractors of the phase using sticky notes (among other means) on a wall (or other physical and digital media). Then, a reverse plan of the phase's tasks is devised, pulling the tasks from the phase deadline towards the phase start date (Alarcon, Betanzo, & Diethelm, 2004). The contractors define the handoffs collaboratively between the crews and project phases, insert buffers, and guarantee the completion of the work on time (Alarcon et al., 2004; Ballard, 2008; Ballard & Howell, 2003).

One of the outputs of the PS is the plan of the project's phase (Ballard, 2008). The plan can be scheduled using traditional tools, such as a Gantt chart (Knapp, Charron, & Howell, 2006), or LBS techniques, such as LOB (O'Brien et al., 1985), flowline (Seppänen et al., 2010) and TTP (Fiallo C & Howell, 2012). Moreover, computational simulations can be used to support the decision-making process by the phase's participants (Tsao, Draper, & Howell, 2014).

As PS is a transparent and collaborative process of decision-making, it promotes the "teamwork, awareness of the impact of individual actions on all participants" which enhances the subcontractors' commitments (Alarcon et al., 2004).

2.4.2.7 Construction System Operation

1.1.1.1.2 Production Planning and Control

After the design stage, the next managerial action of the production system is to operate the production. The production planning and control (PPCa) refers to the production operation act (Koskela & Ballard, 2003). According to Schramm et al. (2004), Schramm, Rodrigues, and Formoso (2006), and Biotto, Formoso, and Isatto (2015), the same tools used during the production system design can be applied in the PPCa, including to evaluate different solutions to recover the construction plan. Tommelein (1998) states that the PPCa includes the role to adjust the production operation in order for it to continue be efficient when faced with the uncertain effects.

The objective of the production planning is to present what must be done and how, followed by the production control to keep the execution more effective (Laufer & Tucker, 1987). The process of PPCa can be divided into two dimensions: horizontal and vertical (Laufer & Tucker, 1987). In the horizontal dimension are defined the process phases of the PPCa (Laufer & Tucker, 1987): 1) Planning the planning process; 2) Gathering information; 3) Preparation of plans; 4) Diffusion of information; 5) Evaluation of the planning process; and 6) Action.

In the vertical dimension, these phases are linked to the managerial levels of the organisation and objectives (Laufer & Tucker, 1987). Bernardes and Formoso (2002) define three hierarchical levels of PPCa: (a) strategic; (b) tactic; and (c) operational. In the strategic level are defined the project strategic objectives, the project scope, goal and duration to achieve the stabilised objectives. The tactic level defines the means and limitations to achieve the project goals (Bernardes & Formoso, 2002). The operational level refers to the selection of actions to achieve the goals (Laufer & Tucker, 1987).

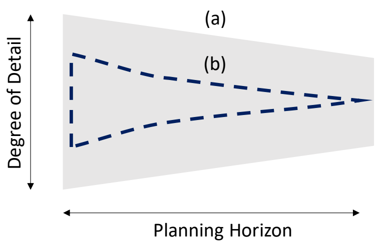


Figure 33: Influence of planning horizon on the degree of detail: (a) low uncertainty; (b) high uncertainty (Laufer & Tucker, 1988)

2.4.2.8 Construction System Improvements

Construction system improvements (CSI) occur after the completion of the production, and aim to promote the improvement in the system based on data received from the design and operational stages (Koskela & Ballard, 2003).

2.4.3 Lean Construction Processes and Tools

In this subsection, the main lean processes and tools are explored to design the production systems in construction, plus operate them. The traditional tools were not discussed in depth due to their limitations for management of complex projects. The focus of this subsection is on the location-based management using very similar, but conceptually different, location-based scheduling (LBS) tools, such as the LOB, flowline and the TTP. These LBS tools are used in combination with the LPS to plan medium and short terms and control the production systems.

The combination of LBS with LPS is known to be a very effective practice to promote stability in production systems, increase the plan's reliability, and mitigate the variability and uncertainty of the system.

2.4.3.1 Location-Based Scheduling Techniques

There are different types of methods to plan the construction: those based on activity or those based on location. Examples of methods to plan construction based on activity are the well-known Critical Path Method (CPM) and PERT. Both methods are frequently criticised by lean researchers due to their incapacity to deal with the construction complexity (Birrell, 1980; Dave et al., 2015; Koskela & Ballard, 2006; Koskela & Howell, 2002; Koskela, Howell, Pikas, & Dave, 2014; Peer, 1974a). CPM is a plan that quickly goes out of date and is put aside by the operational professionals; neither does it support continuous workflow and clear handovers for them (Arditi & Albulak, 1979; Birrell, 1980; Peer, 1974a).

The term location-based schedule (LBS) was proposed by Kenley (2004) to designate the techniques that use the location or unit as a basis for the PPCa. LBS techniques, such as line of balance (LOB), flowline (FL) and takt-time planning (TTP), were initially developed in manufacturing, and have been adapted for construction. The adaptation occurred by changing the vertical axis: from units produced to location units (Henrich, Tilley, & Koskela, 2005; Kenley & Seppänen, 2010).

It is important to highlight that the aim of using LBS techniques is to design a production system with continuous workflow and uninterrupted flow for crews throughout the location units (Moura, Monteiro, & Heineck, 2014). To make the workflow smoother and reduce the WIP, the activities should be planned at only one rate, i.e. in parallel lines (Mendez & Heineck, 1998). The achievement of the same delivery rate is not always possible due to the different amount of work executed by crews and/or different area of the location units, and, when it occurs, the balancing process will guarantee the achievement of similar paces among activities.

Through the LOB technique and, generally, through the LBS techniques, it is possible to visualise the activities sequenced along the time. It contains information such as: the delivery rate; activities synchronism, parallelism and interferences; distribution of workers' and crew's workflow; the strategy of construction execution; buffers; production and transfer batches; activities cycle time in a batch; and activity lead time (Moura et al., 2014) (Figure 34).

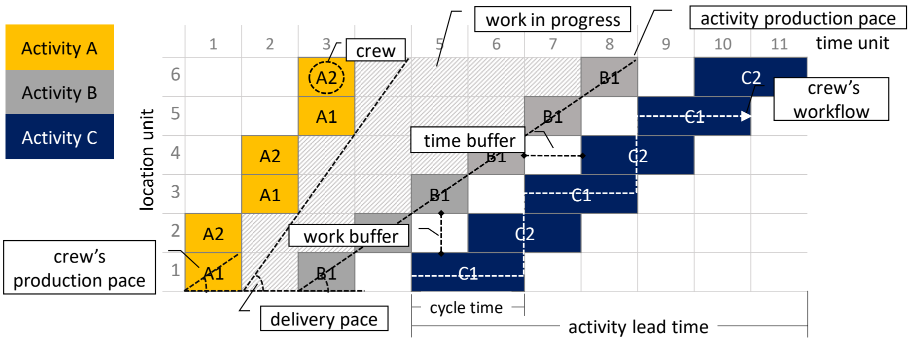


Figure 34: Visual information in a Line of Balance - based on Moura et al. (2014).

2.4.3.2 Line of Balance

Line of Balance is a planning technique developed by Goodyear Company in the 1940s and then used in the manufacturing industry for repetitive processes. It was then developed for an industrial programme by the US Navy in the 1950s (Arditi, Tokdemir, & Suh, 2001). Currently, the LOB is also used by the construction industry, especially in repetitive projects, such as high-rise buildings, tunnels, roads, and so on (Biotto, Kagioglou, Koskela, & Tzortzopoulos, 2017).

The LOB is a diagram that represents units in the vertical axis, and time on the horizontal axis. Initially, the tasks were represented as dual parallel lines. As the LOB is based on activity-on-arrow (AOA) networks, the task lines represent an activity between two event nodes (the delivery of a production unit) (Su & Lucko, 2015). Hence, the line slope means the delivery rate. Because this method is focused on the delivery of completed units, the delivery rate starts counting "when the first unit has been finished" (Su & Lucko, 2015).

The LOB technique allows the project team to achieve continuous workflow and uninterrupted flow for crews through the location units. This technique is appropriate for planning projects of a repetitive nature by taking advantage of continuity of work (Mendez & Heineck, 1998). The main idea in the LOB is that all activities can be performed at only one production rate, i.e. parallel programming between the activities (Mendez & Heineck, 1998) to reduce the WIP.

The LOB is being used to devise the production system design, as well as the master plan of construction projects (Kemmer, Heineck, & Alves, 2008; Schramm et al., 2004). It also can be detailed in different forms, i.e. the time units can be days (Valente et al., 2014) or weeks (Seppänen, Ballard, & Pesonen, 2010) according to the level of uncertainty in defining the duration of the task.

2.4.3.3 Flowline

Flowline is a term coined by Mohr (1979). However, the method was developed earlier by (Selinger, 1973) and Peer (1974a). The flowline consists of a derived method from the LOB. However, the activity is represented by a single line, which Kenley and Seppänen (2010) consider a much cleaner representation than LOB. In order to visualise the crews' workflow, the activity flowline can be broken down into crews' lines (Kenley & Seppänen, 2010).

The flowline can also be designed for normal construction projects, rather than the repetitive ones, by breaking down the project locations in equal sizes or work content (Kenley & Seppänen, 2010). As the flowline is rooted in activity-on-node (AON) representation, which is used to draw the CPM network, the tasks represent the start and end of a process and the logical link among tasks (Su & Lucko, 2015). For that reason, the slope of a line represents the production rate, which is the total quantity of units divided by the total duration (Su & Lucko, 2015). The task is graphically represented by starting in the point of the first unit location (Y-axis) and start of duration (X-axis), finishing at the point of the last unit location (Y-axis) and end of duration (X-axis) (Kenley & Seppänen, 2010).

2.4.3.4 Takt-time Planning

The takt-time planning (TTP) in construction is derived from the takt time used in lean manufacturing to plan the production system by setting its rates according to the demand rate. The use in construction started recently, with some works on its application in the development of the production system design, or, more specifically, the PS (Frandson, Berghede, & Tommelein, 2013; Linnik, Berghede, & Ballard, 2013).

Frandson et al. (2013) define takt time as the "unit of time within which a product must be produced (supply rate) in order to match the rate at which that product is needed (demand rate)". The main aim of the TTP is to design the production system for continuous workflow, keeping the trades at a balanced pace of work (that match the demand rate) through a sequence of zones (Frandson et al., 2013).

The zones are "physical and clearly defined locations" to avoid ambiguity about location boundaries, the same as in the LOB (Frandson et al., 2015). In a production plan devised using the TTP method, the trades must complete their work in the assigned zone in the time set by the takt time (Frandson et al., 2015).

To develop a production plan using TTP, it is necessary to define zones and takt time, the trades sequence and duration, and balance their workflow (Frandson et al., 2013). All these steps are devised with the participation of trades and general contractor in an iterative fashion, and the decision is made collaboratively by communicating and exploring production systems alternatives (Frandson et al., 2015).

2.4.3.5 The Last Planner System in Construction Stage

The Last Planner System (LPS) of PPCa (Ballard, 1994) is based on the TFV theory of production management. The traditional model of project management focuses on the individual workers' task accomplishment, while the LPS focuses on the workflow that connects them (Wesz et al., 2013). The LPS converts what SHOULD be done, from the long-term plan, into what CAN be done, through the identification and removal of constraints, and then an inventory of ready work that WILL be formed in the short-term plan (Ballard, 2000a). This mechanism is the main differential regarding the traditional model of project management, whereby what should be done is pushed directly to the execution process (Viana, 2015) (Figure 35). A primary technique of the new production management thinking is pull (Ballard, 1999a).

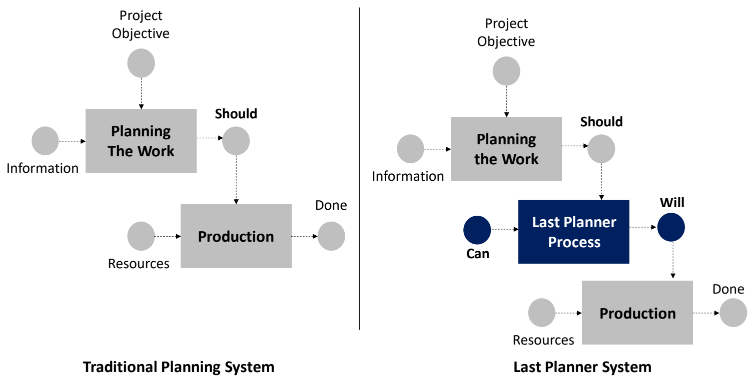


Figure 35: Traditional and Last Planner systems (Ballard, 2000a).

LPS is defined in the same two dimensions (horizontal and vertical) according to Laufer and Tucker (1987). Besides this, the vertical dimensions of the SLP are known for providing its reliability, and it comprises five phases (Figure 36): master planning, phase scheduling, lookahead planning, weekly work planning, and learning (Ballard, 2008). Although LPS has similar phases as the traditional project management (master plan), it is in the tactical level, i.e. lookahead planning, where the production is shielded, and in the weekly planning where the workers commit themselves with tasks execution (Ballard & Howell, 1998).

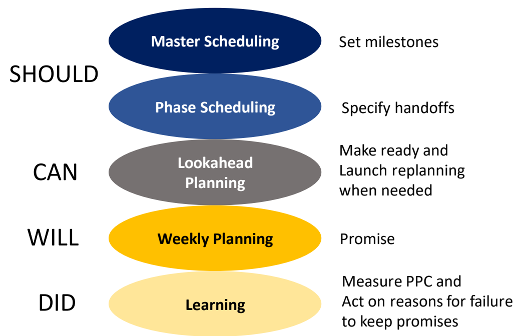


Figure 36: Hierarchical levels of LPS (Ballard, 2008).

2.4.4 Conclusive Discussion on Lean Construction Management

Section 4 presented the foundations of the Lean Construction since the conceptual basis of lean production and the Toyota House. Pull systems were explained with examples from the manufacturing and a few works in the construction environment, more precisely in ETO companies. In the lean construction management concepts subsection, the production system design activities were introduced. In the following subsection, that looked at the lean construction processes and tools, the focus was on the LBS tools, and the LPS used on-site.

In order to summarise subsection 2.4.2, a comparison was made among the production system design activities of Construction System Design, Phase Scheduling and Work Structuring. Four aspects were analysed: 1) The focus of the production system design; 2) The stakeholders' collaboration for decision-making; 3) The project stage when it was deployed; and 4) The output of the design process (Biotto & Kagioglou, 2019) (Table 8).

Table 8: Comparison of the production system design activities (Biotto & Kagioglou, 2019).

	Focus	Decision-Making	Stage	Output
Construction System Design	Strategical decisions about the whole production system, including organisational levels and product design	Collaboration is desirable	Before the construction stage	Project master plan
Phase Scheduling	Project's phase activities, handoffs between subcontractors	High collaboration between contractors	During the construction stage, before project phase	Project phase plan
Work Structuring	Project activities, product design, assemblage, handoffs	High collaboration between design, manufacturing and contractors	During the construction stage, before activities	Activities plan

The CSD focuses on strategic decisions about the construction project, regarding project viability, budget and lead time, which are consequences of the production system organisation (Ballard et al., 2001a; Ballard, Koskela, Howell, & Zabelle, 2001b; Mota, Mota, & Alves, 2008; Schramm et al., 2004; Schramm et al., 2006). In contrast, the PS tries to ensure that phase activities are clearly defined in handoffs for participants and the phase lead time fits into the master schedule. WS, on the other hand, focuses on the process view and it is used in both design processes, CSD and PS, considering the information available for the decision-making to break down the work in work chunks, handoffs, and production units, and in order to make the workflow smooth (Biotto et al., 2017) (Figure 37).

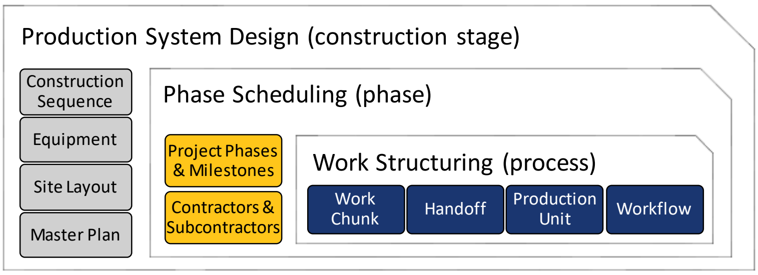


Figure 37: Work structuring is part of the decision scope of phase scheduling and construction system design (Biotto et al., 2017).

Another comparison was conducted for subsection 2.4.3 surrounding the LBS techniques. It was realised that there are similarities among the three LBS techniques (LOB, Flowline and TTP) for construction planning: all achieve continuous workflow by simultaneously setting a unique production or delivery rate among activities in order to reduce the WIP. However, as visual tools, they have different graphical representations of activities (Biotto & Kagioglou, 2019) (see Figure 38).

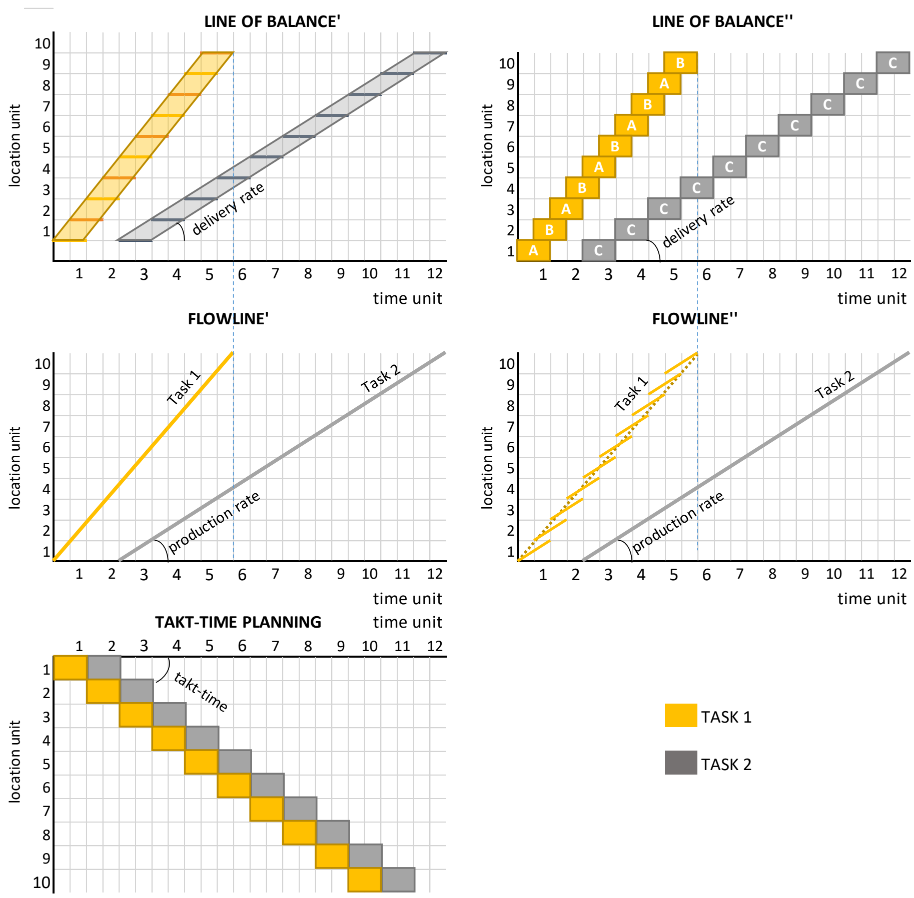


Figure 38: Different construction planning techniques based on location (Biotto & Kagioglou, 2019).

In the LOB technique, one activity is visualised by dual parallel lines. The crews' workflow becomes clear in the current LOB, through the use of boxes with the crew's label. In turn, the flowline represents activity by a single line starting at the beginning of the first day and finishing at the end of the last day (Biotto et al., 2017). Moreover, in the TTP, the activity is illustrated by coloured boxes.

Both flowline and TTP are based on AON networks, which focus on defining the logical link among the activities. In contrast, the LOB plans are developed based on AOA networks that explore the events that mark the beginning and end of tasks. That is the reason why the pace visualised in the LOB plans is the delivery pace (counted at the end event of an activity), while the activities' slopes in the flowline plan illustrate the production pace of a whole task or crews (when detailing the crews' workflow). The TTP has focused on keeping the production pace equal to the delivery pace, and both match the takt time established for the plan.

Buffers are also used in different ways: the LOB uses time and work buffers between activities and production units respectively, similar to the flowline. The TTP, however, incorporates buffers in the crew's production capacity (i.e. the activity's cycle time is shorter than the takt time) (Frandson et al., 2015). Also, the TTP employs workable backlog to avoid trades' idleness when the work is finished earlier than planned. One critique that the authors point out about this type of buffer is that, in construction projects where the workforce is specialised, it is more challenging to plan workable backlogs because the amount of work is already forecasted in the contract and the construction plan. Usually, in the TTP, the workable backlogs are not visualised graphically in the plan, thus becoming a peripheral plan (Biotto & Kagioglou, 2019).

Regarding the balancing process of the activities' pace, it is possible to observe that the LOB and flowline are flexible techniques which study adjustments in the crews' composition, and the amount of work in a work package to achieve a common pace. Also, in the TTP the planners can study the "work density" to meet the takt time by modifying not only the crews' size, but also the production batch size, the amount of work in the work chunk, and the means and methods used by the crews to perform the tasks. It is worth highlighting that, in the TTP, only one crew is assigned to execute a task in a particular zone.

The context of the construction project uncertainties also influences the way that these methods are implemented. In low complexity projects, or in projects with intense collaboration of partners, the uncertainty is lower, so the interdependencies are known. In this scenario, buffers between activities can be reduced, and TTP can be applied, in most of the cases, in the PS. However, in scenarios where the project has high uncertainty, it is recommended to protect the production from cascading delays by allocating time, and work buffers between activities, such as that shown by the LOB and Flowline.

The LOB and flowline are usually devised for the whole construction project, which allows the visualisation of WIP in the early stages of planning. On the other hand, in projects that apply TTP, the master plan is devised using CPM and a Gantt chart, i.e. traditional methods that do not allow the visualisation of WIP on locations. Based on this, the use of TTP focusing on a unique construction phase may hinder the visualisation of WIP between project phases (unfinished location units from the end date of a phase until the start date of the next phase); also, the takt time required for one phase may not be the same for the next one, which nullifies the idea of phase demand rate used to plan the activities (Faloughi et al., 2015).

As mentioned previously, the TTP may use different production batch sizes between phases. Contrary to this, the LOB and flowline are more flexible regarding the production and transfer batch sizes. The use of a common location breakdown structure for the whole project is useful for the visualisation of activity interferences and WIP.

A comparison among the LBS techniques is presented in Table 9 (Biotto & Kagioglou, 2019).

After explaining the characteristics of the location-based tools, it is possible to relate them to the production system design activities. Some factors, such as availability of information, of contractors and subcontractors, and their collaboration, impose different barriers and opportunities for the location-based tools.

For example, the production system design occurs before the production operation, when strategical decisions for the project are made, often at a high level of uncertainty. In this scenario, it is suitable to use the LOB or the flowline to plan the production system, because these tools are flexible about the level of detail, buffers and paces. In fact, after concluding the CSD, these location-based tools become the project master plan, and their information will be used to operate the production system.

Table 9: Comparison of the lean LBS techniques for construction planning (Biotto & Kagioglou, 2019).

	Line of Balance	Flowline	Takt-time Planning
Tasks are represented by	Formerly: two parallel lines; Currently: boxes	One line	Boxes
Tasks lines or boxes are represented by	Formerly: Start and finish dates of first and last units; Currently: box at the start and finish dates per each unit	Start date at the first unit; moreover, finish date at the last unit	Box at the start and finish dates per each unit
Slope of line represents	Delivery pace	Production pace	Takt time: available production time divided by demand
Type of buffers	Production capacity buffers (inside the work package duration per unit); Buffers between activities	Production capacity buffers (inside the task duration); Buffers between activities	Production capacity buffers (inside the work package duration): the difference between takt time and cycle time
Pace achievement (balancing the lines)	Adding or reducing the number of crews to execute an activity; Changing the crews' composition and amount of service inside the work package	Changing the crews' composition	Changing the crews' composition and amount of services inside the work package; Distributing the workload among crew's members; workable backlogs
Level of planning detail	Flexible, mostly used in the Master Planning	Flexible, commonly use at and Master Planning	High, mostly used in Phase Scheduling
Collaboration	Varies according to the level of planning detail	Varies according to the level of planning detail	Highly necessary due to a high level of planning detail

Throughout the system operation, the level of uncertainty may be reduced considerably, compared to the CSD. Here, the main contractors and subcontractors are on board and may take an essential role in the PPCa. In this scenario, the TTP is the suitable location-based tool to plan the work; the demand is known, and the work can be structured precisely, suppressing the buffers between activities. Thus, TTP is suitable to be deployed in the phase scheduling.

The WS is the basis of any production system design effort. It must be used before and during the production system operation. What differs from its use in the CSD and PS is the availability of information at the moment of decision-making. The higher is the certainty, the more accurate decisions can be made (Biotto & Kagioglou, 2019). Besides, every activity of production system design and planning has an opportunistic character regarding information.

The potential applications of LBS techniques in the production system design activities described in this section are presented in the conceptual framework of Figure 39.

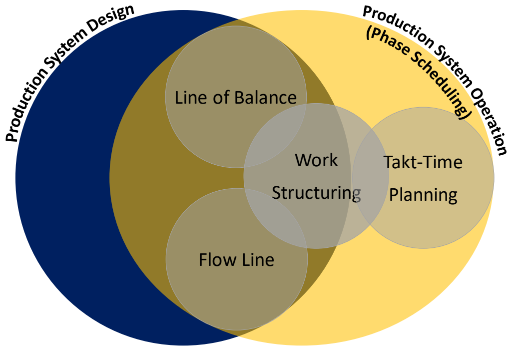


Figure 39: Position of lean tools about planning activities in lean construction management (Biotto & Kagioglou, 2019).

To conclude, when analysing the context of overlap between the design and construction phases, there is a high level of uncertainty when designing the production system, due to construction start dates without completed information from the design. In this scenario, and mainly when the principal contractors' availability for planning is not available, it is suitable to use the LOB or flowline to devise the master plan (Biotto et al., 2017). The former tools allocated buffers of capacity, time and space in order to shield the production against variability. This conclusion was based on the fact that the TTP requires fewer uncertainties in the production system, e.g. most of the production constraints are removed and contractors and subcontractors are on board because there are no buffers between activities.

2.5 BUILDING INFORMATION MODELLING

The final section of the literature review addresses the Building Information Modelling (BIM). In this section, BIM will be explored regarding levels of maturity and development and its potential use with lean construction. For projects where there is overlap between the design and construction stages, the agility in which designers can provide reliable information for downstream activities is critical for the success of the project. For this reason, BIM is explored in this investigation.

Initially, the BIM concept was proposed by Eastman in the 1970s (Liu, Gao, & Wang, 2011). In 1982, Graphisoft developed ArchiCAD software in order to create virtual models of buildings based on the idea of BIM (Liu et al., 2011). There are several BIM definitions, sometimes referring to the model (Building Information Model), or to the modelling process (Building Information Modelling) or the management process (Building Information Management).

According to BuildingSMART (2008), BIM is a digital representation of physical and functional characteristics of a building that serves as a source of building knowledge sharing, forming a reliable database to support decision-making throughout its cycle life. According to American General Contractors (AGC, 2011), BIM is the development and use of computer software to simulate the construction and operation of a building. The resulting model, namely a BIM, is a rich representation of the building data, object-oriented, intelligent and parameterised, from which appropriate visions and data needs of multiple users can be extracted and analysed to generate information that can be used to make decisions and improve the delivery process of the building (AGC, 2011).

Succar et al. (2007, cited in Guillermo, John, Agustin, and Thomas (2009)) argue that BIM is an emerging technological and procedural change, which tends to affect everyone involved in the construction industry. The implementation of BIM systems requires drastic changes in current business practices (Aouad & Arayici, 2009).

Using BIM technologies can support the construction professionals to perform analysis at different stages of a project, through the manipulation and evaluation of the impacts of changes in project parameters, and the provision of new information for decision-making.

BIM has been used to produce virtual models of facilities and production process. There is a wide range of BIM applications in the construction industry, including constructability analysis, design verification and analysis of the product lifecycle (Leite, Akcamete, Akinci, Atasoy, & Kiziltas, 2011); quantitative take-off, cost estimation, environmental comfort simulations, customer requirement modelling (Nisbet & Dinesen, 2010); simulation of energy use, lighting, computational dynamics fluid and checking of building codes (GSA, 2007).

BIM models consist of a set of intelligent objects, which are geometrical elements that represent zones, components and equipment of construction (for example, doors, windows) and that store this information, which can be extracted in the automatic representations, such as plans, elevations, sections, details, quantitative, budget, maintenance, and so on (Lee et al., 2003). Also, BIM models are parameterised, which means that an object can automatically adjust to a design change (Eastman, Teicholz, Sacks, & Liston, 2011). For example, a wall that initially contains a window with its removal, the space occupied automatically fills the wall, reflecting in the drawings and information extracted from the BIM model.

These characteristics allow professionals of design and construction to create, review and edit the models more often, which facilitates the implementation of based-construction design (Eastman et al., 2011). Therefore, the BIM modelling enables faster and automated edits, obtaining information and more accurate updates on all documents compared to CAD (Computer-Aided Design) models (GSA, 2007).

In BIM models, objects are semantically rich with product data in the model, which consists of an object or set of objects (Halfawy & Froese, 2005). The data not only represent the geometric attributes of these objects, but also keep the behaviour and intelligence of it, through behavioural attributes, inter-relationship of objects, design rules, and setting restrictions (Halfawy & Froese, 2005).

The use of BIM models has the potential to generate productivity gains (AGC, 2011) by reducing the need for recollecting and reformatting information, resulting in increased speed and accuracy of the information transmitted, reduction of costs associated with the lack of interoperability, automate check and analysis, and support the operation and maintenance activities (Eastman et al., 2011; GSA, 2007).

2.5.1 Level of BIM Maturity

Tobin (2008) proposed three levels of use of BIM for the AEC industry, naming the BIM 1.0, 2.0 and 3.0. According to the author, BIM 1.0 refers to development projects through parameterised 3D models, but there is no collaboration between designers and other areas of professionals. BIM 2.0 corresponds to an implementation phase where other information is added to the 3D model, such as time (4D), cost (5D), energy efficiency analysis, among others (nD) (Tobin, 2008).

In the last phase of BIM deployment, namely 3.0, which Tobin (2008) describes as the post-interoperability era, solutions are needed for compatible data standards in open and neutral format to ensure compatibility of data between different applications that are used throughout the project lifecycle (Aouad & Arayici, 2009; Lee & Sexton, 2007). At that stage, the exchange of information is done through standards IFC (Industry Foundation Classes) and other protocols developed by the buildingSMART.

Another classification of the use of BIM in the AEC industry is proposed by Succar (2009). In his framework, BIM has three stages of maturity, going from the Pre-BIM, passing through: 1) Object-based modelling; 2) Model-based collaboration; and 3) Network-based integration, and achieving the ultimate goal of IPD (Figure 40).

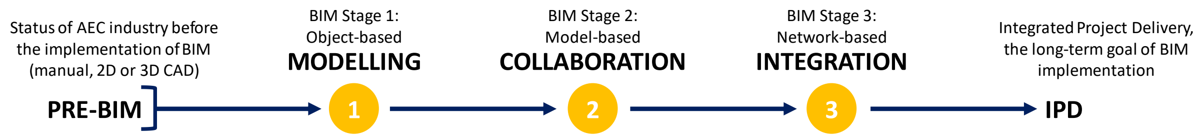


Figure 40: BIM maturity divided into three stages (Succar, 2009).

The pre-BIM status is characterised by “adversarial relationships where contractual arrangements encourage risk avoidance and risk shedding” (Succar, 2009). The workflow between stakeholders is linear and asynchronous, and there are no incentives for collaboration (Succar, 2009).

In the BIM stage 1, the stakeholders deploy object-based 3D parametric software tools to generate sing-disciplinary models (Succar, 2009). The collaborative practices are similar to pre-BIM, without “significant model-based interchanges between different disciplines” and unsynchronised communication (Succar, 2009). However, the object-based modelling encourages the fast-tracking between design and construction stages, which is only possible from BIM stage 2 (Succar, 2009) (Figure 41).

In the BIM stage 2, the stakeholders collaborate and exchange information with other disciplinary players (Succar, 2009). The model-based collaboration may occur within one or between two stages of the product development; for instance, between design-design stakeholders, or design-construction, and so on (Succar, 2009). The communication is still unsynchronised, but a clear definition of roles, disciplines and lifecycle phase starts to emerge (Succar, 2009). Due to changes in deliverables format, from documents to model, some contractual arrangements are necessary.

The BIM stage 3 is characterised by the integration and collaboration of stakeholders across the project lifecycle phases (Succar, 2009). Data is synchronously exchanged between stakeholders, and information is integrated to deploy more complex analysis about constructability, operability and safety, and other nD modelling. At this stage, there is CE of the construction project (Figure 41), which requires reconsiderations of contractual relationships, risk-allocation and workflows (Succar, 2009). Also, the maturity of network and software technologies enable an interdisciplinary model sharing in two-way access to project stakeholders, which facilitate the adoption of the IPD. The ultimate goal of construction projects is achieved by the IPD (AIA, 2007), which was previously described in section 2.1.4.4.

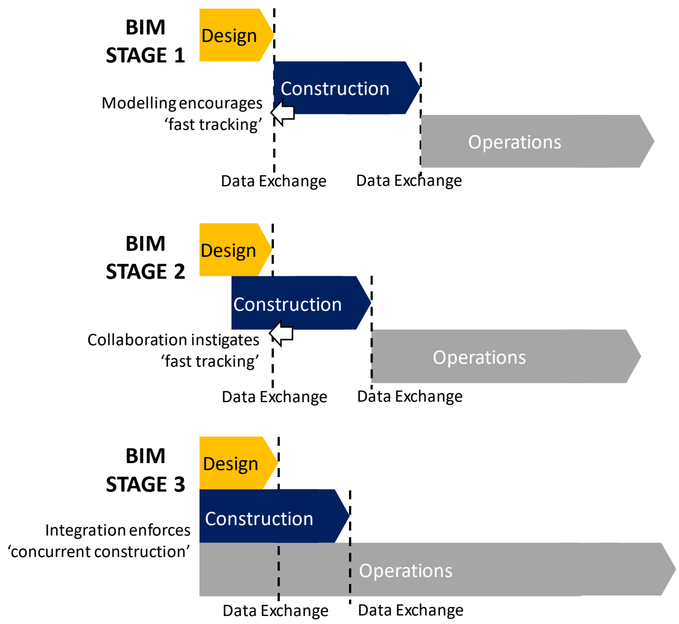


Figure 41: Product development stages at BIM Stage 1, 2 and 3 (Succar, 2009).

2.5.2 Level of Development (LOD)

"The Level of Development (LOD) Specification is a reference that enables practitioners in the AEC Industry to specify and articulate with a high level of clarity the content and reliability of Building Information Models (BIMs) at various stages in the design and construction process" (BIMForum, 2017). Vico Software Inc. first conceptualised it as a progression specification of components in the model: from lowest level of approximation (conceptual), approximate geometry, precise geometry, fabrication, to highest level (as built).

In 2008, the American Institute of Architects released a protocol form to determine the level of development of BIM models, which was refined in 2013; it expresses the following levels (AIA, 2013; BIMForum, 2017):

- LOD 100 – conceptual: the BIM element is graphically represented with a symbol or other generic representation; the non-graphical information is attached;
- LOD 200 – generic placeholders: the BIM element is graphically represented as a generic placeholder with approximate quantities, size, shape, location, and orientation; non-graphic information may be attached;
- LOD 300 – specific assemblies: the BIM element is graphically represented as a specific system, object, or assembly regarding quantity, size, shape, location, and orientation; non-graphic information may be attached;
- LOD 400 – detailed assemblies: the BIM element is graphically represented as a specific system, object or assembly regarding size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information; non-graphic information may be attached;
- LOD 500 – As built (AIA, 2013): the BIM element is a field-verified representation regarding size, shape, location, quantity, and orientation; and non-graphic information may be attached.

The Royal Institute of British Architects specifies the LOD according to the phase of the product development (RIBA, 2013). The level of detail may be 2 - concept stage; 3 - developed design; 4 - technical design; and 5 - construction (NBS, 2015).

Identifying the right LOD for the BIM model is crucial for the purpose of its use and to achieve the planned value-added (Leite et al., 2011; Luth, Schorer, & Turkan, 2014). Also, increased the LOD "does not necessarily means more modelling work", which sometimes is beneficial to support decisions during design and construction (Leite et al., 2011).

2.5.3 The synergy between Lean & BIM

The lean construction management paradigm can be implemented without any technology. However, some technological tools can support its implementation (Sacks, Korb, & Barak, 2018). The synergy between Lean and BIM started to be explored by scholars in one article entitled "The interaction of Lean and Building Information Modelling" (Sacks, Koskela, Dave, & Owen, 2010a). In the latter paper, interactions between 24 Lean Construction principles and 18 BIM functionalities were analysed. The authors concluded that it is highly recommended to implement Lean Construction and BIM concurrently as most parts of the interactions are beneficial (Sacks et al., 2010a). One of the negative interactions concerning the BIM and Lean interaction relies on the need to produce a large amount of information such as design solutions, drawings and alternative plans, sometimes highly detailed (Sacks et al., 2010a).

Therefore, to achieve a successful introduction of Lean and BIM, both processes must have compatible workflows (Sacks et al., 2018). Some software emerged integrating Lean and BIM for the construction management, such as VisiLean and KanBIM (Dave, Boddy, & Koskela, 2011; Gurevich & Sacks, 2014; Sacks, Radosavljevic, & Barak, 2010b). Bhatla and Leite (2012) developed a framework to integrate BIM with the LPS. The work was expanded in the context of a mechanical contractor perspective on how to improve the workflow of complex and fast-track projects through the integration of BIM and LPS (Tillmann & Sargent, 2016). Another work improved the framework BIM and LPS based on two case study implementations (Toledo, Olivares, & González, 2016).

Although these works demonstrate many initiatives to deploy BIM and Lean in construction projects, few researches study how the BIM models should increase the level of development along the design development stages until they reach construction. Svalestuen, Knotten, Lædre, and Lohne (2018) identified that the increased use of BIM in construction projects imposes new challenges for the design planning and control. The BIM objects can have different levels of development, which is also an additional challenge for planning the design process (Hooper, 2015).

Svalestuen et al. (2018) developed a model integrating the product development stages with the LOD of BIM models (Figure 42). In their model, the detailed design stage is divided into minor phases following the construction sequence (foundation, structure, façade and inner work). The cross-functional designer's team (structural engineers, MEP engineers and architects) is responsible for increasing the BIM model's information richness in different levels of development along the minor phases. This model, based on a stage-gate approach, is used as a decision plan to plan the design production.

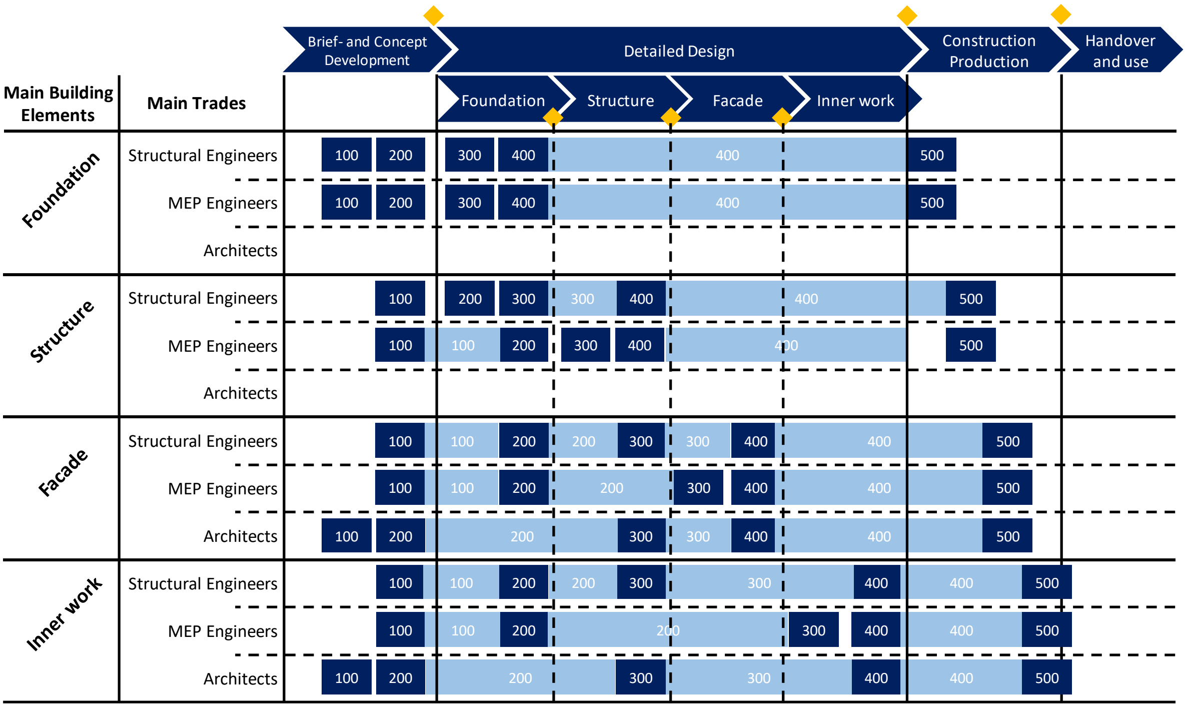


Figure 42: Conceptual model of workflow in a LOD-decision plan (Svalestuen et al., 2018).

The construction companies are already embedding the BIM within the construction sites through the BIM-stations (Vestermo, Murvold, Svalestuen, Lohne, & Lædre, 2016) or BIM-kiosks, first used by Skanska (Bråthen & Moum, 2016). The BIM-stations are computer terminals on-site that share with workers the real-time updated BIM models. They are proven to enhance productivity, mainly for the MEP workers (Bråthen & Moum, 2016).

2.5.4 Conclusive Discussion on BIM

It is crucial for the companies to have their data integrated through different sectors, even when using a different software system to develop their activities. The integration of data can save time and costs in the same company, or among different stakeholders in a project. However, it is necessary to create a new process of project management in order to integrate people into making the decision jointly and to share data.

The level of maturity of BIM is correlated with the level of overlap that can be performed between design and construction activities. In the BIM stage 2, the overlap is possible, but it requires different contract forms rather than the traditional ones.

Recent discussions around the level of development of the BIM models show that the input of information is not the same for different disciplines throughout the product development. The LOD may be pulled by the construction sequence (foundations, structure, façade and inner work). It is the first time that the LOD is embedded in the design production planning, which adopts the stage-gate and cross-functional teams. According to the design progress across the phases, more information is necessary to be incorporated in the BIM models, which guarantee no wastes in the modelling process.

2.6 LITERATURE REVIEW CONCLUSION

The literature review tackled different perspectives of projects with overlap between design and construction stages: from the macro view, presented in section 1 of New Product Development, passing through the interface design-construction, design management, and then to the construction management. BIM was also discussed as a supportive information technology and process to provide fast and reliable design information for downstream dependent activities.

Overlapping sequential and dependent design and construction activities

Contrary to the researches regarding overlapping dependent and sequential activities, which use the concept of sensitivity and evolution (Bogus et al., 2011; Bogus et al., 2006; Hossain & Chua, 2014; Krishnan et al., 1997; Levina & Vaast, 2008; Srour et al., 2013), this thesis uses the TFV theory (Koskela, 2000) to consider flow activities in the interface D-C to plan the overlap of activities. The limitations on these researches are the neglecting concepts as a reduction of production batch size, reduction of cycle time, capturing user's requirements, pull production, and so on (Liker, 2004; Ohno, 1988).

Instead of releasing incomplete information to construction, with calculations without considering all activities in the interface between design and construction, why not break the production batch of the design based on the building chunks (Tiwari & Sarathy, 2012) and then pull by construction (Kiiras & Kruus, 2005)? The crews on the construction site are the final customers of the value chain (design, procurement, suppliers, contractors, subcontractors). Consequently, why not pull all the chain through the construction plan, thus design could be produced and delivered smoothly. By removing the overlap of activities with large production lots, the design could produce detailed design, specifications, design for production and procurement according to the needs of downstream activities.

Management of Complex Projects

Another essential foundation to understanding the production planning in design and construction overlap is the complexity of project management. The variations in the management focus throughout the NPD are trivial for the success of projects (Austin et al., 2002). From negotiation, at the early stages of the NPD, to coordination at the final stages, the production planning must be adaptable to offer space and tools to enable collaborative decision-making and coordinate the workflow of multiple project teams. Correspondently, the structural complexity increases across the NPD process such as the LOD of BIM models. In this correlation, the level of information input in models is higher because the level of detail of the models is also higher. It is also an important concept to take to the study's development.

Design Management

Design changes with negative iterations (Ballard, 2000d) can increase the risk of success of the whole project. For this reason, the necessity to make the right decisions, especially in the design stage, is critical for the project performance. In CE and lean design management, there are many methods by which to capture the user's requirements, develop optimal design solutions, and deliver more value for clients that could be applied in the context of overlapped projects.

Construction Management

Lean construction methods to PPCa were implemented in a variety of case studies, and researches have reported the benefits and efficacy of them. Compared to lean design management, lean construction management is more consolidated in the AEC industry. However, the method used in construction that can look at the design stage is the LPS, more precisely through the pull planning technique.

The LPS lacks the methods to plan the integrated design and construction, mainly because it was developed in the construction stage. Hence, there is a need to investigate how to plan design and construction in an integrated plan where the different nature of both processes is considered.

The previous works presented in the tools subsection explored the use of LOB, flowline and TTP structuring. The achievement of the common takt time for production activities can also be exploited in the design processes (Holm, 2014; Tiwari & Sarathy, 2012). Then, with a construction plan devised using LBS tools, the pull flow (Bolviken et al., 2010; Kiiras & Kruus, 2005; Sivaraman & Varghese, 2016; Viana, 2015) can be triggered by the needs of small construction batches such as building locations. It could promote the reduction of the batch size in all upstream activities of the value chain until the DP (interface between push and pull flows).

The literature review outlined two conceptual models to support the development of the studies. The first model exposes the idea that complex projects should be integrated vertically and horizontally and involves the three levels of designing from Young's model, which advocates the design of the context as a holistic view of how the project should be, designing context as the systems that compose the whole, and the design in context as the operation of the all systems to produce the product (Young, 2008). The model was adapted to the context of the project, rather than only the design process. Figure 43 represents the tools and process from the literature review in each of the project level.

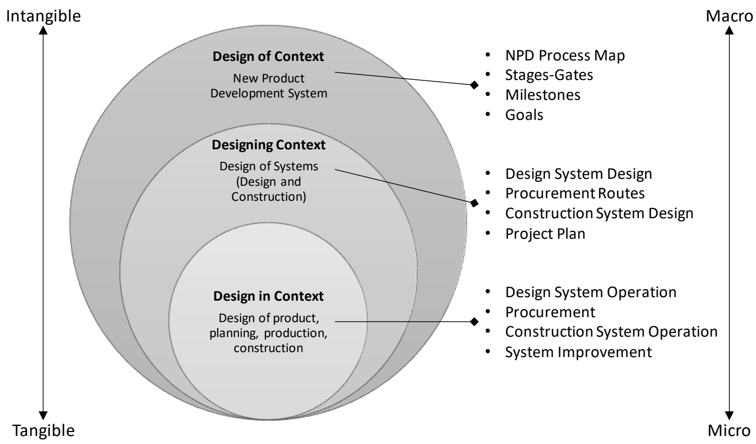


Figure 43: Project management should tackle from macro to micro planning.

Highlighting the management of a complex project with overlap between the design and construction stages, Figure 44 demonstrates the variations in the uncertainty and structural complexity throughout the NPD. In projects overlapping its stages, the structural complexity is anticipated through much negotiation to define the goals and expected product. Until this moment, the cross-functional teams are dealing with high levels of uncertainty and designing by pull techniques. Along with the product development, the levels of uncertainty reduce while the structural complexity increases up to the moment when negotiations surrounding the product reduce. Collective decisions among the team members reduce throughout the design fixities and phases. At the moment when the cross-functional teams do not need to make collective decisions, i.e. negotiate, their focus turns to coordinate the workflow. Herein is the interface between push and pull workflow, and should be conducted by the construction management.

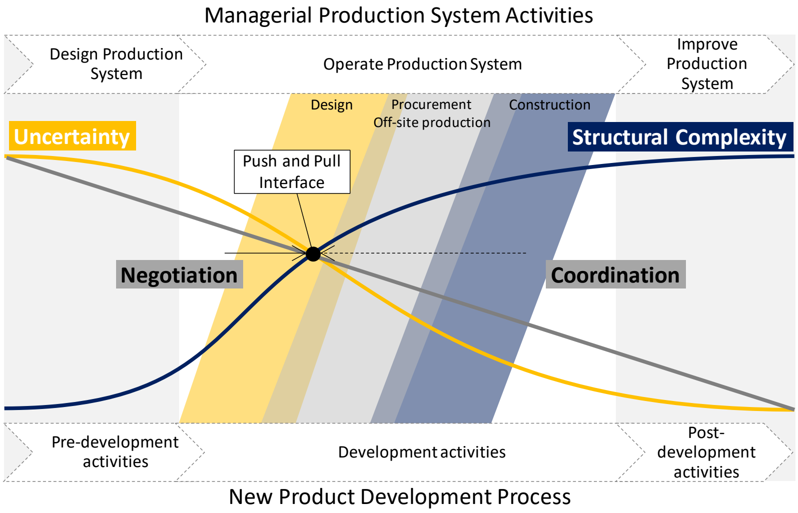


Figure 44: Model that combines the NPD with overlap between design and construction stages with the production management activities over the changing nature of construction project complexity.

3 RESEARCH METHOD

This chapter describes the research method adopted in this investigation. The first and second sections present the context of this research and the researcher's methodological choices, respectively. The third section discusses the research design. The fourth section describes the research studies and the research process carried out during the thesis development.

3.1 CONTEXT OF THE RESEARCH: RESEARCH IN MANAGEMENT

Research in management uses a range of theoretical content from other disciplines and interactions between theory and practice in order to produce new knowledge (Saunders, Lewis, & Thornhill, 2016). According to Saunders et al. (2016), there are three modes by which to produce knowledge in management research: 1) Knowledge created by academics' interests with no emphasis on practical application; 2) Knowledge created based on and to solve practical managerial problems, although focusing on creating theoretical knowledge; 3) Knowledge produced with a focus on the human condition as it is and as it might become, i.e. the findings of management research might have relevance for a society, and not only for the actual managerial practice.

Although this intrinsic relationship between practice and theory exists, there is a gap between what is practised by managers in everyday life, and what theories claim as ideal practice. Additionally, management research offers stylised and abstract models to increase and assess project performance, which might be unhelpful in changing work practices as these models were based on a rational logic that ignores specific contexts (Sandberg & Tsoukas, 2011). For this reason, the practitioners may say that the theory is irrelevant for practical actions (Gill, Johnson, & Clark, 2010; Koskela, 2017).

Management research not only needs to provide findings that advance knowledge and understanding, but it also needs to address business issues and practical managerial problems (Koskela, 2017; Saunders et al., 2016). Moreover, the researcher believes that research with a close relationship with practice can produce better solutions for management, besides theoretical knowledge. Therefore, in order to try to fill this gap between theory and practice, this investigation follows the second mode to produce knowledge in management research, i.e. the researcher is interested in creating theoretical and practical knowledge based on, and to solve, practical managerial problems.

Then, so as not to produce irrelevant research for the construction management practice, the researcher is adopting a set of research philosophies, approaches, strategies, methods and techniques that better deal with construction management practices and fill the gap between theory and practice.

3.2 RESEARCHER'S METHODOLOGICAL CHOICES

Coherence in the research method is critical for the reliability of any research. The research method is a set of procedures used to conduct a research. Considering the context of this research, i.e. construction management, the methodological choices in this investigation are justified as those that best fit the researcher’s experience in lean construction, the availability of studies, and the design science research approach.

The research framework developed by Saunders et al. (2016) is used to explain the research method. In summary, the position of this research according to the researcher’s methodological choices is presented in Figure 45.

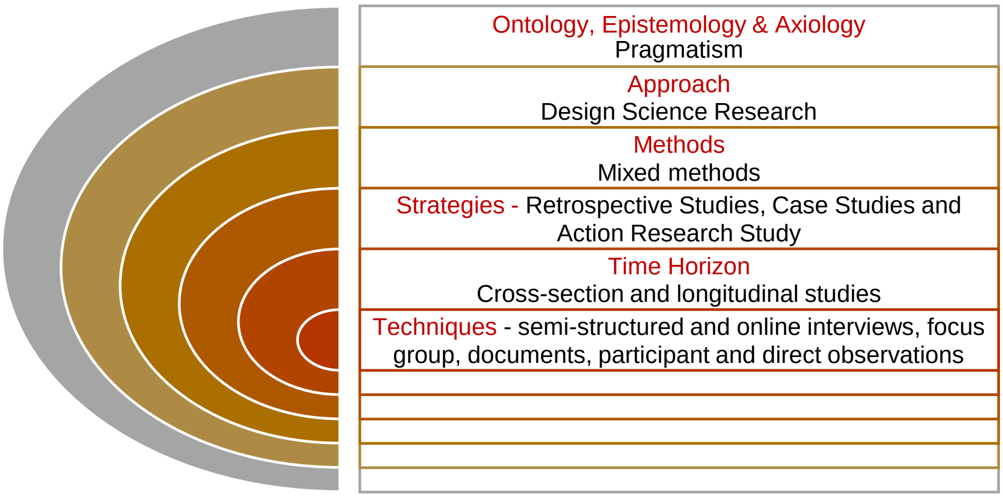


Figure 45: Researcher’s methodological choices in the research onion using Saunders et al. (2016) framework.

Construction management is a relatively new field of research practices compared to the established domains (Dainty, 2008). In construction management, there is the study of the organisational environment as a social science branch, but also the study of engineering as a natural science, i.e. it studies both physical and social phenomena (Dainty, 2008). For that reason, different theories of knowledge are applied, such as positivism and quantitative methods, which are recently being combined with interpretivism methods to enrich the researches with the human perspective (Dainty, 2008).

The combination of different epistemological and ontological research philosophies is called pragmatism. It was used in this investigation because it is action-driven, and allows the researcher to choose the most suitable philosophical positions to address a particular research question (Saunders et al., 2016). The philosophical positions of pragmatism are described in Table 10.

Table 10: Philosophical positions of pragmatism.

Pragmatism			
Ontology	**Epistemology**	**Axiology**	**Data collection techniques**
Phenomena can be both independent and/or constructed by the social actors, including the researcher. Multiple reality. View chosen to best answer the research question.	Both observable phenomena and subjective meanings. Focus on practical applied research, integrating different perspectives to interpret data.	Values from both objective and subjective points of view to interpret results.	Mixed or multiple methods, quantitative and qualitative data.

The research question concerns a **generic practical problem** across the construction industry, and the design of its **solution** is created within **specific organisational contexts** and relies on **social actors** to be effective. Based on this scenario, the researcher’s views of the research problem include the objectivist and constructivist realities, which are explicated in Table 11.

Table 11: Researcher's view of construction management according to research philosophies.

Pragmatic view	Construction Management Reality
Objectivism	Management functions are similar in all organisations. The organisation's culture is treated as a variable, and it is something that the company has (Saunders et al., 2016).
Constructivism	Organisation's culture is created and re-created by the social actors through a complex array of phenomena: the meanings attached to the phenomena must be understood to understand its culture (Saunders et al., 2016).

In pragmatic research, the practical consequences of the research findings are also significant. Therefore, by considering the relevance of practice as a means of research and also a phenomenon to be studied, the researcher conducted this investigation work as "practice-based research", which means that the creative production of the output of this investigation can also be understood as a research method.

3.2.1 Practice-Based Research

Practice-based research is a method undertaken to generate new knowledge about and through the practice. It is used in areas such as creative arts, design, architecture, education and health. Research by design is becoming more central as a new mode to produce knowledge due to present insider perspectives related to real-life contexts: a type of knowledge that can be found only within design practice (Sevaldson, 2010). In case studies, the researcher is an external observer of the practice, instead of in practice-based research, where the researcher develops participatory research through his/her own practice as a means for investigation, and "subject for reflection and knowledge production" (Sevaldson, 2010).

In practice-based research, the practitioner is also the researcher who: (1) creates the artefact; (2) documents the process; and (3) reflects: contextualises and interprets the working processes (Mäkelä & Nimkulrat, 2011). The processes of making and reflecting on generate knowledge (Mäkelä & Nimkulrat, 2011; Sevaldson, 2010), which is called "creative discovery" by Fleishman (2009) as cited in Mäkelä and Nimkulrat (2011).

What differentiates the practice-based research from the everyday practice is the transferability of the understandings achieved at the end of the investigation (Candy, 2006). Herein, practice becomes an integral part of the method, and the outcomes must be demonstrated by documentation and reflections about the creative process taken throughout the research (Mäkelä & Nimkulrat, 2011). The systematic documentation is essential in order to communicate, make explicit and accessible the researcher's learns (Scrivener, 2000), and the reflection upon practice must occur in and on action (Schön, 1991).

Another term for research developed based on, and for, practice is the practice-oriented research (Dul & Hak, 2008). Herein, the authors define research that aims "to contribute to the knowledge of a specific practitioner". The practitioner can be defined as a person or group of persons, or even a company, business sector, nation. The knowledge produced will support the practitioner to solve a problem identified in practice (Dul & Hak, 2008). By contextualising the real-life problem to this research, we have a failure in construction project management regarding the production coordination of design, off-site elements (supply) and construction activities in projects with an overlap of design and construction stages. The solution to this problem will provide knowledge for the construction project managers and companies to better coordinate the whole project participants' production, and then increase the chances of delivering projects within the defined quality, time and cost.

Practice-based or practice-oriented researches fit in pragmatism philosophy, as the latter is concerned with the effectiveness of thinking and doing (Cassell, Cunliffe, & Grandy, 2018). According to Schön (1991) and his theory of design as a reflective practice, the designers' "knowing-in-action" is a practical knowledge built throughout their professional work and cannot be formulated in propositional terms. The professional knowledge is developed within action without purpose and, by means of the "reflection-in-action", the practitioner gains new knowledge. Instead, when the professional reflects on his/her previous action using reasoning, he/she is creating knowledge with purpose (Schön, 1991).

This experimental learning was also discussed by Kolb (1984), who highlights the transformation of information from a concrete experience into knowledge: an abstract conceptualisation that is possible by means of observations and reflections on the experience. As a result, this new knowledge is applied in new situations to test the implication of the concept. This process is continuous and builds on the practitioner application and reapplication of knowledge.

The reasoning logic in Kolb's model is further clarified in the work of Kayes, Kayes, and Kolb (2005), in which the inductive reasoning processes are used for learning from concrete experiences (practice) to generalisation and abstract conceptualisation (theories). The opposite occurs when the practitioner uses deductive reasoning processes for learning from the abstract concepts (theories) towards concrete experience (practice) (Figure 46).

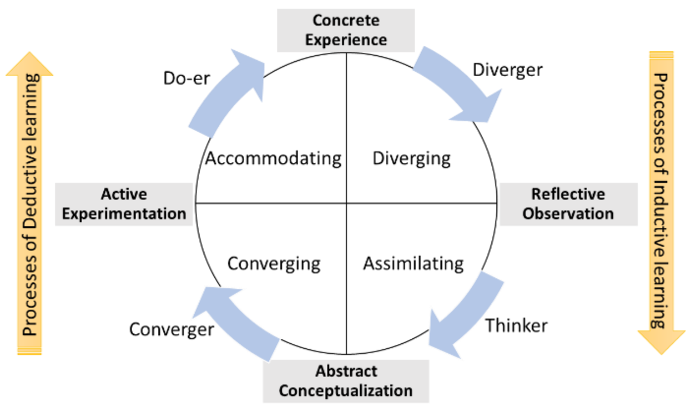


Figure 46: Learning cycle: combination of Kayes et al. (2005) and Kolb (1984) works.

Every practitioner action is based on his/her prior knowledge and experience. The "knowing-in-action" is influenced by theories known by the professional. In research, theories have an important role in determining the research methods used in an investigation: "Theories influence how we understand and explain what is going on around us and how we practically do things" (Gill et al., 2010).

The research approach that better fits in pragmatism philosophy and practice-oriented research in construction management is the Design Science Research (DSR). This uses a similar approach of Kolb's model in order to analyse practical and research problems, design a solution and develop it through cycles of testing and redesign (J. van Aken et al., 2016).

3.2.2 Design Science Research

In contrast to the typical investigations of the natural sciences, which develop theories that explain and predict natural phenomena, the design research paradigm "dares to invent virtual artefacts that intervene to support and improve real phenomena" (Purao, 2002). As opposed to natural and social sciences, the DSR is framed in the science of the artificial, which is a "body of knowledge about artificial (man-made) objects and phenomena designed to meet certain desired goals" (Simon, 1996). According to van Aken (2004), the DSR occupies a middle ground between descriptive theories and practice and typically involves social and technical systems. As pointed out by Hevner (2007), DSR has an application domain in people, organisational systems and technical systems. The product of design, i.e. the artefact, can be studied using positivist or interpretive positions (Purao, 2013).

Some researchers conceptualise the management research as design science rather than social science (Saunders et al., 2016). The contribution of the DSR is the possibility to fill the gap between the theory and practice through the development of an artefact (Rocha et al., 2012). This middle ground between practice and theory is necessary in order to develop a valid and reliable knowledge to support practitioners in organisational/business to devise solutions to problems (van Aken, 2005).

The fundamental characteristics of constructive research are (Lukka, 2003):

1. Focus on relevant real-world problems to be solved in practice;
2. Produce an innovative artefact to solve an initial problem from the real world;
3. Implement the developed artefact, and then test its practical applicability;
4. Involve the researcher and participants as a team, in which learning is based on experimentation;
5. Explicitly connect to a prior theoretical knowledge; and
6. Pay attention to the reflections of empirical findings based on the theory.

Vaishnavi and Kuechler (2015) state five stages: (1) awareness of the problem; (2) suggestion; (3) development; (4) evaluation of the artefact; and (5) conclusion of the research that contributes to the stage of awareness of the problem. In DSR, the processes of "be aware of the problem, build a solution for it, and evaluate it" are a circumscription cycle, which allows the researcher to learn when the solution works or not (Vaishnavi & Kuechler, 2015).

The pragmatic reasoning for DSR is simple and, as suggested by van Aken, Chandrasekaran, and Halman (2016), should be a one-liner, such as the CIMO-logic (Denyer, Tranfield, & Aken, 2008): "for this Problem-in-**C**ontext it is useful to use this **I**ntervention, which will produce through these **M**echanisms this **O**utcome".

The DSR may have different outcomes according to the authors. Lukka (2003) points out two main contributions in constructive research: (1) the developed artefact (designed solution), based on its usefulness to the organisation and contribution to existing knowledge; and (2) the application and development of theoretical knowledge throughout the study. The theoretical and practical contribution of the results of such research may be satisfactory from the point of view of everyone involved in the research project (Lukka, 2003). Notwithstanding, some research may have limited results at the practical level, although with relevant theoretical implications (Lukka, 2003). A summary of the outcomes of the DSR is shown in Table 12.

Table 12: Possible outcomes of the DSR.

Outcomes	Description	Author
Constructs	The conceptual vocabulary of a domain	March and Smith (1995) and Hevner (2007)
Models	A set of propositions or statements expressing relationships between constructs	
Methods	A set of steps used to perform a task – how-to knowledge	
Instantiations	The operationalisation of constructs, models, and methods	
Better theories	Artefact construction as analogous to experimental natural science	Purao (2002) and Vaishnavi and Kuechler (2015)
Technological rule	"a chunk of general knowledge, linking an intervention or artefact with a desired outcome or performance in a certain field of application", grounded in scientific knowledge	van Aken (2004)

It is part of the DSR that the evaluation of the outcomes are generated during the research process. In the design cycle proposed by Hevner (2007), the construction of the artefact and its evaluation is an iterative process which provides feedback to refine the design further (van Aken et al., 2016). The findings are assessed according to the value or utility to a community of users. However, it can be evaluated by its effectiveness and other relevant criteria (van Aken et al., 2016). In order to prove that the solution works, the researcher can use the stakeholders' perceptions, measurement, simulation, and other evidence. Some authors proposed different criteria for the artefact's evaluation (Table 13) in which the artefact is tested in different contexts to analyse its generalisation (van Aken et al., 2016).

DSR has further criteria to evaluate the research result such as to assess its generalisability for different contexts, which supports a pragmatic validity and the practical relevance (van Aken et al., 2016). The DSR seeks to provide generic design to be applied in different situations and not just for case-specific improvements (van Aken et al., 2016).

Table 13: Several types of assessment in DSR.

Different types of design assessment in DSR		
March and Smith (1995)		
Models: "fidelity with the real-world phenomena, completeness, level of detail, robustness and internal consistency"	Methods: "operationality, efficiency, generality, and ease of use"	Instantiations: "efficiency and effectiveness of the artefact and its impacts on the environment and its users"
Kasanen et al. (1993)		
Weak market test: adoption of the artefact in an organisation scale	Semi-strong market test: the solution was widely applied by companies	Strong market test: the business units had better results by using the design solution
van Aken et al. (2016)		
Alpha field testing: design tested by the designers themselves	Beta field testing: design tested by third-party stakeholders	"Peer reviews" or focus group discussions with experts, operators and other stakeholders

Generalisation in DSR occurs when the generic design can be transferred to other contexts and tested without losing its basic effectiveness (van Aken et al., 2016). The author highlights that, due to the significant social components of the studies, the researcher should use cross-case analyses to strip the design down to its generic essentials: what is specific to the context of the specific instantiation and what is generic and transferable (van Aken et al., 2016).

The Hevner's model (2007) was used to contextualise the DSR in this investigation. In his model, Hevner divides DSR into three parts: Environment; Design Science Research; and Knowledge Base. In the Environment, there are the practical domains: people, organisational and technical systems, plus the problems and opportunities. In this research, the Environment is represented by the studies, where the practice occurs and the solution designed is tested. On the other hand, the Knowledge Base is constituted by scientific theories, researcher's experience and meta-artefacts. The DSR is in the middle ground between practice and theory, where the artefact is designed and evaluated.

As a result, in this work, the researcher used the literature review and her professional experience as a knowledge base to design solutions for the practical problem faced in the studies of the thesis. The knowledge base assures the rigour cycle of the theoretical contributions of the artefact, while the study requirements and field tests enable the practical relevance of the artefact. The adaptation of Hevner's model to this thesis is demonstrated in Figure 47. Although DSR can provide many different types of outcomes, in this thesis the central artefact designed is a model that was created and evaluated in the studies.

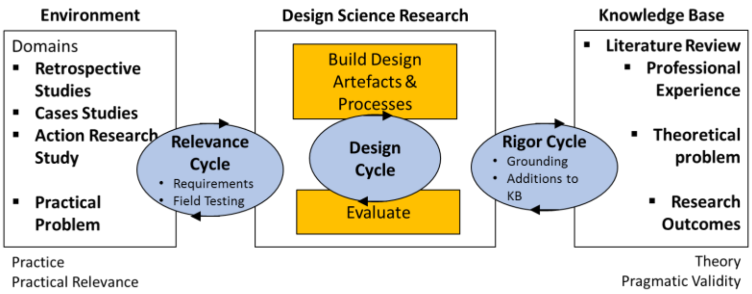


Figure 47: DSR model used in this investigation, based on Hevner (2007).

3.2.2.1 Justification for adoption of DSR

In the specific field of the construction management, the DSR is a mode of research that uses the practice as a source for new knowledge creation. The DSR intends to build an artefact to solve a practical and organisational problem where the researcher is immersed in practice. Thus, it is a wide research approach that accommodates different research strategies to pragmatically create new knowledge. Its main purpose is to generate an artefact which carries knowledge about the practice, and how to improve it, while comprising theoretical contributions.

Among other research approaches, the choice of the research approach is highly influenced by the research strategies deployed for conducting the investigation. As a result, DSR was chosen for the development of this research due to its suitability to the context of high uncertainty and different types of empirical studies. The researcher had different levels of interference in the studies, which had different time scales and project characteristics. DSR enabled the researcher to collect the necessary data in order to pragmatically answer the research question and progressively evaluate the artefact.

3.2.3 Research Methods

The research method used in this investigation was the mixed methods. It combines quantitative and qualitative methods in a way that is best for a specific research project (Matthews & Ross, 2010). Sometimes, to understand a phenomenon holistically, it is necessary to look at it from different perspectives, and so different types of data and methods are used. Choosing mixed methods is a pragmatic decision.

Quantitative research methods are concerned with collecting and analysing data in a structured way and for it to be represented numerically (Matthews & Ross, 2010). Qualitative research methods are concerned with stories and accounts including subjective understandings, opinions, feelings and beliefs (Matthews & Ross, 2010).

In this investigation work, both methods were used and combined. However, the dominant method was the qualitative research. The benefits of using mixed methods are, according to (Saunders et al., 2016), the generalisability, diversity, problem-solving, and confidence. The latter authors point out that mixed methods combine with pragmatism philosophy as well.

3.2.4 Research Strategies

In this research, data was generated by three different sources: (a) previous professional experience of the researcher in construction project management; (b) construction project managerial practices of companies; and (c) implementation of managerial practices in a construction project. Due to this variety of sources, the researcher used three different types of research strategies with different purposes and time horizons: 1) Retrospective practitioner studies (Sevaldson, 2010); 2) Case studies (Yin, 2014); and 3) Action research study (Susman & Evered, 1978).

3.2.4.1 Retrospective Practitioner Studies

The retrospective practitioner study is named by Sevaldson (2010) as a type of prototypical design research process. The researcher is the practitioner who looks back at his/her own practice and analyses it retrospectively (Sevaldson, 2010). This research strategy may be descriptive, process-oriented, abductive and uses the researcher’s perspective to make a tacit knowledge explicit (Sevaldson, 2010). The time distance from when the phenomenon occurred and when the researcher will analyse it helps the re-understanding of the practice. On the other hand, the researcher may forget some data.

In this investigation work, the researcher looked back at her own practice as a lean consultant in three different projects. The researcher analysed it retrospectively as longitudinal studies to make her tacit knowledge explicit. Reflections on the practice of design and construction interface management were used to frame the research problem, understand it deeply, and design the first proposition of solution.

Here, personal records and documents were used as the principal data source. Due to the difficulties in obtaining feedback from the projects' participants, the solution was evaluated by lean experts.

These retrospective studies demonstrate any axiomatic bias the researcher might have introduced in the research, as well as to solidify research methodological choices around practice and development of methods and tools. Importantly, the methodology for this thesis relies on the fact that the researcher has a good understanding and ability to interpret context in the prospective studies. These retrospective studies demonstrate these competencies through the research reflections and the correlations between practice and theory.

3.2.4.2 Case Studies

The case study strategy intends to explore "in detail and great depth" a case (Matthews & Ross, 2010). The case may refer to a person, group, an organisation, process, and so on (Saunders et al., 2016). The study boundaries must be defined in the case to study a phenomenon in its real-life context. It often has descriptive, exploratory or explanatory purposes, and may be used to test or build theories. Different types of data are gathered in the case studies, from qualitative to quantitative data.

In this thesis, two cross-section studies were used to describe and explore how other companies in the construction industry solved the (research) problem. The researcher reflected on others' practices of project management regarding the coordination of designers, suppliers and builders' activities.

3.2.4.3 Action Research Study

Action research strategy is carried out by the practitioner in "an attempt to improve practice through a systematic cycle or cycles of planning, doing and reflecting" (Hammond & Wellington, 2012). According to Eden and Huxham (1996), it also promotes social changes in the organisation systems while producing new knowledge. The action research is developed in collaboration with the members of an organisation in order to solve a practical problem. It should be carried out with activities of (Susman & Evered, 1978): (a) diagnosing; (b) action planning; (c) action taking; (d) evaluating; and (e) specifying learning.

One action research study was carried out in a construction project of a company facing similar challenges of management such as the research problem. Then, a longitudinal study within this organisation was prepared, in which the researcher, through an iterative process, identified some management issues, planned an action, implemented it and evaluated it in order to develop a solution for the company's problem. Although the repeatability of the cyclical process of the action research study is crucial, in this investigation it was limited due to external factors affecting the project.

3.2.5 Data Collection Techniques

DSR does not prescribe any limits on the data collection techniques. As a result, evidences were collected in the studies through different sources: semi-structured interviews; online interview; focus group; documental analysis; participant observations; and direct observations. The decision of these techniques in each study relied on the availability of the researcher's resources and participants' time.

The amount of data collected relied on achieving a saturation point in theoretical contributions, where no new data provided additional results. In general, the interviewees were professional practitioners at a senior management level who had been involved in lean construction projects and played significant roles in the project management process. They had the potential to provide reliable and high-quality data from different perspectives. Moreover, the documents collected corroborated with the speeches of the study participants and illustrated how the management activities had been operationalised in the projects.

By crossing the study's data, the researcher achieved a measure of external validity, together with the participants' opinions and the researcher's own understanding of integration between design and construction through the production planning and control.

3.2.5.1 Semi-Structured Interviews

Interviews are conversations between the researcher and the participants in the research, or interviewees. This technique of data collection is one of the most important sources in case studies (Yin, 2014). During the interview, the researcher makes explicit the rules of conversation: the subject of discussion, duration, and roles that each party will take (Hammond & Wellington, 2012). Interviews promote flexibility and interactions between the interviewee and the researcher. The researcher "goes deep in capturing participant's thoughts, values, feeling and perspectives" (Hammond & Wellington, 2012).

In this research work, the semi-structured interviews were used to guide the researcher to collect primordial data through the structured questions, while the open questions enabled the researcher to deepen the investigation in particular subjects judged essential to understand.

The semi-structured interviews were also used in the studies' evaluation process of the studies. The interviewees were scholar-experts in lean construction, and studies' participants such as a real estate manager, project manager, construction manager, design manager, designers and constructors.

The interviews lasted from 60 to 120 minutes and were recorded as digital audio files, which were transcribed to text format.

3.2.5.2 Online Interview

The online interview technique may be synchronous or asynchronous (Quinlan & Zikmund, 2015). In the first technique, the question is answered immediately by the interviewee, in chatrooms for example. In the second one, the interviewee has time to answer the question as the interview is not being conducted in real time.

In this thesis, the researcher used the online interview in the action research study to collect the participants' opinions about the workshops, development of tools and implementations made by the researcher together with the company's employees. An email was sent to all the study participants requesting them to write a testimonial about their experience.

3.2.5.3 Focus Group

Focus group is a type of group interview, but the interviewees concentrate in depth on a particular topic "with an element of interaction" (Walliman, 2017). In this thesis, the focus group was applied at the end of the case studies to evaluate the designed solution for the research problem. Some standardised questions were used to guide the discussion among the study participants.

3.2.5.4 Documents

Documentary information is relevant to every case study, and it can comprise a variety of documents, such as letters, agendas of meetings, reports, communication emails, among others (Yin, 2014). The most important use of documents in case studies is to corroborate and increase the variety of evidence sources (Yin, 2014). The researcher had to be careful with documents because, commonly, they were elaborated for different purposes than the case study. Hence, they do not express the truth.

The documental analysis was used in all studies to understand how the companies were managing the production by designers, suppliers and builders. A variety of documents were collected such as drawings, design specifications, emails, schedules, last planner system spreadsheets, photos, figures, among others.

3.2.5.5 Participant Observations

In the participant observation, the researcher is not only a mere viewer. Instead, he/she is also playing a variety of roles in the fieldwork, or participating in the actions being studied (Yin, 2014). This data collection technique allows the researcher to be inside the case, rather than be an external observer. Hence, the researcher can manipulate minor events, which, in other techniques, do not occur (Yin, 2014).

In this thesis, participant observations occurred during the planning and design meetings in the retrospective practitioner and action research studies.

3.2.5.6 Direct Observations

Direct observations are an opportunity to collect data from the real world, through the observation of social or environmental conditions such as meetings, sidewalk activities, factory work, and other events (Yin, 2014). This technique can be viewed as additional evidence to be used to corroborate with other techniques applied, e.g. interviews.

The researcher had the opportunity to use direct observations in construction and office site visits in only one case study.

3.2.6 Data Analysis

Subsequent to the data collection, the researcher analysed the data and separated them according to the management actions phase. Six categories were used based on the literature review: 1) Design system design; 2) Design system operation; 3) Design system improvement; 4) Construction system design; 5) Construction system operation; and 6) Construction system improvement. However, after case study 4 and 6, three new categories were added: 7) Project system design; 8) Project system operation; and 9) Project system improvement.

The categorisation facilitated the analysis of the applied tools, IT, processes and people involved in each study. Although the participants deployed different tools, they developed similar processes to enhance the design and construction management in an integrated fashion.

3.3 RESEARCH DESIGN

The research process was divided into five phases related to the contributions to the model development (the artefact): 1) Literature Review; 2) Retrospective Practitioner Studies; 3) Case Study 4; 4) Action Research Study 5 and Case Study 6; and 5) Contributions. The phases where the studies were developed, i.e. phases 2, 3 and 4, followed the DSR steps proposed by Vaishnavi and Kuechler (2015): awareness of the problem; suggestion; development; evaluation; and conclusion. The research design is presented in Figure 48.

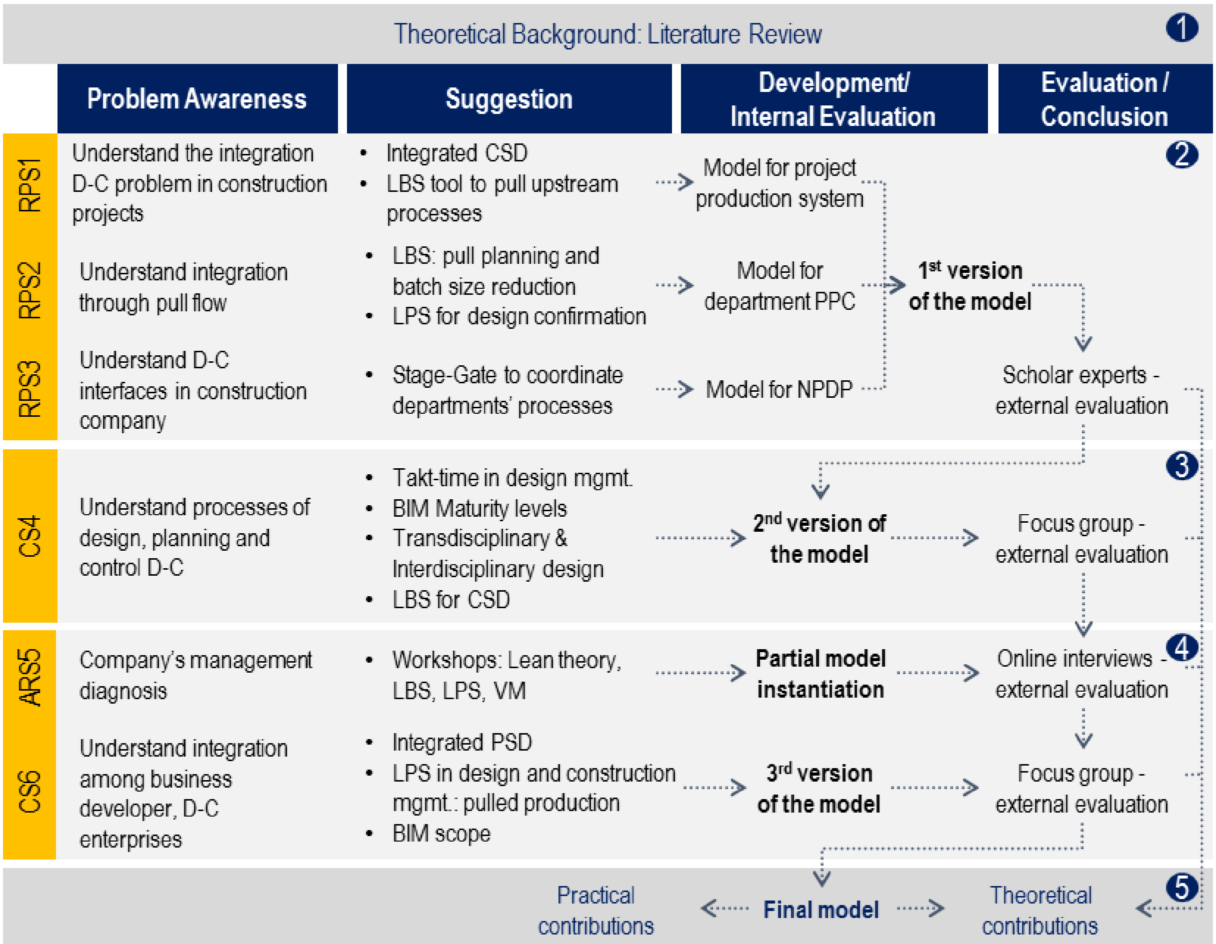


Figure 48: Research design.

The Problem Awareness occurred in the studies because the practical problem can only be identified in practice and its practical relevance established (van Aken et al., 2016). In Kolb's model (1984), the practice to recognise a problem is represented by the Concrete Experience and, according to Hevner

(2007), this process provides the requirements to be fulfilled by the solution. The studies were classified in Kolb’s model (1984) as Concrete Experience, where the researcher and practitioners applied their knowledge to solve real problems during the project execution.

The Suggestion step is where the researcher must reflect on practice and produce the design suggestion itself. It requires Reflective Observation (Kolb, 1984) to evaluate the suggested solution internally. The Development step can be compared to the Active Experimentation of Kolb’s model (1984), in which the suggested solution should be implemented in order to be evaluated in the real world. At this step, the practical contributions of the solution can be measured through an iterative process of design, evaluate and redesign. The Evaluation and Conclusion steps are very closely connected to the Abstract Conceptualisation, where the researcher must assess the practical relevance and pragmatic validity of research results, i.e. clarify the practical and theoretical contributions of the solution.

The **Phase 1 - Literature Review** was carried out throughout the whole period of the PhD in order to provide theoretical background about the research topic and, as a DSR, find out the theoretical gap of the problem. The research was based on the theoretical knowledge of lean project management, design and construction planning and control techniques, problems in the interface design-construction, just-in-time, pull planning, overlap activities, and so on.

The **Phase 2 - Retrospective Practitioner Studies (RPS 1, 2 & 3)** were developed to frame the research problem in different contexts and to reflect on the researcher’s practice to solve the problem and connect those studies to the theory. RPS1 shed light on the overall problem of lack of integrated management of design and construction stages in overlapped projects. The study was conducted in the context of a public construction project, where the researcher was managing the project and coordinating other companies, such as design offices, builders, suppliers, and so on.

In RPS1, the data analysed showed a strong attention to the Construction System Design activities. The latter was developed with participation of designers, contractors, suppliers and the researcher. The tools used were the Line of Balance (LOB) and the Supply System. The upstream activities in the product development process were pull planned. Thus, with this information, the researcher depicted a model for devising the project production system.

RPS2 was selected as a study due to its particular context of integration between design and construction in two construction companies’ departments. The data collected showed again the use of the LOB to pull plan the department activities regarding the customisation process. The planned activities were confirmed through the Last Planner used by construction. Thus, participants from both departments (customisation and construction) interacted and worked in collaboration facilitated by the LOB. This process was depicted in the model for the production planning and control of the customisation activities.

The RPS3 extended the context of two departments, by representing all the company’s areas and their relationship with the activities of design, supply and construction. The data collected through the interviews proved the existence of a complex net of information flow. The interviewees were questioned about the main process of the department, the information and document exchanged, tools used, milestones, joint decisions, and so on. The data provided insights on how to improve the new product development process which was depicted in a model.

The suggestions learnt from practice in these studies in conjunction with the literature review findings were converted in the **first version of the model** and in conceptual assumptions.

The initial design solution (model) was externally evaluated by scholar experts at the summer school presentation in the IGLC (International Group for Lean Construction) Conference in Greece, on 9 July 2017. The academics' opinions were used to refine the model.

In the following **Phase 3 - Case Study (CS4),** the researcher understood how other companies managed a construction project with an overlap of design and construction stages. The project was also the construction of a public facility headed by a state company. At the end of the data collection, a case study report was used to check the data accuracy with the Head of the project. The analysis of data collected, added to the feedback from the first model evaluation, resulted in the **second version of the model**. Its evaluation was handled through a focus group, in which the researcher presented the model to the case study participants, and then asked questions about its use in real projects.

Phase 4 - Action Research Study (ARS5) and Case Study (CS6) started with the partial instantiation of the model in the ARS5, and its further filed test. For that, it was necessary to diagnose the project managerial practices of the construction company. Three workshops were proposed to the companies' employees in lean theory and practices, such as Production System Design (PSD), Location-based scheduling (LBS) tools (line of balance), Last Planner System (LPS) and Visual Management (VM). Every week the researcher was implementing, jointly with the company members, the tools and practices at the construction site. At the end of the process, the participants were asked to evaluate the work developed and the utility of the new practices. For that, the respondents wrote down an email with testimonials.

Still in phase 4, the CS6 was conducted within a mature construction company that already deployed many lean practices. The focus of the study was to understand the collaborative planning that integrated design, supply and construction. The results of this study comprised the **third version of the model**, which had shown to be very similar to the second model, showing that it achieved a saturation point in data collection;

Phase 5 - Contributions, in which the practical and theoretical assessment of research findings will take place and contributions will be established in the model for integrating design, plan and control of design and construction stages in overlapped projects. The process of creating the final version of the model/solution will also create constructs, a method for its instantiation which enables the field test of the solution. All design produced in this research was by means of assessment, reflection and abstraction, and produced the theoretical contributions as well. The same evaluation process of the final solution implementation will contribute to practice.

3.4 THE STUDIES

The studies in this investigation have distinct roles, contexts and research processes. Each study occurred in different stages of design and construction management. Thus, it is essential to present the project managerial activities used in this research to facilitate the understanding of the contexts. The management of a production systems starts with the design of this system, followed by its operation and improvement (Koskela & Ballard, 2003). Both design and construction stages should be managed by these activities.

The design stages adopted in this research follow the RIBA plan of work (RIBA, 2013), which considered the phases of (a) concept; (b) developed; and (c) technical, plus the construction stage. Figure 49 presents the overlapped managerial activities in design and construction.

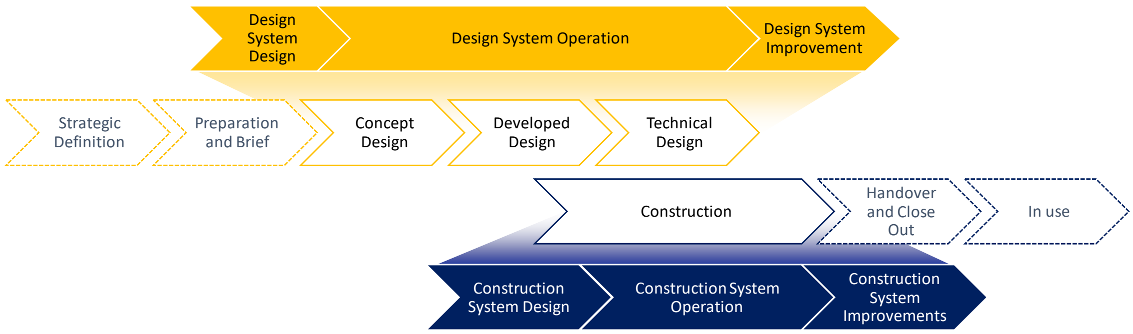


Figure 49: The context of this research.

The retrospective practitioner studies are the leading cases from the researcher's professional experience related to the overlap of design and construction stages. It is important to clarify that the researcher played different roles in the studies, which took place in different contexts and organisational environments. The retrospective studies occurred during the period when the researcher was working as a lean consultant in Brazil.

In the first study, the researcher was working at the leading project company, which means they had contractual power to interfere in other companies' management activities in order to conduct the project as desired. The second study was conducted when the researcher was working as a consultant for the residential units' customisation department and was in charge of the technical design for construction. The third study, carried out at the same construction company, focused on all the company departments that interacted with design, supply and construction.

The case studies were selected according to the level of management maturity of the companies and, no less important, the availability of the professionals and information. Case study 4 presented the same context as shown in RPS1, i.e. a leading company managing the project and stakeholders' activities. Case study 6 introduced the context of a construction company that was the general project contractor and could lead the design process, as well as closely interact with the project owners.

In the action research study 5, the construction company had an engineering and construction contract with the client in which they shared risks. The design office was subcontracted by the company to develop the detailed design.

In Table 14 is presented each study carried out in this research. The difference in the unit of analysis demonstrates the different perspectives and stakeholders' power for promoting the integration between design and construction management.

Table 14: Studies of this investigation.

Study	**RPS1**	**RPS2**	**RPS3**	**CS4**	**CS6**	**ARS5**
Type of Study	Retrospective practitioner studies			Case study		Action research study
Time Horizon	Retrospective longitudinal studies			Cross-section studies		Longitudinal study
Location	Fortaleza – Brazil			Bergen -Norway	Trondheim - Norway	Lemming - UK
Type of Project	Aquarium building	Residential units' customisation	Integrate company's sectors	Academy of Arts and Design	Commercial building	Highways depot area
Unit of Analysis	Project	Two company departments	All organisation's departments	Project	Company/Project	Company/Project
Purpose	Understand and frame the research problem; Reflect on researcher's practice; Evaluation; Design a solution			Wider understand of solutions and contexts; Evaluation; Refine a solution		Solution instantiation; Field test; Evaluation
Design Stages	Developed and Technical	Technical	-	Concluded	Developed and Technical	Developed and Technical
Design Managerial Activities	Design System Operation	Design System Operation	Design System Design	Design System Improvement	Design System Operation	Design System Operation
Construction Stage	Yes	Yes	-	Handover	Yes	Not initiated
Construction Managerial Activities	Construction System Design and Operation	Construction System Operation	Construction System Design	Construction System Improvement	Construction System Design and Operation	Construction System Design
Evidence Sources	Participant observation, interviews and documents			Interviews, focus group and documents	Direct observation, documents, interviews and focus group	Participant observation, documents and online interview
Output	1st version of the model			2nd version of the model	Final version of the model	Solution implementation and field test
	Theoretical and practical contributions					
Evaluation	Internal and external evaluation with academic experts through interview			Internal and external evaluation with studies' participants through focus group		Online interview with project participants

The studies took place throughout 2017. At the beginning of the year, the researcher gathered the available data from the RPS1, 2 & 3. It took four months to analyse all the data and devise the first version of the model. Then, in July, it was evaluated externally. In the same month, a diagnosis was conducted at the company of ARS5, followed by three workshops from September to November 2017. At the same time, the instantiation of part of the model took place at the company. CS4 and CS6 had data collected in Norway during the end of August and beginning of December of 2017, respectively. Figure 50 presents the timeline of the studies' development.

Studies Activities	Start	Finish
Studies Development	**02/01/2017**	**01/02/2018**
Retrospective Studies 1, 2, 3	**02/01/2017**	**07/07/2017**
Data Collection and Analysis	02/01/2017	28/04/2017
1st version of model evaluation	07/07/2017	07/07/2017
Case Study 4 (Norway)	**28/08/2017**	**01/02/2018**
Data Collection in locus	28/08/2017	01/09/2017
Report feedbacks - data check	01/11/2017	01/02/2018
2nd version of model evaluation	01/09/2017	01/09/2017
Action Research Study 5 (UK)	**19/07/2017**	**25/01/2018**
Diagnosis	19/07/2017	19/07/2017
Workshop 1	14/09/2017	14/09/2017
Workshop 2	12/10/2017	12/10/2017
Workshop 3	16/11/2017	16/11/2017
Instantiations	14/09/2017	16/11/2017
Evaluation	10/01/2018	25/01/2018
Case Study 6 (Norway)	**04/12/2017**	**08/12/2017**
Data Collection in locus	04/12/2017	08/12/2017
3rd version of model evaluation	08/12/2017	08/12/2017

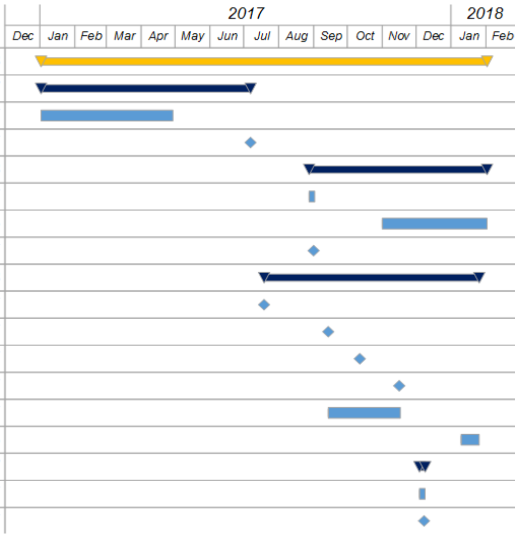


Figure 50: Timeline of the studies developed in the thesis.

During the studies, 15 firms provided data for this research. Some companies participated in more than one study. The list of the participant enterprises of the studies is depicted in Table 15 below.

Table 15: List of the participant companies in the studies.

Study	Companies Involved	No. of Particip.	Participants' role (Company)	Activities
RPS1	Company A - Architecture Office Company B - Construction Management Company C - Construction Management (sub-contractor and researcher's company) Company D - Concrete Structure Contractor	1	CEO (C)	4 interviews
RPS2	Company C – researcher's company Company E – Construction Company	6	Customisation department employees (E)	4 trainings; 4 interviews
RPS3	Company C – researcher's company Company E – Construction Company	36	2 employees from each department (E); CEO (E); Finance Director (E)	2 workshops; 1 training; 24 interviews
CS4	Company F – Owner Company G – Design Management Company H – Architecture Office Company I – Engineering Office Consultants – Lean Construction Consultant	5	Head of Project (F); User & Consultants Manager (F); Design Manager (G); Head of Architects (H); Head of Construction (I)	2 workshops; 6 interviews
ARS5	Company J – Construction Company	6	Project Manager; Planner; Sub-agent; Quantity Surveyor; Graduate Engineer; Design Manager	3 trainings; 2 interviews; 8 meetings
CS6	Company K (Construction Company) Company L (Architecture Office) Company M (Engineering Office) Company N (Client)	7	Project Manager (K); Design Manager (K); Site Manager (K); Architects (L); Structural Engineer (M); Project Manager (N)	2 workshops; 8 interviews

3.4.1 The Studies Evaluation

As a DSR, this investigation used three modes to evaluate the artefacts: 1) Internal – made by the researcher through reflections on practice and connections with theory; 2) External – carried out by the studies' participants and scholar experts; and 3) Field-test – through the instantiation of the artefact in an organisation.

These modes were based on the ones proposed by van Aken et al. (2016): the alpha field testing (artefact evaluated by the designer); beta field testing (artefact evaluated by stakeholders); and "peer reviews" or focus group (discussions with experts, operators and other stakeholders). However, adaptations were made due to the lack of availability for field tests – only the action research study 5 had the artefact partially implemented to enable it.

The internal evaluation followed the assessment of studies outcomes and models utility in solving the research problem. The utility was broken down into some criteria to facilitate the assessments of the models (Figure 51). The criteria considered in this research are measurements to ensure that the final model is robust, connected to the real-world research problem, and, mainly, that it works (March & Smith, 1995).

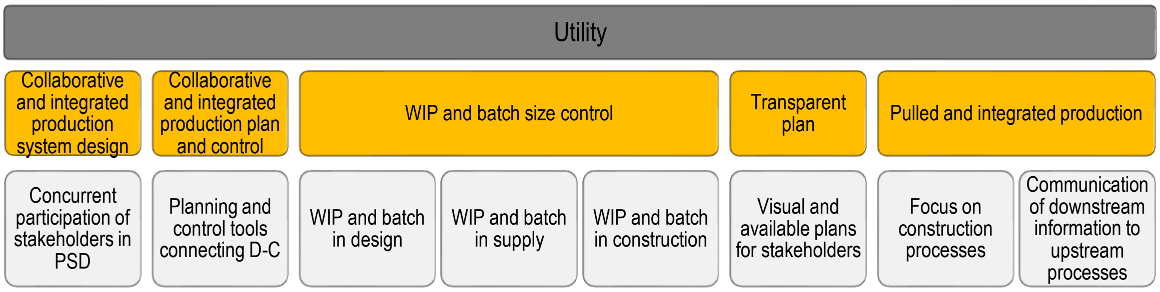


Figure 51: Criteria for model evaluation.

The criteria for internal evaluation of studies and model are described in detail as follows:

- **Collaborative and integrated production system design:** evaluate if there was participation of the main project's stakeholders in the process of designing the project systems, i.e. during the design system design and construction system design using a location-based scheduling tool;
- **Collaborative and integrated production plan and control:** to ensure that the production plan was devised collaboratively and controlled by the project's stakeholders through lean processes, such as LPS;
- **Work in Progress (WIP) and batch size control:** using location-based planning tools, it was expected to reduce the WIP and batch size throughout the product development process. The WIP should be measured from the design stage until the completion of the construction package;
- **Transparent plan:** location-based planning tools enable transparency and can be used as a visual management tool. It is essential to assess if the plans were available for, and understandable by, all stakeholders;
- **Pulled and integrated production:** the main idea of using pulled production from the construction is because it is the final internal client in the process of product development analysed in this research. For this reason, it is critical to assess whether the decisions were made focusing on suppliers and construction processes and requirements; also, whether the information from construction stage was achieving the upstream process.

The external evaluation of the model was conducted first with the model presented for the studies participants followed by a focus group interview about the model. The questions are in Appendix 6.

The action research study 6 also had an external evaluation of the instantiation process: it included the workshops content, development and relevance of the model tools for the project management. The participants used an email testimonial to write down their opinions about the process. However, the field-test of the model implemented was not satisfactorily completed due to external factors, for instance, the client put the project on hold to change important requirements.

The main idea of all evaluations is to assure the pragmatic relevance of the model by the CIMO-logic (Denyer et al., 2008): In the <u>C</u>ontext of projects with overlap between design and construction stages which are unintegrated managed; It is useful to use the <u>I</u>ntervention (model) developed throughout the studies; Which through the <u>M</u>echanisms of: integrate design, supply and construction stages through location-based scheduling tool and other lean practices to align, pull and control production; Will produce the <u>O</u>utcome: reduce the WIP between product development stages, reduce production batch size, increase the collaboration and information exchange by means of transparent plans.

This chapter described the context of the research, followed by the methodological choices made by the researcher to align her expertise with the studies' availability and the design science approach. It also presented the research design which summarised the phases of the research and the procedures adopted to evaluate the findings of the studies.

The next chapter contains the retrospective practitioner studies. The data presented is a reflection on the researcher's practice regarding the context of project management of the stages of design and construction in overlap. These studies enabled the production of the first version of the artefact of this thesis, which is a model to scholars and practitioners to manage the design and construction stages in overlap by integrating the production system design, planning and control activities.

4 DEVELOPMENT OF THE FIRST VERSION OF THE MODEL

This chapter presents retrospective reflections on relevant works that the researcher has undertaken during her professional experience/practice in implementing lean construction in Brazil. These works have informed the researcher's thinking and also developed the necessary knowledge and skills base that resulted in providing practical validation of the research gap identified in this thesis. More importantly, this vehicle of informing studies is used to bring about more explicitly the implicit knowledge that the researcher built over a period of time through practice and academic reading, and to demonstrate the researcher's critical thinking and reflection capacity in theory and practice. Three different retrospective studies were chosen to be analysed due to their relationship with the topic of this thesis: the overlap between design and construction stages.

The studies provided an essential understanding of problem-solving in three different contexts of project organisation. The first study with overlapping between design and construction is the project of an aquarium facility. The second study describes the integration of the construction plan with the customisation of residential units within construction Company E. The last study presents a lean office implementation in construction Company E, in which the design process was responsible for connecting all the company's areas.

In these studies, as used in the literature review chapter, the researcher decided to use the term Construction System Design (CSD) rather than Production System Design (PSD) to avoid possible misunderstandings about the referred project stage. This decision is based on the fact that PSD can address any production system, for example the project as a whole, or only one stage.

The studies were structured first to describe briefly the project, followed by the presentation of the research process, in which the principal evidence sources and research activities are depicted. Further, the studies are described, and the production system management explained. Next, the internal evaluation is set out, accompanied by the studies' contributions to the model evolution.

Finally, at the end of this chapter, the contributions from all three studies and the literature review findings were combined in the first version of the model to integrate design and construction management. The model was evaluated to make further improvements throughout the prospective studies, described in subsequent chapters and articulated in the research methodology chapter.

4.1 RETROSPECTIVE PRACTITIONER STUDY 1: AQUARIUM FACILITY

The retrospective practitioner study 1 (RPS1) was selected as it represents the research problem in the context of complex projects, i.e. complex architectural solution with high number of interdependent elements, an extensive supply chain with uncertainties in goals and methods (Williams, 1999). The solution described: to integrate the interface Design-Supply-Construction in the project, which was analysed and evaluated to develop the artefact of this thesis.

Section 4.1.1 describes the project description and context. The research process is presented at Section 4.1.2. Sections 4.1.3 to 4.1.8 introduce the major project management challenges and the solution for the project planning and control system that integrated design, supply and construction stages. Section 4.1.9 points out the findings, internal evaluation and discussions around the study, correlating it with the pre-existing theoretical knowledge. Section 4.1.10 concerns the main contributions of the study to the model development.

4.1.1 Project Description

The aquarium facility project is located in Fortaleza, in the state of Ceará, Brazil. The primary purpose of this project is to increase the tourism in the city and to renovate a heritage and cultural area of the centre of Fortaleza (Figure 52). The project is owned by a public institution and was developed during the years 2009 and 2016, although development was paused due to financial and political challenges.

This aquarium will be the largest in the Southern Hemisphere and the fifth largest in the world. The facility will contain a 7.5 million litre ocean tank, 1.5 million litre shark experience tank, 21 freshwater tanks, various walk-through fish tank tunnels, and some touch tanks spread over 21,515 m². It will support an educational programme and scientific research of sea life and will contain many interactive attractions, such as a 4D cinema, submarine simulators, interactive character, sea globe and others.

Figure 52: Aerial view of the aquarium facility. Source: Company A.

There were involved in the project different Brazilian offices: architecture, structure, MEP (mechanical, electrical, plumbing), HVAC (heating, ventilation, and air conditioning), landscaping, and so on. Moreover, there are Brazilian suppliers and contractors for civil works, and international suppliers and contractors for aquaria specialised services, such as pumps and pipes, acrylic panels, interior theming, theming roof cover, facades, entertainment media, and so on (Figure 53), managed by the American company responsible for the construction management.

The design office (Company A) was responsible for the design coordination and to deliver the final design documentation for the client. They then hired and managed the complimentary designers. The concrete structure was built by a construction company that won the tendering process promoted by the client. The construction management was carried out by an American company that was selected by the client as it specialised in aquaria tanks. The contract between the client and this company was a turnkey with a fixed price, i.e. the company should build, install equipment, furniture, theming, insert the fish and animals, hire the staff and deliver the aquarium facility for the client.

Aquarium	**Brazilian Designers**	Architecture (**Company A**)	
		Structure	
		MEP	
		HVAC	
		Landscape	
	Main Construction Suppliers/Subcontractors	Brazilian Contractors	Concrete Structure (**Company D**) Civil Works
		International Contractors/Suppliers	Interior Theming Exterior Theming/Roof Aquaria Filters Aquaria Pipes Acrylic Panels
		Construction Management	**Company B** **Company C** (sub-contractor)

Figure 53: Main stakeholders in the aquarium project.

The researcher started her participation in the project working for Company C, a subcontractor of the American company to develop the PSD, plan and control the construction, and to mainly integrate designers and suppliers with the construction. This research presented the work developed during the years 2012 and 2014. When the researcher began her participation in the project, the architectural design development was in its basic stage: the building geometry and materials were, for the most part, defined and there was a specification book; however, the geometry and location of some rooms were still being changed due to conflict with the building services systems.

4.1.2 Research Process

This study was the first Concrete Experience study based on the researcher's practice. The research process was based on reflections on the practice. The primary objectives of this study were to (a) understand the research problem in depth; (b) understand the context in which the solution to the problem was developed; (c) understand how the solution was developed to design, plan and control the stages of design and how construction integrated both stages; (d) connect the designed solutions with the theoretical background.

As a retrospective study, the data was produced between the years 2009 (before the researcher's participation on the project) and 2016 (after the researcher left the project). The data was analysed between January and April of 2017. The evidence source collected comprised documents, such as MS Excel sheets of planning documents (Line of Balance, Supply System, and others), CAD drawings, BIM models, meetings minutes, 4D simulation videos, figures, photos, organisation charts, MS PowerPoint presentations, among others. The researcher also interviewed the Company C's CEO in order to collect more qualitative data about the solution developed for the project.

The data collected was organised according to the steps carried out to develop the solution to integrate design and construction, i.e. according to the managerial activities of design of the production system, to operate it and improve it. As the study took place at the beginning of the design development, most parts of the management actions were focused on designing the construction and the supply systems. The design was affected by the way it was planned. The findings were evaluated as clarified in the Method chapter: by analysing the utility of the solution in promoting the management integration between design and construction. Afterwards, the findings were translated into contributions to the first version of the model.

The data collected, analysed and its outputs are disclosed in Table 16.

Table 16: Sources of evidence for each phase of the RPS1

Study Phase / Aim		Sources	Developed in
1.	**Awareness of the problem**		
a.	Understand the project's stakeholders' contractual relationships and responsibilities	• Secondary document analysis: Organisational charts and contracts • Semi-structured interview with Company C CEO	Organisational chart of the project
b.	Understand the project context, timelines and the overlap between design and construction stages	• Secondary document analysis: MS Excel sheet of project milestones, project master plan, PowerPoint presentations, pictures, photos	Project timeline of design and construction stages; project's milestones
c.	Understand the process to plan and control the design stage, the participants, tools used and information exchanged	• Semi-structured interview with Company C CEO about project routine for design management • Secondary document analysis: MS Excel sheets for planning design, RFI, minute meetings, emails	Data Flow Diagram of the design planning and control process
d.	Understand the process to plan and control the construction stage, the participants, tools used and information exchanged	• Semi-structured interview with Company C CEO about project routine for construction management • Secondary document analysis: MS Excel sheets for planning construction, RFIs, meetings minutes, emails	Data Flow Diagram of the production planning and control process
2.	**Suggestion of solution for project**		
a.	Understand the production management philosophy change from CPM to LOB	• Secondary document analysis: MS Project files, Line of Balance (MS Excel) • Semi-structured interview with Company C CEO about the transition of tools	The original files were kept
b.	CSD: how the project was structured		
i.	Understand the location breakdown structure and construction sequence	• Secondary document analysis: MS Excel sheets of construction design system, BIM models, 4D simulation of the construction sequence	The original files were kept
ii.	Work packages and sequence of activities	• Secondary document analysis: MS Excel sheets of construction design system	The original files were kept
iii.	Duration and production capacity estimation	• Secondary document analysis: MS Excel sheets of construction design system	The original files were kept
iv.	Master plan using Line of Balance	• Secondary document analysis: MS Excel sheets of construction design system	The original files were kept
v.	Site layout study	• Secondary document analysis: CAD drawings, BIM models, 4D simulations of site development	The original files were kept
vi.	Integrated supply system	• Secondary document analysis: MS Excel sheets of the Supply System, reports, suppliers' MS Project files, MS Excel sheets of construction master plan for suppliers • Semi-structured interview with Company C CEO about the system development	The original files were kept
c.	Design System Operation: how the design was planned and controlled		

i.	Planning the architectural design activities	• Secondary document analysis: MS Excel sheets of the design plan • Semi-structured interview with Company C CEO about the plan development and designers' participation	The original files were kept
3.	**Development and internal evaluation of study's model for project production system**		
a.	Understand how the solution adopted by the project influenced the stakeholders' work, the main problems faced and suggestion for improvement	• Semi-structured interview with Company C CEO about the impacts of the solutions applied in the stakeholders' work • Secondary document analysis: information format exchanged, drawings, supplier's material on-site (photos), emails, RFIs, meeting minutes	Internal evaluation of project's solution
b.	Understand the correlation between the solution developed in the project and the literature concepts and tools	• Literature review in Toyota Production System, WIP, design problems, information flow management, location-based planning tools	Internal evaluation of project's solution
c.	Translate the project's solution in a theoretical model	• All study's data and information	Model for project production system

4.1.3 Project Management

The aquarium facility is a project owned by a public institution who is also the client. The design stage of the aquarium started in 2009, and it was the responsibility of a local architecture office (Company A) who contracted the complementary designs.

In the following years, the client did a public bidding to select the company responsible for executing the aquarium foundations and concrete structure. The foundation's execution started in June 2012, and the concrete structure commenced in December 2013.

This project had several stoppages, which extended the lead time of design and construction development. In general, the overlap between design and construction started in 2012, when the design was still at the basic level of development, and the foundations started being executed (Figure 54).

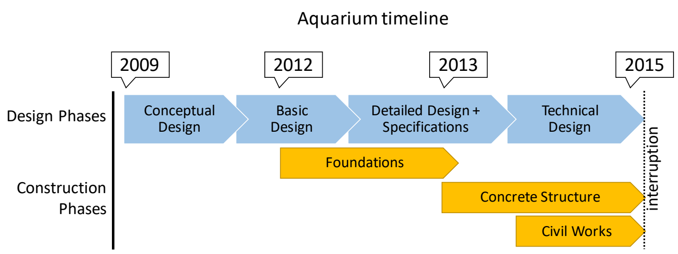


Figure 54: Schematic project timeline.

The client also had hired an American company (Company B) to manage the construction under a turnkey contract, i.e. the American company was responsible for managing all the construction process, theming, furniture, equipment, staff hiring and deliver the aquarium facility ready to use for the government. For this reason, Company B was responsible for managing the international and national suppliers and subcontractors. Company B had outsourced the production planning and control to Company C. As well as this, company B needed to supervise the concrete structure execution made by Company D, but there is not a contractual relationship between them. These relationships among the companies are presented in the project organisation chart (see Figure 55).

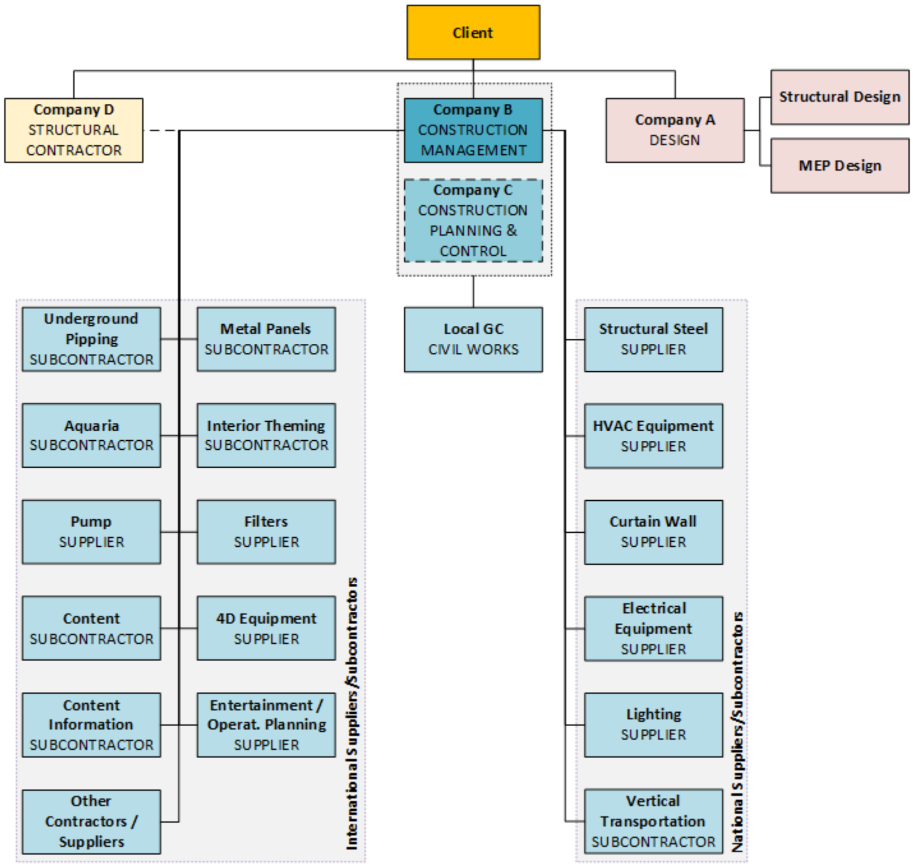


Figure 55: Project organisation chart. The dotted line represents the company where the researcher worked.

Company A conducted the process of design coordination. However, as the client has contracts with Company A, B, and D, all the exchange of design packages among them was formally carried out by the client. Notwithstanding, these companies were continually participating in meetings and requesting information and design documents by Request for Information (RFI), meeting minutes or emails. Company A conducted these meetings with the participation of designers and suppliers to collect information and to produce detail design for construction.

Furthermore, as the suppliers have a contract with Company B, and the designers with Company A, all information necessary to be exchanged between designers and suppliers was intermediate by Company A and B. This exchange occurred formally by RFI and meeting minutes, and informally through the meetings promoted by Company A. This process for **design coordination** is shown in the Data Flow Diagram (DFD) in Figure 56, in which the lines represent the informational flow between two entities.

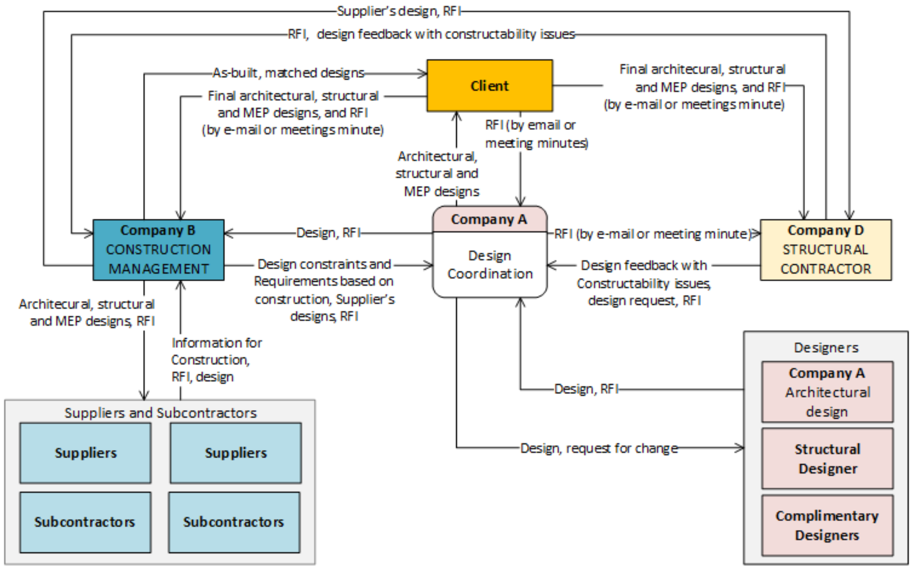


Figure 56: Information and documents exchanged for design coordination.

The process of **construction planning and control** was conducted by Company C, hired by Company B. The relationship among the stakeholders is presented in the DFD in Figure 57. Company B formally held the exchange of documents and information for the process of production planning and control between Company C and other stakeholders; however, during the meetings, Company C could collect data informally.

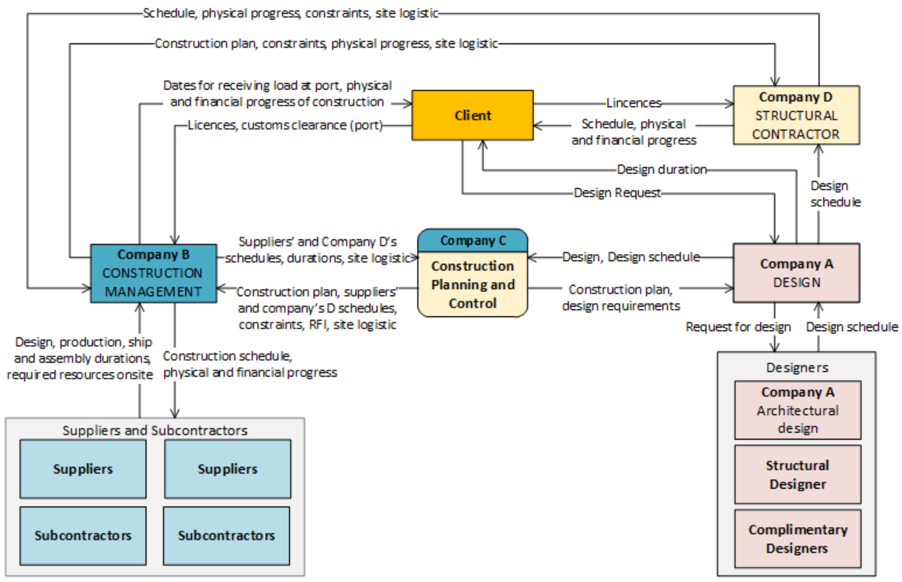


Figure 57: Information and documents exchanged for construction planning and control.

The information necessary to produce the plans comprised: design documents; suppliers' durations for shop drawings, fabrication, ship and assembly; suppliers' and designers' schedules; suppliers' requirements of resources for construction; and site logistics information. To control the plan, Company C needed to receive the concrete structure progress, and the designers' and suppliers' activities progress. Company B was responsible for providing information about the construction performance to the client and information about the receiving load at the port.

Comparing the three most important ways of communication in the project (meetings minute, emails and RFI), the most transparent and straightforward way to register and control the requests for information was the RFI document. Company B used to work with RFI in the USA, and the Brazilian companies used to request information via email or meetings minutes. The email proved to be the most unreliable way of gaining information because the requests in an email could be lost and difficult to track date, deadline and recipient. The meeting minute registers what the meeting participants agreed regarding the requests, yet it is difficult to track the requests for information.

In the RFI, each piece of information necessary to be exchanged is one item to track. Data such as recipient name, deadline, content and format of the information required are registered. This method facilitates the transparency of the participants' requirements to keep their workflow smoothly.

4.1.4 The Beginning of Lean in the Project Management

At the beginning of the design development in 2009, Company C was hired by Company A to prepare a production plan for the project, represented by the construction master plan (Appendix 1 - Figure 165) of the main project phases in the Gantt chart. It was developed based on information gathered from possible subcontractors that agreed to send preliminary schedules. The plan was used to inform the client how the construction should be executed throughout the 24 months. The design stage was not included in this plan.

In 2012, Company B started working on the project. They had developed the project master plan using MS Project (Appendix 1 - Figure 166) to present it to the client. This plan contained the major project phases of international subcontractors, and its comprehension by the client was not very clear. Then, Company B hired Company C to be responsible for the construction planning and control. The researcher was working at **Company C** and was in charge of developing the construction plan. As the researcher had done her Master's degree in lean management, she decided to work with this new production management philosophy and develop the construction master plan using the Line of Balance (LOB). One of the arguments used to convince Company B to use the LOB was the MS Project schedule's lack of transparency to visualise the construction workflow.

Moreover, a CPM activities network for one location is not the same for all locations, and one activity may interfere with another activity from other location. For this reason, it is essential to have a location-based tool for planning and control construction. Adding to this, the LOB presents the physical workflow through the locations and interferences in a visual fashion. It allows the construction teams to understand when and where they will work.

Due to a high number of American suppliers in the project, the project manager from Company B tried to avoid project delays by requesting from designers all the design documents at once. However, in doing so he caused a design overproduction and pressure for the designers, who did not know the priority of production of design documents.

In summary, at the beginning of the researcher's work in the aquarium project, many facts were occurring that supported the CSD using the LOB as a location-based tool for managing the project. They were:

- Lack of workflow transparency of the project plan made in MS Project (CPM and Gantt chart);
- Subcontractors' and planner team's necessity to visualise the activities interferences between different locations;
- Unnecessary design inventory to protect the construction from delays;
- Designers are working under pressure to deliver all design documents without priorities.

4.1.5 Project System Design

The Project System in the aquarium project was designed for the stages of design, supply and construction. The solution to the overlap between design and construction began during the design of the construction system. The design system was already in operation at the basic stage and used in the CSD. While the design was evolving, the CSD was being refined, and Company C developed the design plan in collaboration with the architects. The step-by-step process of the project system development is described below.

4.1.6 Construction System Design (CSD)

4.1.6.1 Gathering Data

The researcher's team began the CSD using the basic architectural design. It collected information from design drawings, e.g. architectural plans, site layout, façades (Figure 58), sections, some BIM models of concrete structure, sketches from the architect showing the material and theming of every attraction room, basic structural design and the available building services designs.

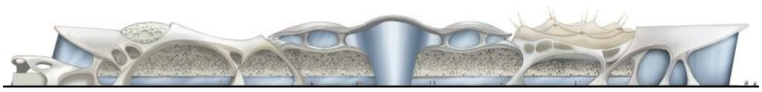


Figure 58: South façade of the aquarium facility. Source: Company A.

While the architectural design was progressing well, the design solution for the building foundation was late. The structural design was defined, and the concrete structure building sections were used as a reference in the location breakdown structure, which is one of the first steps when devising a plan using location-based tools (Kenley & Seppänen, 2010).

Part of the necessary information to design the construction system was collected during weekly meetings with the stakeholders. Companies A, B, C and D would meet every Tuesday morning in the site office to share information about the concrete structure progress, design progress, design information requirements from Company D, conflicts in the interface between concrete structure and international suppliers of pipes, acrylic panels, filters, and so on.

Company B received requests from the subcontractors' schedules. These schedules were produced in MS Project, Primavera or Ms Excel software, and they were "converted" to a LOB.

4.1.6.2 Location Breakdown Structure and Location Construction Sequence

The location breakdown structure followed the concrete structure sections and the building stores. The attack plan was defined based on the site logistic studies. As the construction site is small, the sequence of construction should be from the west to east, where the "Water Square" is located. This square should be the last item to be built, and its area is to be used for temporary facilities along with the construction of the main building.

Adding to this, constraints in the execution of side-by-side concrete structure sections helped to define the construction sequence: technically, it is recommended that adjacent concrete structure sections should not be executed at the same time. The recommendation was to have a difference of one store between the neighbouring batches.

In total, the building was broken down into four sections (1, 2, 3 and 4), and each section contained the floors and exterior area (EXT): technical slab (TS), underground (UG), ground floor (GF), 1st floor, 2nd floor and roof (Figure 59).

SETOR SECTOR	ANDAR FLOOR
TRECHO 1 SECTOR 1	Roof
	2nd
	1st
	GF
	UG
	TS
	EXT

Figure 59: Example of location breakdown structure in sector one in the aquarium project. Source: Company C.

Company C conducted 4D BIM simulations using the Autodesk Navisworks to support the study of the concrete structure sections construction sequence and to clarify the technical constraints in its execution (Figure 60). The construction sequence definition enabled the drawing of the vertical axis of the LOB.

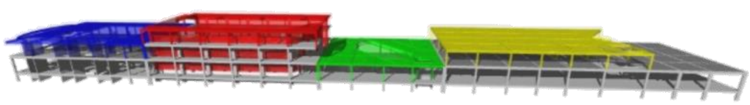


Figure 60: Snapshot of the 4D BIM simulation for the study of concrete structure location sequence for the four zones 1 (blue), 2 (red), 3 (green) and 4 (yellow). Source: Company C.

4.1.6.3 Work Packages and Sequence of Activities

The next step in the design of the construction system for the aquarium facility was to determine the work packages and their sequence in every production batch. To conclude this task, the potential project subcontractors participated in the definition of the sequence of their activities and the dependency relationship between other activities. Two work packages sequence nets were developed: 1) Specific for every production batch (see Appendix 1 - Figure 167); 2) General work package sequence-net (Appendix 1 - Figure 168). As the first work package was very extensive, the general one was proposed to clarify the significant dependencies between work packages and locations. Based on the team experience in previous projects, the work packages for the civil works and their sequence were defined in a joint meeting with the designers.

4.1.6.4 Duration and Production Capacity Estimation

As the design was not detailed at the time of the CSD, a non-accurate quantities extraction was conducted by Company C using the structural BIM model in Revit (Figure 61) and architectural drawings in AutoCAD. With this data, the duration and the number of workers for each work package were estimated. Again, based on the experience from previous projects, the team used the conventional construction technologies, crew composition and productivity for the civil works applied in the city of Fortaleza. The durations were rounded up to insert capacity buffers for the work packages execution.

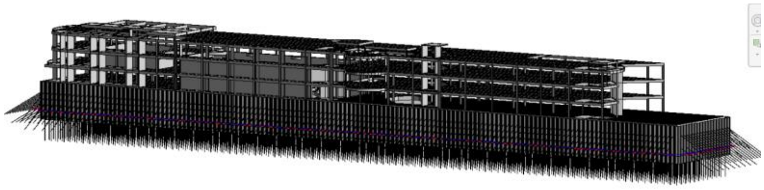


Figure 61: Concrete structure 3D BIM model for quantities extraction. Source: Company C.

4.1.6.5 Defining the Master Plan with the Line of Balance

The LOB was initially devised with the available data from the construction location sequence, work packages dependencies and durations. One of the targets of the use of the LOB was to keep the crews' workflow uninterrupted from the first until the last production batch. As the production batches were of different sizes and complexities, it was not possible to keep a common takt-time along the plan.

Whenever the subcontractors defined information about the production system, the LOB was updated. Consequently, the researcher developed 24 versions of LOB for the aquarium project. This tool was used to support the subcontractors in planning and controlling their activities, visualise their workflow and measure the impact of changes (design, technology, sequence, crew size) on the project lead time. The LOB for the whole project can be seen in Figure 62. It presents the plan of stores and façades at the four building sections.

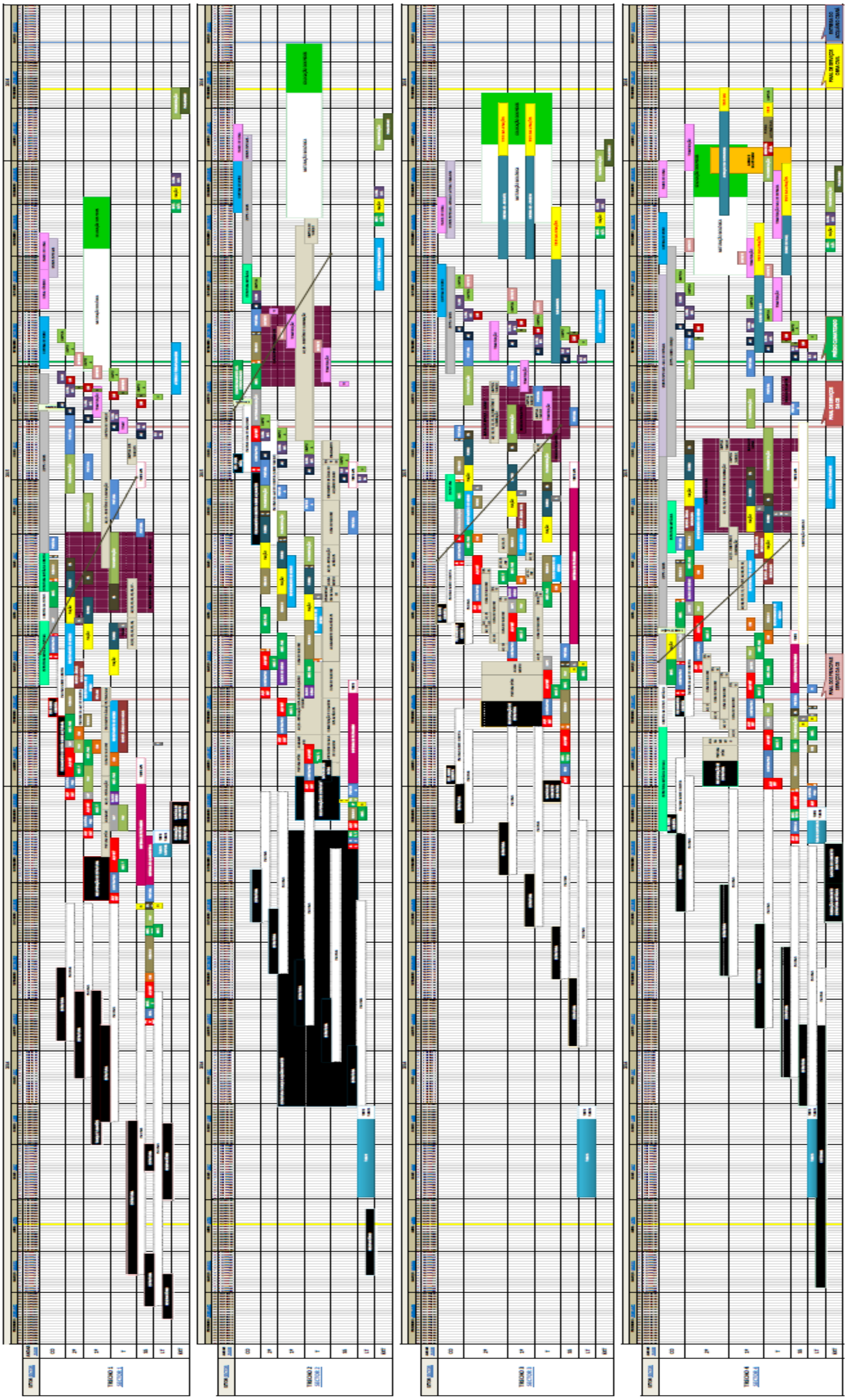


Figure 62: LOB of the aquarium project. Source: Company C.

Separated lines of balance were developed collaboratively and delivered for subcontractors to facilitate the visualisation of their workflow. These lines show the subcontractors' work packages and their items to be produced and delivered in each production batch, as shown in Figure 63.

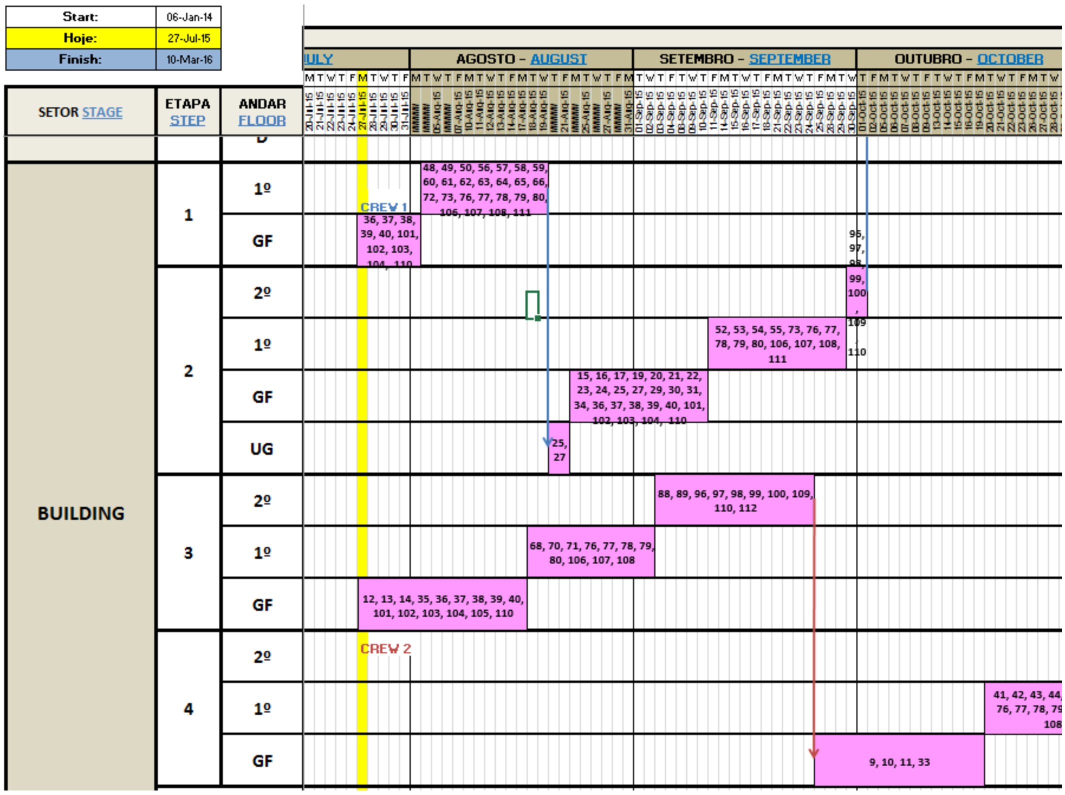


Figure 63: LOB for the interior theming subcontractor, specifying the crews' flow and the item number in each production batch. Source: Company C.

According to the availability of the subcontractor to participate in the planning, some work packages sequence nets were refined and broken down in more detail along the 24 versions of LOB (see Figure 64). Some dependent work packages from other subcontractors or civil works were added in some lines of balance, for example in Figure 65, where the structure and scaffoldings were kept in the line to present to the subcontractor the context of dependent activities in each production batch. Also, arrows were added to show the subcontractor crews' flow throughout the batches.

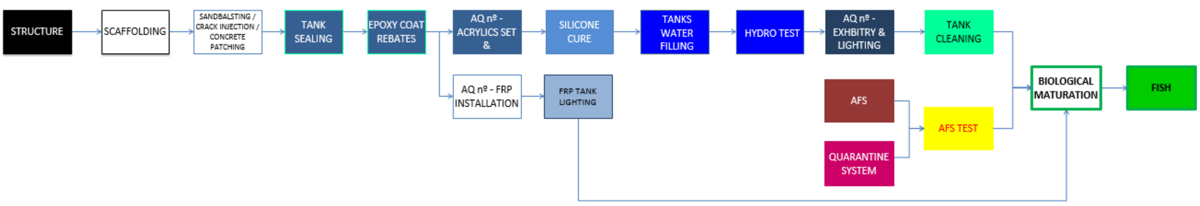


Figure 64: Sequence of work packages for the acrylic panel subcontractor. Source: Company C.

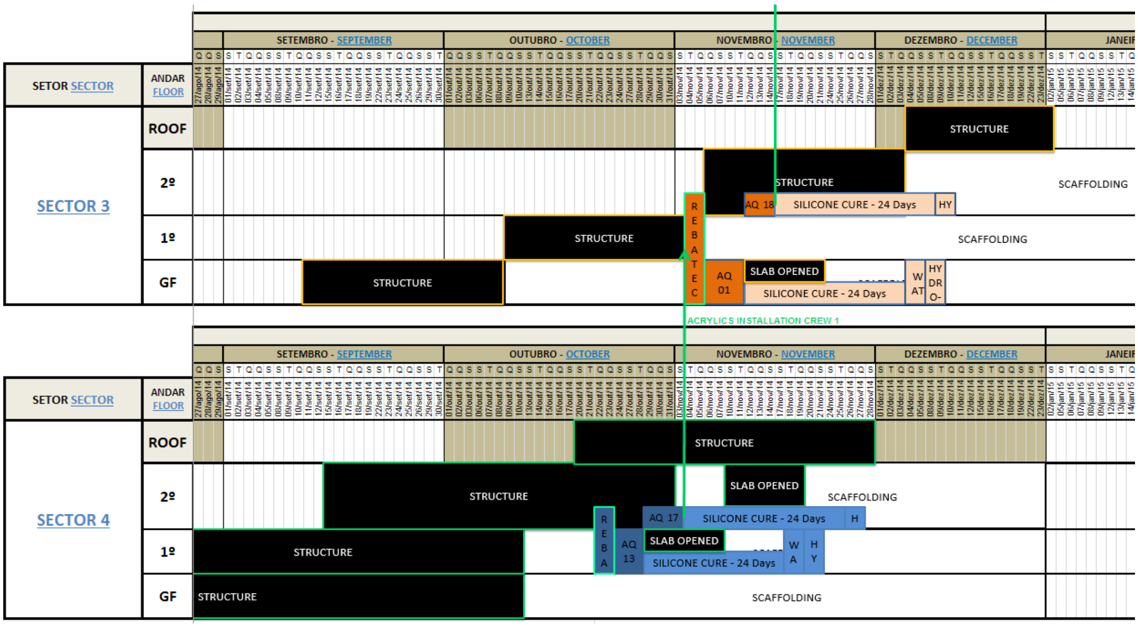


Figure 65: Example of the LOB for acrylic panels subcontractor. Source: Company C.

Some adjustments were required to be made in the production batch for the roof theming cover. Because the roof cover had an organic shape that did not follow the concrete structure sections, the items on the roof were planned in the correspondent building section, as shown in Figure 66. Exterior red squares represent the four building sections 1, 2, 3 and 4, and the interior letters over the roof represent the subcontractor theming elements.

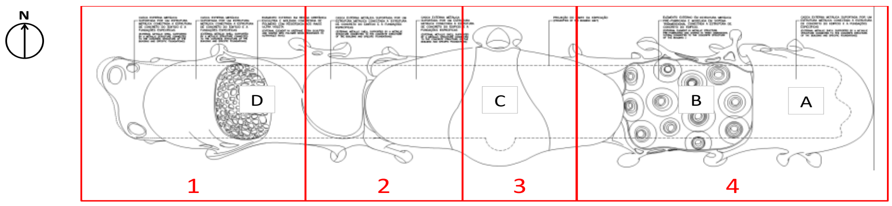


Figure 66: Adaptation in the correspondent roof theming element with the building sections 1, 2, 3 and 4. Source: Company C.

4.1.6.6 Site Layout Study

The site layout study had substantial impacts on the construction plan and deadline. The study was conducted by the Company C planning team using site plans and 3D/4D BIM models. It intended to visualise the vertical flows of transport equipment, such as cranes, mobile cranes, lifts, but also horizontal flows, such as trucks with containers, unloading of containers, material, and workers, as shown in Figure 67.

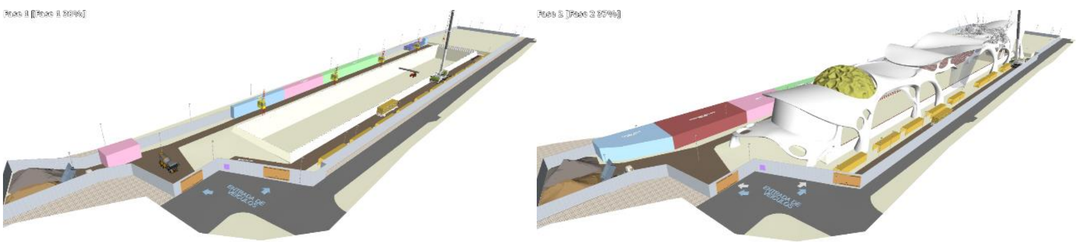


Figure 67: An example of logistic site study for phase 1 and 2 using 4D BIM model. Source: Company C.

Due to the physical constraints of the construction site, it was decided to have three phases of site expansions. The most challenging site study was for the installation of the aquarium master acrylic panel, the dimensions of which were 8.75m (W) x 8.75m (H) and weighed 27 tonnes. The subcontractor produces the panel in the USA and delivers it to Brazil by ship. From the port to the construction site, there was only one motorway large enough for the truck to transport the panel. However, because it was not possible to use two lanes of the motorway, the horizontal positioning of the acrylic panel in the truck was not possible. It was also not possible to transport the panel vertically along the road because there were some bridges with insufficient height for the truck and the panel.

It was then agreed with the acrylic subcontractor to deliver this acrylic panel in three smaller pieces. For that, it was necessary to build on-site a “bonding room”; after it was bonded, the acrylic panel then needed to be transported to the final position inside the building. However, the mobile crane required to do this was bigger than the space available between the aquarium building and the site fence. The solution proposed was to build the “bonding room” at the workplace where the panel should be installed. This strategy was to cause another constraint: in order for the acrylic panels to be bonded no vibration on-site was allowed. This meant that all the parallel works in progress at that moment of the panel installation had to cease. These technical and spatial constraints impacted considerably on the project plan and had changed how the supplier should produce the acrylic panels.

4.1.7 Integrated Supply System

As soon as the LOB was in its first versions, the planning team from Company C developed a supply system to plan and control the services of all suppliers/subcontractors and designers. This system used the work packages, location, and dates from the LOB to produce a reverse schedule (Figure 68). It was based on subcontractors’ information about durations of milestones. The information used was: requests for proposals (RFP); shop drawings; production; shipment; and installation (Figure 69). Buffers between the milestones were used to protect the production system against variability. For instance, 7-day buffers were applied between the installation on-site and the elements delivery.

		Location breakdown structure	ACTIVITIES			
SECTOR	STORE	NUMBER	Room	Description	Status	Serviço da LOB
1	1st floor	AQ 21	Shark Tank	FOR-128	Construction	Pintura Epóxi, Acabamento, Instalação dos Acrílicos, Cura do Silicone, Enchimento de Água, Teste, Esvaziamento do Tanque
			Shark Tank	FOR-129	Construction	
			Shark Tank	FOR-130	Construction	
			Shark Tank	FOR-132	Construction	
			Shark Tank	FOR-133	Construction	
	Groundfloor	AQ 02	Moray Eels Tank (FRP)	FOR-136	solicitar cronograma FRP Manufacturer	FRP Installation
		AQ 03	Nocturne Fishes Tank (FRP)	FOR-137		
		AQ 04	Walking Fishes Tank (FRP)	FOR-138		
		AQ 05	Sand Eels Tank (FRP)	FOR-139		
		AQ 06	Octopus Tank (FRP)	FOR-140		
		AQ 07	Flat Fishes Tank (FRP)	FOR-141		

Figure 68: The supply system is structured according to the LOB structure, i.e. the location breakdown structure. Source: Company C.

DURATIONS						LOB			
RFP	Shop drawing	Production Duration	Ship Duration	Installation Duration	Total Duration	Start Date	x	Finish Date	x
0	60	50	60	103	339	17-nov-14		27-fev-15	
0	60	45	60	103	334	17-nov-14		27-fev-15	
0	60	110	60	103	399	17-nov-14		27-fev-15	
0	60	67	60	103	356	17-nov-14		27-fev-15	
0	60	67	60	103	356	17-nov-14		27-fev-15	
0	60	25	3	18	195	24-mar-15		10-abr-15	
0	60	25	3	18	195	24-mar-15		10-abr-15	
0	60	18	3	18	188	24-mar-15		10-abr-15	
0	60	18	3	18	188	24-mar-15		10-abr-15	
0	60	18	3	18	188	24-mar-15		10-abr-15	
0	60	18	3	18	188	24-mar-15		10-abr-15	

Figure 69: Necessary durations to produce the reverse plan for the supply system based on the dates of the LOB. Source: Company C.

With the determined durations and dates from the LOB, it was possible to set the deadlines for each subcontractor's processes, e.g. the date the product/material/service must be on-site, the estimated time of arrival (ETA), other dates related to the shipping (Figure 70), deadline for finishing the production, other related production dates, including dates for request for proposals (RFP), estimated end date for design and the actual design received date (Figure 71).

SHIPPING														ON SITE	
Flag	Nº of Containers	Nº of Ship	Port	Ready for loading	x	Consolidation	x	Probable Date Shipping	x	Required Shipping	x	ETA	x	Target date on site	x
US		17	A	26-jul-14		24-set-14		1-out-14		11-set-14		31-out-14		10-nov-14	
US		17	A	26-jul-14		24-set-14		1-out-14		11-set-14		31-out-14		10-nov-14	
US		17	A	26-jul-14		24-set-14		1-out-14		11-set-14		31-out-14		10-nov-14	
US		17	A	26-jul-14		24-set-14		1-out-14		11-set-14		31-out-14		10-nov-14	
US		17	A	26-jul-14		24-set-14		1-out-14		11-set-14		31-out-14		10-nov-14	
US		23	A	24-jan-15		25-mar-15		1-abr-15		14-mar-15		1-mai-15		17-mar-15	
US		23	A	24-jan-15		25-mar-15		1-abr-15		14-mar-15		1-mai-15		17-mar-15	
US		23	A	24-jan-15		25-mar-15		1-abr-15		14-mar-15		1-mai-15		17-mar-15	
US		23	A	24-jan-15		25-mar-15		1-abr-15		14-mar-15		1-mai-15		17-mar-15	
US		23	A	24-jan-15		25-mar-15		1-abr-15		14-mar-15		1-mai-15		17-mar-15	
US		23	A	24-jan-15		25-mar-15		1-abr-15		14-mar-15		1-mai-15		17-mar-15	

Figure 70: Estimated deadlines for the shipping process. Source: Company C.

Received Date		Design		PRODUCTION									
Design	x	Design	x	RFP	x	Shop Drawings Start	x	Shop Drawings Finish	x	Fabrication Start	x	Fabrication Finish	x
6-mai-14	x	19-mar-14	x	26-mar-14	x	26-mar-14	x	25-mai-14		30-mai-14		19-jul-14	
6-mai-14	x	24-mar-14	x	31-mar-14	x	31-mar-14	x	30-mai-14		4-jun-14		19-jul-14	
6-mai-14	x	18-jan-14	x	25-jan-14	x	25-jan-14	x	26-mar-14	x	31-mar-14	x	19-jul-14	
6-mai-14	x	2-mar-14	x	9-mar-14	x	9-mar-14	x	8-mai-14		13-mai-14		19-jul-14	
6-mai-14	x	2-mar-14	x	9-mar-14	x	9-mar-14	x	8-mai-14		13-mai-14		19-jul-14	
4-abr-14	x	12-out-14	x	19-out-14	x	19-out-14	x	18-dez-14	x	23-dez-14	x	17-jan-15	
4-abr-14	x	12-out-14	x	19-out-14	x	19-out-14	x	18-dez-14	x	23-dez-14	x	17-jan-15	
4-abr-14	x	19-out-14	x	26-out-14	x	26-out-14	x	25-dez-14	x	30-dez-14	x	17-jan-15	
4-abr-14	x	19-out-14	x	26-out-14	x	26-out-14	x	25-dez-14	x	30-dez-14	x	17-jan-15	
4-abr-14	x	19-out-14	x	26-out-14	x	26-out-14	x	25-dez-14	x	30-dez-14	x	17-jan-15	
4-abr-14	x	19-out-14	x	26-out-14	x	26-out-14	x	25-dez-14		30-dez-14		17-jan-15	

Figure 71: Estimated deadlines for the production and design processes. Source: Company C.

Every major supplier/subcontractor, especially the international ones, had their own supply system spreadsheet. The same occurred with the designers. Through this reverse supply system, it was expected that the construction plan - LOB - could pull the activities of design, fabrication, shipping and installation. Through the pull flow, all the project stakeholders' efforts were spent on producing the right product, in the right sequence, in the right quantity and at the right time – similar to the concept of Just in Time (JIT)

(Ohno, 1988; Ohno & Mito, 1988). An example of the pull system used in the project is presented in Figure 72.

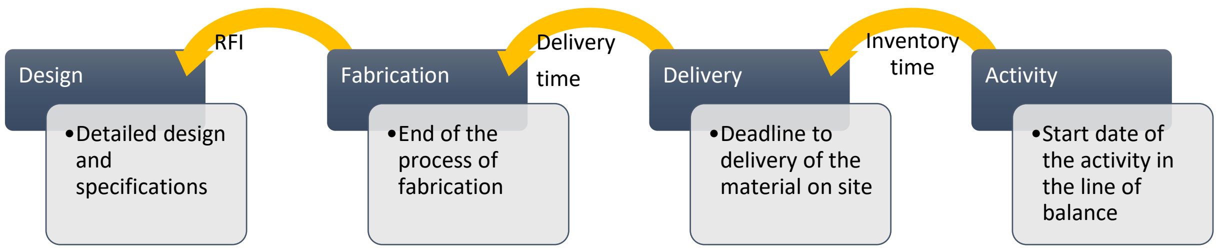


Figure 72: Example of the reverse plan for the supply system. Source: Company C.

However, the main difficulties faced by Company C's team to keep this system working were to consolidate the suppliers' dates, capture their requirements, understand the complete process from shop drawings, production, shipment and installation on-site, and make them understand the advantages of working with the LOB instead of the Gantt chart.

After the supply system was ready, all milestones of the reverse plan were sent to the subcontractors with the respective LOB. They analysed, criticised, and, if more information was necessary, a meeting was arranged to discuss or replan their activities. In the pull flow, variability in the suppliers' and the construction's processes was felt by the designers, who were the first producers of the project's value stream.

4.1.8 Design System Operation (DSO)

While the construction system was being designed by Company C, the design production was already operating. The project adopted three levels of design stages: (1) conceptual design; (2) basic design; and (3) detailed design + specifications (Figure 73). The subcontractors were responsible for the (4) technical designs. At the end of each stage, Company A delivered the design package to the client. However, it was not clear what the expected design content and detail would be at the end of the stages. When some area of the facility needed to be more detailed for a subcontractor, the same design package could contain different design levels of detail of the facility.

Figure 73: Design stages in the aquarium project.

As the client was not requesting for design changes regularly, the design development process had more reworks caused by the subcontractors and complementary designers, such as the foundations, concrete structure, roof theming and facade designs.

Through the support of the LOB and supply system, the Company C team could predict the last moment to make a design decision. For this, Company C called meetings between designers, subcontractors, Company B and D to make a collective decision. In these meetings, the stakeholders discussed the impacts of design solutions in construction, costs and logistics. Some issues from these areas could change the design solution and require more studies of design options.

4.1.8.1 Planning the Architectural Design Activities

At the beginning of the aquarium project, Company C worked closer to the architecture office (Company A). When the first construction LOB and supply system were ready, Company C developed a master plan for the architectural detailed design and specifications (Figure 74), and it was specified to which stakeholder that design document should be delivered.

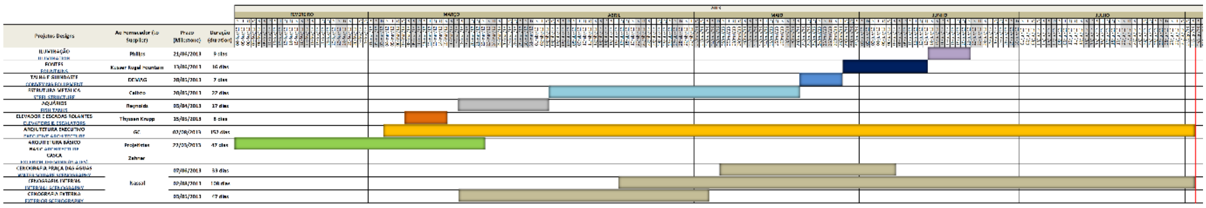


Figure 74: Master plan for architectural design. Source: Company C.

One of the uncertainties the designers frequently reported during the design planning was about the difficulty to predict their work. Then, Company C's team decided to support the designers in the planning of their production capacity and levelling the work. For this, the design master plan was broken down into a tactical plan, contending the duration and the architect responsible for developing each design activity (Appendix 1 - Figure 169). The results were presented to the manager, who realised it was necessary to hire more professionals to meet the project deadlines. A visual board controlled the tactical plan in the office which showed the work progress of each architect week by week.

The planning of the designers' work was essential in order to promote a situational awareness of their own production capacity, but mainly to understand how the deadlines were set up, their production sequence and the impacts of design in downstream processes of suppliers and builders.

4.1.9 Analysis and Discussion of RPS1

The analysis of RPS1 correlates the aquarium project management practices with the literature review. The study was also analysed by the utility criteria, as described in the method chapter.

In the aquarium project, there was **early participation** of the leading contractors in the project management activities that were led by Company C. Even contractors that had not formally signed their contracts were invited to participate and provide information regarding the project planning. Although the project already had the basic design and the concrete structure contractor selected, Company C designed the context of the project (Young, 2008), i.e. design the design, supply and construction systems. At this stage, the structural complexity is not so high compared to the construction operation. However, negotiation between the key participants is crucial in order to make strategical decisions that impact the performance of the whole project (Austin et al., 2002). The LOB performed the role of boundary objects to promote the negotiation necessary at that stage of the project (Lee, 2007; Spitler & Nathan, 2016).

The project planning started with the CSD. Company C had a crucial role in the CSD by pulling information from the owner, contractors, builders and designers. In order to design the construction system, some information needed to be more detailed, such as specific designs that could directly impact the construction. One example was the necessity to forecast the concrete structure openings for the acrylic panels' installation at the tank areas. In summary, the CSD information contains various levels of detail. Sometimes, for critical activities, it is necessary to anticipate some decisions; in order to do this, the stakeholders must cooperate by providing information, developing scenarios, increasing detail and making decisions.

To carry on with the **integrated production system**, Company C needed to visit the architecture office (Company A) to understand their production capacity; also, to understand the main contractors' production steps, duration, logistic requirements and so on.

Most of the decisions about the PSD were made by Company C **collaboratively** with stakeholders. Despite efforts to collocate the stakeholders to make decisions together, the physical distances between them – the main contractors were based in the USA – imposed some difficulties when arranging the frequent CSD meetings. However, the communication channels were effective to overcome this issue, and stakeholders were aware of the impact of the decisions on the production system.

Although the design was already progressing, the decision of Company C's team in planning the architects' work was essential in order to structure the design process for them. As frequently reported in the literature, designers lack confidence to plan their work (Coles, 1990). Therefore, studies about designers' production capacity were carried out to meet the project deadlines. Moreover, to maintain the continuous flow of design, some inputs for design development relied on decision-making with the project's stakeholders. The design plan supported designers to define what was the required information, when was it necessary to receive it, from whom and to whom they should deliver the design package. The idea of this design plan with packages assembled by the reverse supply system and LOB enhanced the management of some lean design aspects of flow, transformation and value (Koskela & Huovila, 2000). The mix of push and pull flows at the design development corroborates with the idea that design packages for procurement should be pulled by construction needs and could be done using location (Kiiras & Kruus, 2005; Tiwari & Sarathy, 2012).

The aquarium project used the LOB as a master plan to operate the **production planning and control**. As long as new information became available, the LOB was updated by Company C and the information disseminated to the stakeholders. The impacts of the plan alteration were discussed with the designers and contractors.

The operation of the construction system did not use any hierarchical production planning and control such as the Last Planner System (LPS). The project was put on hold by the client at the very beginning, more specifically during the concrete structure execution. Collaboration occurred during the project execution, but a more structured system to control the project should have been necessary for its execution.

MS Excel spreadsheets were used to control the supply system, and a customised LOB was provided for the main contractors. However, no metrics or other **collaborative production planning and control (PPCa)** process were developed with the main contractors. It was their responsibility to conduct their own PPCa process in order to meet the deadlines specified in the LOB.

The design development process was not controlled using any lean practice, such as the LPS, or others, e.g. Stage-Gate, Agile, among others. Although Company C could not interfere in the way designers were managing their activities, the implementation of the tools and practices helped them in reducing variability and increasing the reliability of their deliverables (Demir & Theis, 2016; Sommer, Hedegaard, Dukovska-Popovska, & Steger-Jensen, 2015; Wesz et al., 2013). As well as this, Company C was constantly monitoring the information flow and asking designers and subcontractors for feedback from the tasks they needed to accomplish. Company C had a critical role in the aquarium project to keep the workflow smooth. However, in projects where there is not a professional or a team to manage the information flow between stakeholders, it is recommended that participants use a structured production plan and control system, such as the ones mentioned at the beginning of the paragraph.

Tribelsky and Sacks (2011) point out that a well-managed information flow and sharing may reduce waste and improve value. Adding to this, the authors claim that a stable and continuous design flow, with small batches and constant transactions, may enhance the quality of the design documents. Comparing these statements with the aquarium project production system, the location breakdown structure of the LOB enabled the assemblage of smaller subcontractors' and designers' batches compared to traditional projects. Having smaller batches shortened the lead time to complete the design production, facilitate the identification of errors and required inputs for the processes, avoid errors to dissipate across the project, and increase the frequency at which information is exchanged.

The tools used to design the production system and operate it were the Line of Balance, BIM models and MS Excel spreadsheet for the Supply System. Both LOB and BIM models are **transparent tools** that promoted the ease of understanding of activities dependencies, milestones and physical construction clashes. The transparency enabled the shared understanding and supported the decision-making.

Focusing more on how the production system was designed and operated in study 1, the main idea that drew it was the Just in Time (JIT) concept of **pull system** and continuous flow (Ohno, 1988). When the construction stage is seen as a client of design and supply, it is easier to set a demand from downstream to upstream processes.

To implement the pull flow, it was necessary to make use of a smooth "master production schedule that specifies which products are to be produced in each time interval" (Hopp & Spearman, 2011). In the construction stage, it was devised as an output of the CSD activities. The technique adopted was the Line of Balance. It was based on the architectural, structural and building services drawings in the basic design stage. Due to the physical characteristics of the aquarium facility combined with different production batch sizes, it was not possible to keep a unique takt-time for construction activities. For this reason, each construction activity had its own production pace.

After the construction LOB completion, a reverse supply system was devised based on the location breakdown structure adopted in the LOB. The location breakdown structure of the aquarium facility set the designers' and contractors' work packages and deliverables; plus, it enabled the alignment of the production batch sizes and sequence among design, supply and construction. Hence, this system changed how contractors and designers should deliver their products and documentation for construction.

The pull flow in the aquarium project took place at a strategical level, i.e. from the construction master plan (LOB) to the supply master plan; and, from the supply plan to the design master plan. At the operational level, the production system **mixed pull and push flows (Kiiras & Kruus, 2005)**: the production of design and construction followed their master plans in a push flow, while the suppliers produced their elements in a pull flow, known as the CONWIP (Hopp & Spearman, 2011).

The design plan was pushed to meet the deliverables' deadlines specified in the supply system. The design work packages were assembled in consideration of the required design information to the subcontractor's process based on the location breakdown structure. The boundary between the supply system and design plan is the interface between push and pull systems, as described by Hopp and Spearman (2011).

The CONWIP had pull flow at the supply system in two points: (1) at the last supplier's process, i.e. the delivery of the items produced to the client based on construction demand, and (2) at the first supplier's process of the stream, which was pulled by the last process. Figure 75 represents the mixed pull and push flows adopted for the aquarium project.

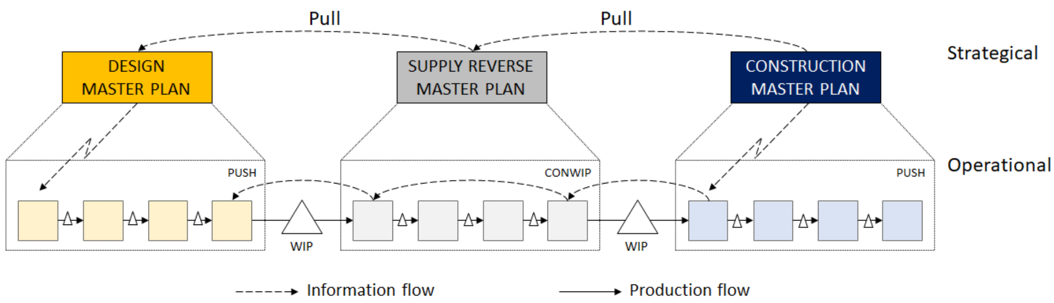


Figure 75: Mixed pull and push flows through the interfaces of Design-Supply-Construction in Study 1.

Although all milestones of the reverse supply system were controlled (shop drawings, fabrication, shipping, inventory on-site, etc.), Company C did not control the supplier's production in its operational level. The milestones were similar to checkpoints in which updates in priorities, sequence, batch and deadlines were reviewed based on the construction master plan (LOB).

The pull flow was quickly deployed in the project due to the adoption of the same location breakdown structure from the LOB by all plans. It reduced the **batch size** for contractors and designers. Consequently, the pull system with small production batches made the communication and exchange of information more effective, reducing the work in progress (WIP) and making the wastes visible. Although the **WIP** in the project was not measured, it was planned to protect the production system. To absorb the project's variability, WIP buffers (Hopp & Spearman, 2011) were distributed into the construction plan, the reverse supply system and the design plan. However, by controlling the LOB could have been to control the execution of the stages of Design-Supply-Construction. This could have been possible especially because the production batches were following the same location breakdown structure, i.e. the same production batch size.

To conclude, the execution of the CSD using the available information from designers and suppliers was essential in order to plan the construction of the aquarium. At the same time, the CSD pulled and supported the stakeholders in the process of decision-making, providing information about the impacts of different design solutions. Moreover, the LOB was being updated along the design development, impacting in the reverse supply system milestones. This production system was created to plan and control the project, but also to support the suppliers and designers in planning their work to meet the construction demand.

4.1.10 RPS1 Contributions to the Model

In this section, the study's outcomes are presented that contributed to the creation of the first version of the model. RPS1 outcomes draw on how to design dependent and connected production systems utilising pull flow. Furthermore, the study introduced the use of a location-based tool to align the production batches, reducing the WIP among the production systems.

Its main contribution relies on the pull system among interfaces of design-supply-construction at the strategical level, since there was not a structured system to operate the production (Figure 76). The development of the project production system started at the CSD, by devising the construction LOB. Following the same location breakdown structure, the supply system was devised in reverse order until the designers' deadlines for final deliveries of design documentation for subcontractors. The design packages were assembled based on the right information needed by the subcontractor to prepare the shop drawings and fabrication of items.

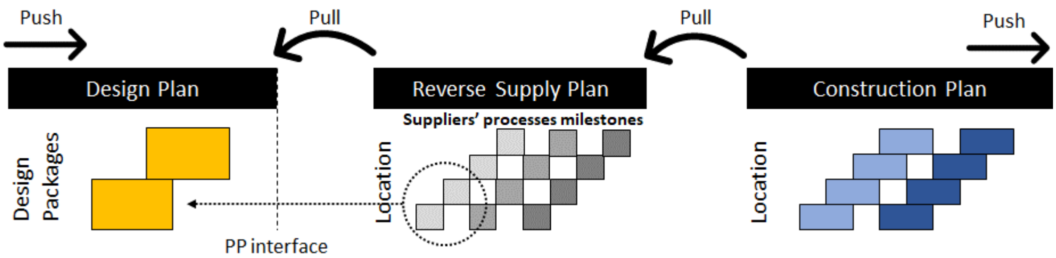


Figure 76: RPS1 contribution to model - project production system.

4.2 RETROSPECTIVE PRACTITIONER STUDY 2: CONNECTING CUSTOMISATION OF RESIDENTIAL UNITS WITH CONSTRUCTION

The retrospective practitioner study 2 (RPS2) was carried out in the construction Company E and developed within the department responsible for controlling the customisation process of the residential units. The study was selected in order to demonstrate the direct relationship between only two dependent departments: the construction and customised design of apartments. It was motivated based on disruptions in the workflow on construction sites due to the late delivery of design of the customised units (apartments). The solution developed was analysed and evaluated to develop the artefact of the thesis.

Section 4.2.1 briefly describes the company and the department of customisation. The research process is presented in Section 4.2.2. Sections 4.2.3 to 4.2.7 introduce the significant integration challenges for the customisation department and the solution implemented to align the customisation activities with the construction. Section 4.2.8 points out the findings, internal evaluation and discussions around the study, in an attempt to correlate it with the pre-existing theoretical knowledge. Section 4.2.9 concerns the main contributions of the study to the model development.

4.2.1 Study Description

RPS2 took place in the residential unit customisation department of construction Company E in Fortaleza, Brazil, between August and September of 2014. Company E was founded in 1980 and has more than 1000 employees spread over four Brazilian states. Moreover, the company develops residential buildings in three main types: economic, standard and luxury apartments. They vary in the unit area, price and location.

The construction Company E began implementing lean construction in 2012, mainly on the construction sites. As a natural evolution of the lean in the company, other departments started implementing lean, such as the purchase and customisation departments.

Company E offers its clients the option to personalise their apartments. The residential unit customisation division has the function of offering to customers options for personalising the design of their residences and controlling the changes of the units regarding the demands of construction and clients. The customisation of the units is a crucial sales strategy for the company; although it is not proven numerically, it adds much value to the customers. On average, more than 50% of the residential units are customised in any one project of the company.

Company E allows the clients to change the apartment layout (with a limited restriction), openings and finishings, which is classified as “free customisation”. The client can also choose one option of personalisation among others, which is called “mass customisation”.

The customisation department is one of 18 departments within the construction company matrix, in Fortaleza. The department is linked to the Planning Department and it comprises six employees.

4.2.2 Research Process

Similar to the previous study, the retrospective study 2 has, as its objectives, to (a) understand the research problem in depth; (b) understand the context in which the solution to the problem was developed; (c) understand how the solution developed for planning, and control the stages of customised design and construction integrated in both departments; (d) connect the designed solutions with the theoretical background.

The data of this study was produced during 2013, yet the documental records from the other company's projects were developed earlier (2008–2013).

The research process started with the diagnosis of the customisation process, followed by the development of solutions, and then their implementation. The sources of evidence used in the study are described in Table 17. The findings were evaluated, and the contributions were translated in the first version of the model.

Table 17: Sources of evidence for each phase of the RPS2.

	Study Phase / Aim	Sources	Developed in
1.	**Awareness of the problem**		
a.	Understand the processes in the residential unit customisation, the context of the study, the relationship between the department and the construction	• Secondary document analysis: MS Excel sheets of customisation control, call for customisation letters, drawings, lookaheads sheets from sites • Semi-structured interviews with department's employees	Flowchart, DFD and VSM of the customisation department
b.	Diagnosis of the customisation demand of the company	• Secondary document analysis: MS Excel sheets of customisation control, archival records of previous four projects with standard typology • Interview with department's employees	Chart and table crossing project typology, customisation options, quantities, percentage
2.	**Suggestion of solution for departments**		
a.	Development of the mass customisation	• Secondary document analysis: MS Excel sheets of customisation, call for customisation letters, drawings, presentations • Interview with department's employees	A set of options for customisation of apartments, new drawings for layout options, new call for customisation letter, new customisation control sheet
b.	Integration between the customisation department and construction	• Secondary document analysis: MS Excel sheets of construction work packages sequence, line of balance • Interview with department's employees	Line of balance for customisation department, new customisation control sheet
c.	Customisation and LPS integration	• Secondary document analysis: Lean System on construction sites, lookahead plan from sites • Interview with department's employees and construction site manager	New Lean System notification for customisation department
3.	**Development and internal evaluation of the study's model for planning and controlling the production system**		
a.	Understand the utility of the solution for the customisation department and the construction sites	• Lookahead plan on-site (check delays), emails of notification for customisation, customisation control sheets and charts • Interview with department's employees and construction site manager	Internal evaluation of the solution
b.	Understand the correlation between the solution developed in the department	• Literature review in Toyota Production System, WIP, design problems, information flow management, location-based planning tools	Internal evaluation of the solution

	and the literature concepts and tools		
c.	Translate the department's solution in a theoretical model	• All study's data and information	Model integrated production system between customisation and construction

4.2.3 Lean Training

The study began with a kick-off meeting in September 2013 to present to the customisation staff about what lean thinking is, how the consultancy work was structured and the method to implement lean office.

Previously, at the beginning of the lean office implementation, four pieces of training, totalising 16 hours, about the lean management were taught by the consultants to the employees of the department. The content was defined based on the consultants' previous experience in the department and mainly in the construction sites of the company. The training was considered indispensable for the employees in order to: (a) understand how the construction is managed on the company's sites by the use of LOB; (b) understand which lean metrics the company uses and what options exist for customisation control; (c) learn about visual management and how it can be applied in the office environment; (d) what is mass customisation and how to define the company's strategy for residential units customisation.

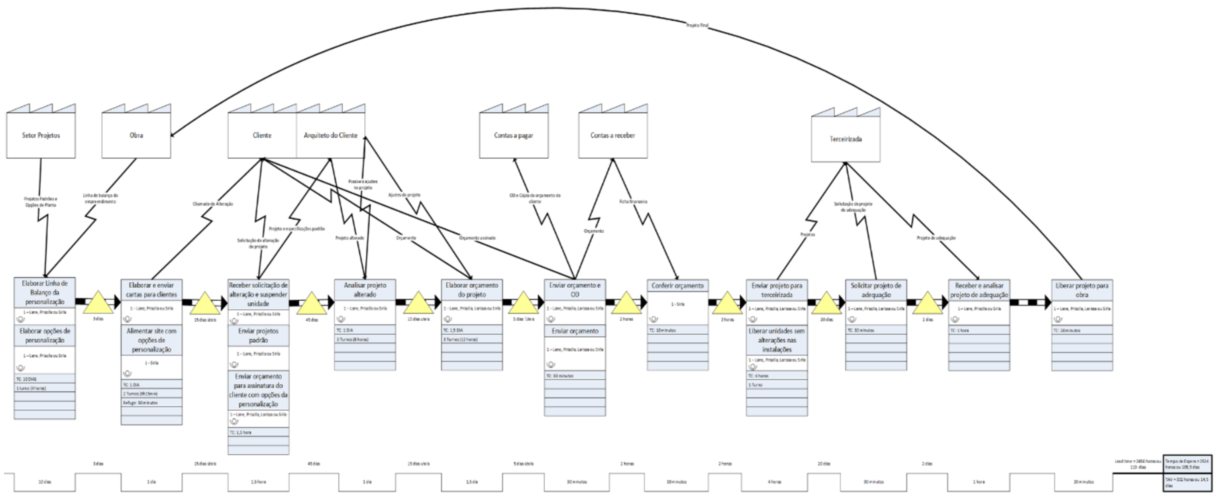
The training in visual management was based on Tezel (2011), and the content about mass customisation and how to reshape it was based on Rocha (2011a). After the training, the participants were capable of understanding the purpose of the tools, the concepts and, mainly, to visualise the problems through the lean perspective of flow, value and waste, and apply the proposed solutions easily.

Table 18: Training content and date.

	Training topic	Date
1	Line of Balance Exercise for devising a line of balance	11/09/2013 14.00–18.00
2	Metrics for production, process and customisation Exercise to control customisation processes	18/09/2013 14.00–18.00
3	Visual Management Exercise to apply visual management at the office	24/09/2013 14.00–18.00
4	Mass customisation Exercise to reshape the customisation strategy of the company	27/09/2013 14.00–18.00

4.2.4 Awareness of the Problem: The Processes in Residential Unit Customisation

In order to improve the department effectiveness, the researcher needed to understand which processes were necessary to customise a residence. The Value Stream Mapping (VSM) (Rother & Shook, 1999) was used to visualise the transformation activities, flow between them, who executed the activity, how information was exchanged, the duration of transformation activities and flows, and how to see the waste in the whole process. The VSM was developed by the researcher with the participation of two employees in the customisation department. A set of questions was devised in order to produce the tool that represents the activities in the customisation of one residence unit (Figure 77).



VSM	Lead Time	Waiting	Value Adding Time	% Value Adding
Current-State	119 days	105 days	14,5 days	12,18%

Figure 77: Current-state VSM of residential customisation processes. Source: Company C.

The customisation of units used to begin when the residential tower had the concrete structure executed on the third floor. This was the moment when the customisation team elaborated the letters to be sent to all the clients at once, informing them that the customisation of their units was available and they had two months to deliver the design of their unit to the department, and two weeks to notify the company of the desired customisation. If the client wished to have his/her unit default, it was not necessary to respond to the letter, and if he/she wished to customise it, the unit was immediately held off for the construction team, and the customer received the design documents for further customisation with his/her architect.

When the team received the architect's design, they would develop its budget and have the approval of the client. Next, the employees of the office would send the approved budget to the area of Accounts Receivable. This department elaborated a bill with the amount that should be paid by the client.

Afterwards, the payment related to the personalisation was paid, the unit was released to be executed at the construction site. If there was a change in the MEP design, the release could only be made after the appropriate adjustment of design made by an outsourced MEP office. Finally, after receiving the final design, a design documentation package of the customised unit was sent to the Construction Manager.

These processes described were impacted by:

- uncertainties from the construction progress;
- client’s commitment to deliver the design on time;
- design department in providing the right version of the detailed design;
- later units acquisition: when the clients buy a residential unit after the execution of the unit in the construction site, generating rework.

In order to reduce the variability in the customisation process, the researcher with her team decided to reduce its batch size and offer to clients standardised options for customisation. Then, the construction should pull this process – after all, the construction company could not control the moment when the clients should buy their residential unit. However, to implement this solution for the customisation office, it was first necessary to understand what the client was demanding for its residences.

4.2.5 Diagnosis of Demand for Customisation and the Mass Customisation Implementation

The researcher's intervention began through the identification of a pattern in the customisations made by the company in previous projects. Documents from the department about the customisation options of the clients in the last four projects were analysed. The data were inserted into an MS Excel spreadsheet to assess how the clients were demanding the customisation of units in standard projects. The free customisation was occurring at an average of 70% of the residential units of a project. It was identified that the items most customised were the worktops for the kitchen and bathroom (43.5%), followed by the enlargement of the living room by the reduction of one bedroom (34.8%), and the change of floor tiles and sinks, toilets and taps (26.1%) – see Figure 78.

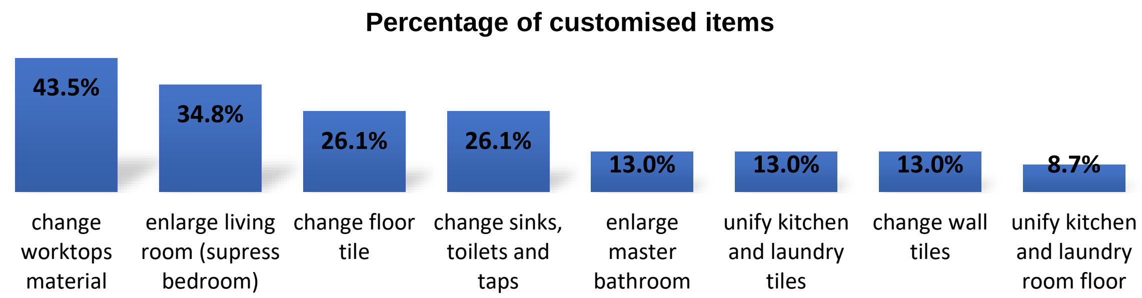


Figure 78: Percentage of customised items in the company's projects with typology standard. Source: Company C.

With this information in hand, it was proposed the mass customisation of units should take place, i.e. the company should present for the client a limited number of options for the apartment layout, finishing and among other customised items. Then, through the combination of choices, the client could have a unique apartment.

After adopting the mass customisation, the client started to receive call letters for customisation by mail and email (Figure 79) from the company, containing:

- Deadline to make the choices and communicate with the company;
- Apartment layout options;
- Options for floor and wall tiles;
- Worktops for kitchen and bathroom;
- Kitchen and bathroom sinks and taps;
- Costs of each option for customising the residence.

The number of choices and the customisable items in the apartment varied according to the project typology. The client could still opt for the free customisation; for this, the deadline was extended to enable the customer to develop the design with an architect and deliver it to the company. However, to determine the client’s deadlines, it was first necessary to plan and control the customisation process integrated with the construction plan.

Figure 79: Call letter for customisation containing a range of options. Source: Construction Company.

4.2.6 Integrating Customisation with Construction

By using the current-state VSM, Company C produced a net of work packages sequences for the customisation activity. This net was further connected to the construction work packages net (Figure 80). The construction work packages impacted by the customisation were also highlighted in a project construction net. However, the construction work packages will vary according to the type of project, the customisation strategy for the project, and the construction methods adopted by the company.

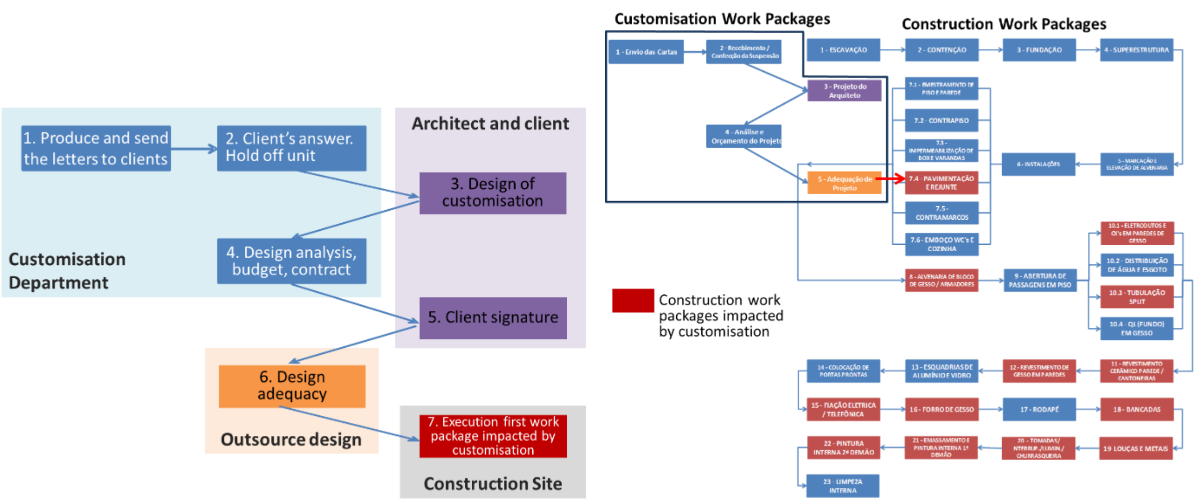


Figure 80: Net of customisation work packages sequence and its connection with the construction work packages. Source: Company C.

With the department employees' participation, the customisation activities were repackaged using the criteria of gathering similar tasks that one employee executed at once to transmit this information to an external stakeholder. The reassembled customisation packages were:

1. Produce the "customisation letters" and send them to clients.
2. Receive client's answer and hold off his/her unit with the Construction Manager.
3. Support the client's architect in the design.
4. Analyse the client's design: check for interferences, produce the budget and the additional contract, and collect client's signature.
5. Forward the client's drawings for design adequacy to the subcontractor of building services.
6. Control the execution of the first work package impacted by the apartment customisation.

Next, the duration of these packages for the batch of one residence was collected in the current-state VSM and multiplied by the two, which is the number of residences in one building store (Table 19). It was decided to work with two units because this was the batch that construction had planned and was controlling the activities. Company C decided to round up the packages duration as capacity buffers. The process should be monitored in weeks.

Table 19: Customisation packages duration.

	Customisation Packages	**Duration for 2 residences**
1.	Produce Call for Customisation Letters	1 week
2.	Receive answers and suspend the residential unit	1 week
3.	Support the client's architect	10 weeks
4.	Design analysis, budget, contract, signature	4 weeks
5.	MEP design adequacy	4 weeks
6.	Control the construction package impacted by customisation	4 weeks

Then, the line of balance for the customisation began to be devised based on the construction LOB. It was used as reference the first construction package impacted by the customisation. The customisation plan is a reverse LOB of the construction plan represented in Figure 81.

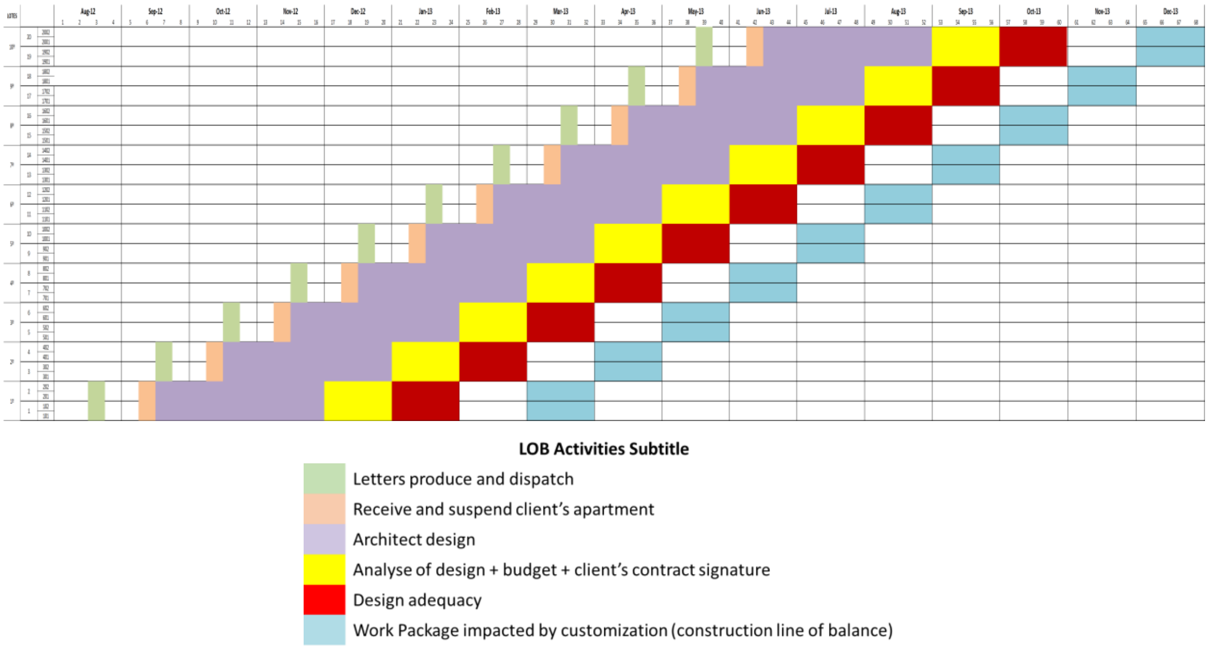


Figure 81: Line of balance for project customisation. Source: Company C.

Due to previous experiences in receiving later designs from the clients, it was adopted one month from time buffer, between the end of the customisation process and the execution of the impacted construction package. This duration should be adjusted according to the necessary time to construction purchase and to receive the material for the customised unit on-site. Usually, the first work package impacted by customisation was the apartment pavement; however, for each new project, the customisation office studied the construction packages sequence to verify it.

The activities carried out by the customisation department were controlled by a spreadsheet developed by Company C in MS Excel. Here, the deadlines were set for every apartment, and the team just needed to fulfil the executed dates and the customisation options chosen by the clients. The time limits were organised per colour header: light blue for customisation team processes; light purple for clients' deadlines; and light orange for outsourced MEP designers (Figure 82). With the data inserted, automatic dashboards and charts were generated to visualise the adherence to the plan (Figure 83), and the distribution of customisation choices per item (Figure 84).

Obra	Andar	Apartamento			Carta		o Envio da Carta	Recebimento Resposta do Cliente		o Recebimento da	Recebimento dos Projetos		para o Recebimento dos	Limite (*Buffer*)	Orçamento		o Envio do Orçamento	Assinatutra		a Assinatura	projeto à adequação		de projeto à adequação	Recebimento da Adequação		o Recebimento da	da unidade customizada		a Liberação	Crítico da Obra
	22º	2204	CM	88	10/10/2013	✗ -17	23/09/2013	13/10/2013	✓ 5	18/10/2013	13/11/2013	✗ -1	12/11/2013	17/11/2013	07/12/2013	✓ 5	12/12/2013	07/01/2014	✗ -1	06/01/2014	13/01/2014	✓ 18	31/01/2014	07/03/2014	✗ -10	25/02/2014	17/03/2014	✓ 5	22/03/2014	01/04/2014
		2203	L	87	02/09/2013	✓ 10	12/09/2013	09/10/2013	✗ -2	07/10/2013	01/11/2013	! 0	01/11/2013	06/11/2013	23/11/2013	✓ 8	01/12/2013	27/12/2013	✗ -1	26/12/2013	04/02/2014	✗ -15	20/01/2014	12/02/2014	✓ 2	14/02/2014	11/03/2014	! 0	11/03/2014	21/03/2014
		2202	P	86	10/09/2013	✗ -2	08/09/2013	13/10/2013	✗ -10	03/10/2013	02/11/2013	✗ -5	28/10/2013	02/11/2013	27/11/2013	! 0	27/11/2013	12/12/2013	✓ 10	22/12/2013	15/01/2014	✓ 1	16/01/2014	10/02/2014	! 0	10/02/2014	08/03/2014	✗ -1	07/03/2014	17/03/2014
		2201	CM	85	20/08/2013	✗ -19	01/08/2013	18/08/2013	✓ 8	26/08/2013	05/09/2013	✓ 15	20/09/2013	25/09/2013	11/10/2013	✓ 9	20/10/2013	14/11/2013	! 0	14/11/2013	09/12/2013	! 0	09/12/2013	05/01/2014	✗ -2	03/01/2014	31/01/2014	✗ -3	28/01/2014	07/02/2014
	21º	2104	CM	84	10/06/2013	✓ 30	10/07/2013																							
		2103	CM	83	09/07/2013	! 0	09/07/2013																							
		2102	P	82	24/06/2013	✓ 1	25/06/2013																							
		2101	CM	81	26/06/2013	✗ -6	20/06/2013																							

Figure 82: Spreadsheet to control the residence customisation process. Source: Company C.

Figure 83: Charts organised by processes of responsibility of customisation department, client and MEP designers. Source: Company C.

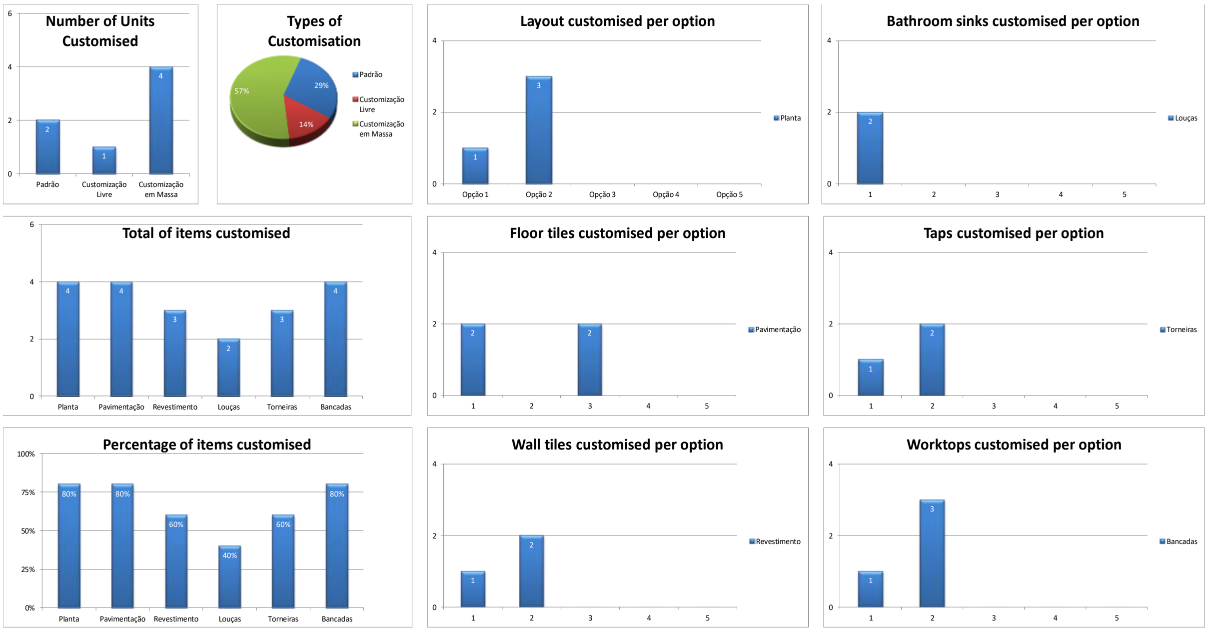


Figure 84: Charts presented the customisation options in a project. Source: Company C.

4.2.7 Customisation integrated with the Last Planner™ System

In projects where the LPS was implemented, the design of customised units was pulled by the construction site through the lookahead planning (Figure 85). Hence, if activities on-site were delayed, the request for the design was also delayed.

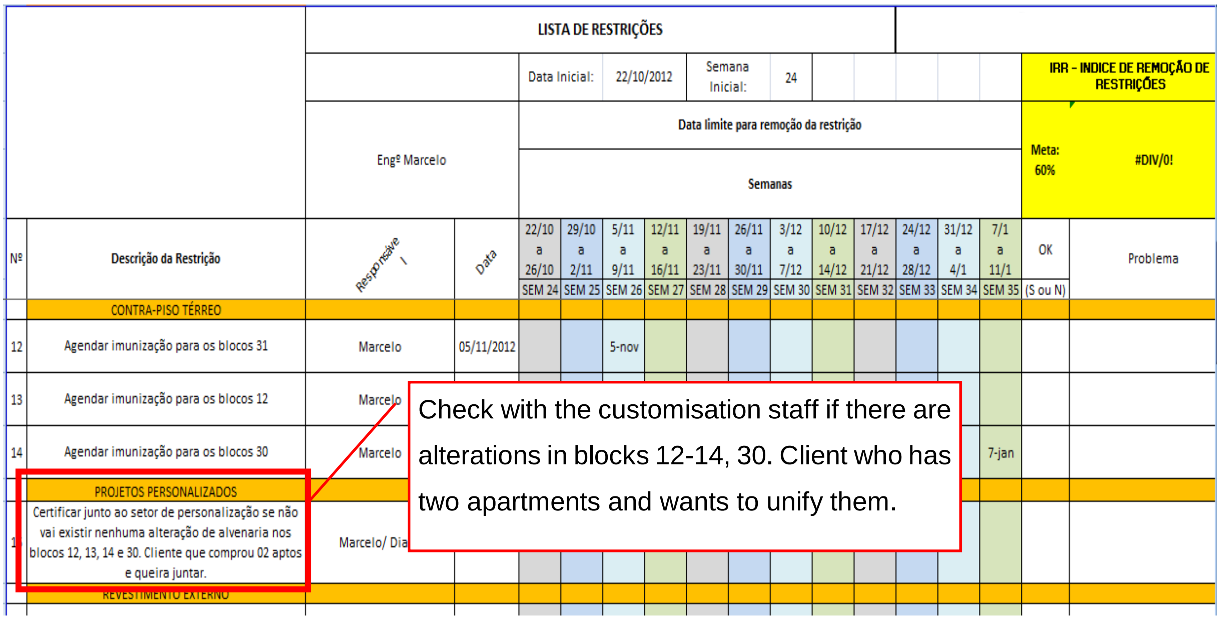


Figure 85: Lookahead sheet pulling information from the customisation department. Source: Construction Company E.

In some construction sites where the Lean System[7] was implemented, the control for the customised design was automatically made by the system. An email was sent to the customisation staff and the

[7] Lean System is a software developed by Company E in partnership with Company C to control production through the LPS. More details can be seen in (Barbosa, Andrade, Biotto, & Mota, 2013).

engineers on-site. The message stated that a work package was going to initialise on a specific date and apartment, and its respective drawings were required.

The Lean System also had a dashboard presenting four charts (Appendix 2 - Figure 171): 1) Percentage of default residential units vs the customised ones; 2) Percentage of sent call letters for customisation; 3) Percentage of call letters for customisation sent on time vs delayed; and, 4) Percentage of customised construction packages authorised for execution on time vs delayed.

4.2.7.1 Integration Benefits

The integration between the units' customisation and the construction plans was beneficial for the control of the customisation process. Previously, the department used to send the letters to all clients at once at the beginning of the concrete structure, i.e. the batch size was all the project's residential units. It caused many reworks due to the fact that not all the units were sold at that time. Moreover, some clients of the latest units to be built did not want to decide about the customisation so early.

The adoption of the LOB for planning the customisation process enabled the batch size reduction. The new customisation batch was a set of apartments, which reduced the customisation process cycle time, improved the control of the units, and clarified problems in the process which could be solved. Another benefit was brought by the common pace to customisation and construction; this means that, if the production pace changed, the customisation plan followed this variation, avoiding wastes, such as overproduction, inventories, reworks, and so on.

The mass customisation options had drawings and budgets previously defined, which reduced the impacts of delays in construction. The implementation of mass customisation was primarily to reduce variability and lead time, plus to improve the decision-making process by the clients. An example of a reduction in administrative activities and lead time can be seen in Figure 86, which represents the comparison of activities net for free and mass customisation strategies.

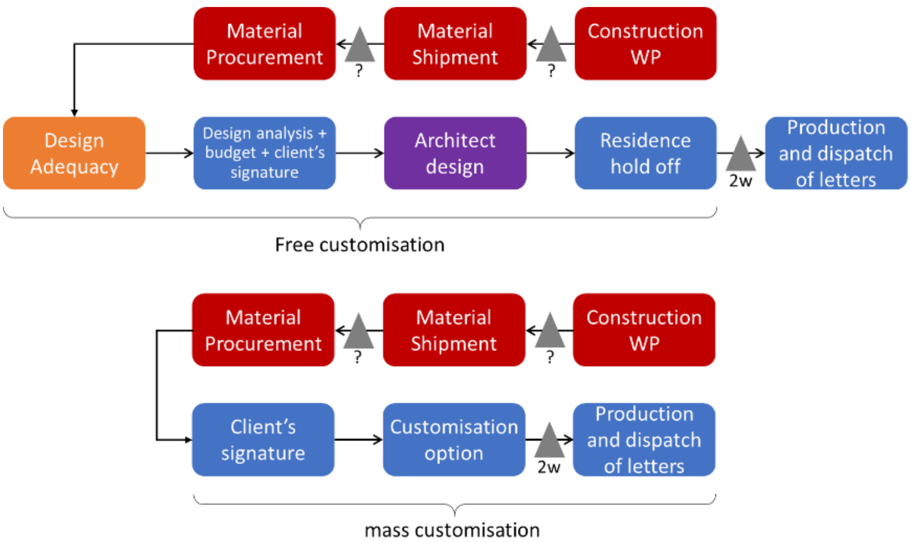


Figure 86: Comparison between the activities in free customisation and mass customisation strategies.

The results showed that clients were choosing mass customisation options rather than free customisation. Namely, half of the customised residential units in a project were built by a mass customisation option offered by Company E, as presented in Figure 87.

Customisation in residential projects

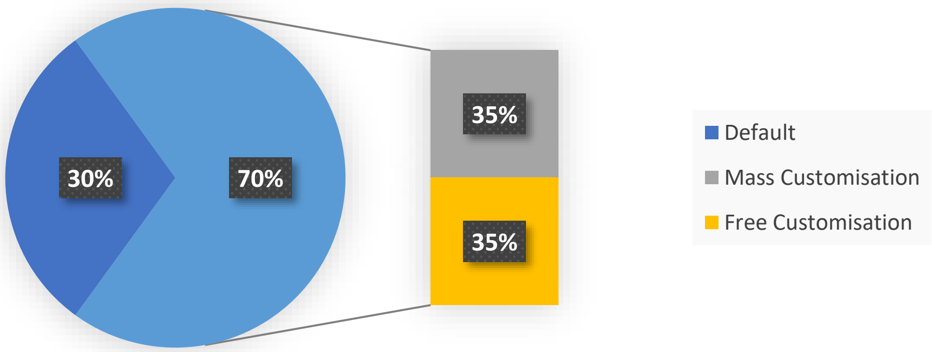


Figure 87: Impact of the mass customisation in residential projects of the company.

These implementations increased the company's interest in producing more flexible apartment layouts for customisation, to change the construction techniques and products, and the sequence of construction work packages to postpone/minimise the customisation impacts on construction workflow.

Before Company C's intervention, the construction Company E included in the client's budget only the cost of alterations, not considering the costs of rework in the apartment. After the changes promoted by this new system to plan and control the customisation process, the company began including the client's budget costs of rework, plus costs of customisation, plus costs of having an extra crew on-site just to execute the work. It reduced disruptions on the workflow caused by the late sales of apartments.

4.2.8 Analysis and Discussion of RPS2

Study 2 showed the integration between the residential units customisation with the construction. It involved the **cooperation** among the consultant, construction and customisation staff.

The **design of the customisation system integrated with construction** began by collecting information from the construction LOB and activities network, plus the company's database on customisation. The study of the company's customisation history was essential to produce a database and analyse the client's preferences according to the project typology. The company became more interested in retail sales in order to offer more options desired by the clients. This corroborated with TFV theory (Koskela, 2000), in which the processes must add value for their customers/clients.

Moreover, it was also necessary to understand how the staff work, sequences of activities, duration, required buffers, and so on. For that, the VSM was used to visualise and identify the processes, flow and wastes in the customisation of one residential unit. Added to this, the VSM was also used to define customisation packages. Then, these packages were connected to the construction packages sequence. This enabled the **decoupling point** to be defined between customisation and construction: the first construction package responsible for pulling the customisation processes (Rocha, 2011b; Rocha et al., 2016). It is important to highlight that the decoupling work package identified in the construction LOB was also drawn in the customisation LOB as the source of the pull flow in the system. The decoupling point (first construction work package impacted by customisation) determined the interface between pull and push flows (Kiiras & Kruus, 2005).

The integration between customisation and construction occurred by devising the customisation LOB in alignment with construction: same batch sizes, pace and sequence. Its **operation** required confirmation of construction demand by the customisation staff. Delays on the site should be followed by the customisation. The last planner used on-site was updating the customisation activities, and the lookahead plan was pulling the customisation deliverables for construction. As claimed by Viana (2015), in order to keep a pull production system, it is necessary to use confirmation points to check the orders, batches, sequence and deadlines. In the customisation department, this was done by following up the construction LOB.

In study 2, the JIT concepts of continuous flow, takt-time and pull system (Ohno, 1988) were applied in the production. The Customisation and Construction systems utilised a **mix of pull and push flows**. First, the construction LOB was used to pull the customisation activities and devise the reverse plan in the strategical level. As customisation activities have long lead times – 6 and a half months – it was not possible to apply a pure pull system. For this reason, the master plan was only a target to plan the department activities.

At the tactical level, before sending the call letters to clients, the staff needed to pull information from the construction site to **confirm** if the units were sold, what were the expected dates to execute them, and then update the master plan. This information was controlled by the construction team at the lookahead planning, which also performed the role to pull customisation drawings as a form to remove constraints of a particular work package. Thus, there was a pull flow between the tactical level of the construction, specifically pulled by the first customisable work package, and the operational level of customisation, at the first and last activities of sending letters and delivering drawings, respectively.

For construction, the master plan pushed the activities to the lookahead planning, which also removed its constraints, and received feedback from the weekly plans about the execution of the activities. The lookahead was crucial to bridge the strategical and operational levels of production, as well as the customisation activities. At the operational level, the weekly planning pulled from the lookahead only the work packages that were free of constraints. Figure 88 summarises graphically the pull and push flows in the production systems.

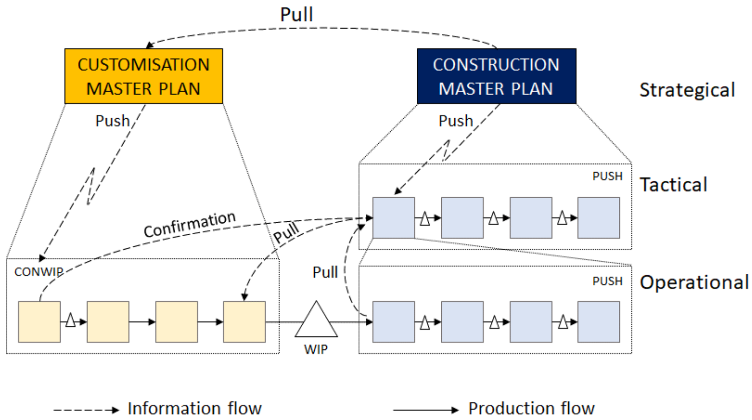


Figure 88: Pull flows at the interface customisation-design-construction.

The feasibility of the pull system is due to the use of small batches by the customisation processes. The construction **batch size** from the LOB was used to reduce its size and enhance the control of the residential units by the customisation department. Comparing the scenarios before and after the solution implementation, there was a considerable reduction in the **WIP** in the customisation processes. Yet, it was not measured at the project. It is possible to simulate the WIP in a LOB similar to the way the customisation staff used to perform their activities, versus the current mode: i.e. from the one large batch to all residential units and many months of WIP, versus 2 residential unit batch size and few months of WIP (Figure 89).

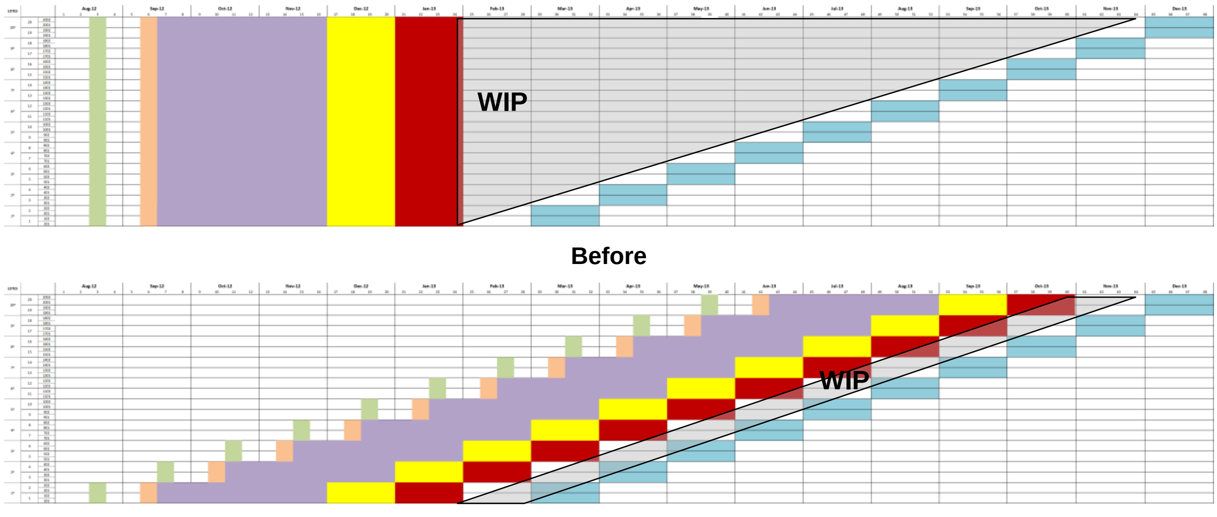


Figure 89: LOBs before and after the solution instantiation at Company E: batch size and WIP reduction.

Some WIP were planned buffers to protect the downstream activities. They could be smaller if the clients had a higher degree of reliability in delivering design drawings on time. Maybe in other cultural backgrounds it could be possible to reduce the WIP buffers.

Even in production systems protected by buffers, the customisation of units causes disruptions to the workflow. This could be avoided if other configurations of project financing could be adopted, or a superior amount of residential units sold could trigger the beginning of construction, combined with a product design flexible enough for customisation. Case Study 6 (CS6) presents another customisation strategy that provoked fewer disruptions to the workflow.

In study 2, many visual devices were used to control the project progression. Both LOBs (customisation and construction) were **transparent** in order to communicate the production strategy for both teams, performing the role of boundary objects (Star, 2010). Added to this, the customisation dashboard, plus the Lean System's dashboards and notifications emails, made the control of customisation progress simpler for both teams.

4.2.9 RPS2 Contributions to the Model

The RPS2 has brought some additional contributions to the first version of the model. The first contribution is the **integration of the work packages sequence** between two dependent systems. In study 2, this was done by drawing the work packages of customisation and construction as a unique production line. Subsequently, it is possible to identify the **decoupling point** between the pull and push flows, which, in study 2, was the interface between the delivery of the drawings for customisation and the first construction work package impacted by it. The identification of the decoupling point is crucial to understand when to pull the flow in the production system.

The adoption at the LPS, or another hierarchical production planning and control system, proved to be crucial to pull systems. The **lookahead planning** used by the construction team was the core of the system. It had four important roles: 1) Plan the pushed activities from the Master Plan; 2) Remove constraints by pulling information and actions – which, in study 2, was the pull of customisation drawings; 3) Receive information from the project execution from the operational level; and 4) Make ready work packages free of constraints for the weekly planning.

To conceive a production system progress accessible to all involved stakeholders, it is crucial to use visual management tools, such as LOBs, dashboards, and other visual devices that make the understanding of data effortless.

When comparing with RPS1, study 2 contributed to the model with the production system **control**. As opposed to the study 1, where there was a central concern in designing the project system aligned and integrated with the minimal of WIP, study 2 focused on operating the production system.

To illustrate the production system that resulted in study 2, Figure 90 presents the relationship between the construction LOB and the customisation plan graphically. In study 2, the pulled activities regarded the preparation of customisation outputs (clients' decisions, drawings, payments, and so on) as generalisable: the border system could be an engineering-to-order, make-to-order or stock-to-order fabrication items, or the detailed design. It is noteworthy that, in the line of LOB, it is possible to integrate the production batches and pace between production systems.

The construction LOB pushes the processes to be planned and controlled on-site through the lookahead planning of the last planner, while the customisation LOB pushes the processes to their execution and control. The latter is performed by the customisation control spreadsheet complemented by dashboards containing data from the clients' options and customisation progress. Before the customisation work packages execution, the confirmation from the construction progress is mandatory in order to avoid wastes in the production system.

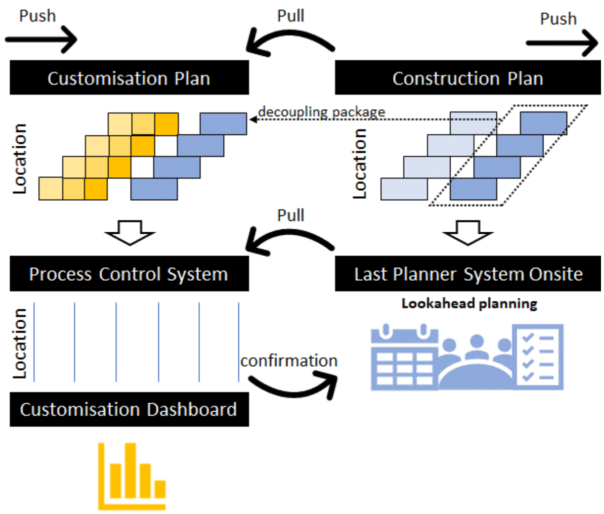


Figure 90: RPS2 contribution to model – integrated production system between customisation and construction.

4.3 RETROSPECTIVE PRACTITIONER STUDY 3: LEAN OFFICE IN A LEAN CONSTRUCTION COMPANY

The retrospective practitioner study 3 (RPS3) was chosen for this thesis in order to present the research problem in the context of an organisation. This is a construction company that outsources the design development and has several other departments to support the development of the new products. The solution devised in this study to connect, not only two (RPS2) but the whole company's departments, was used to develop the artefact of the thesis.

Section 4.3.1 briefly describes Company E. The research process is presented in Section 4.3.2. In Section 4.3.3, all the stages of the work are presented, followed by its execution at Sections 4.3.4. Section 4.3.5 shows the solution proposed for the company integration around the design development. Section 4.3.6 points out the findings, internal evaluation and discussions around the study, in an attempt to correlate it with the pre-existing theoretical knowledge. Section 4.3.7 raises the main contributions of the study to the model development.

4.3.1 Study Description

The retrospective study 3 was conducted in the same Company E from study 2. It was the last lean work the researcher did for the construction Company E, after its 13 lean construction implementations on-site and two lean offices at the Purchasing and Customisation areas. It was a result of employees' commitment to making the construction company lean: not only the sites, but also the administrative departments.

The study is a lean office analysis and proposes improvements to connect all the construction company's divisions along the new product development process. It includes integrating their processes and information systems. Although the consultancy work was conducted throughout the whole company, study 3 focused on the design area specifically, due to the fact that this department is the backbone of the company by triggering the beginning of other departments' work.

In construction Company E, the overlap between design and construction stages is a survival practice. The company begins advertising its product on the market to initiate the sales and capture some money for construction. In parallel, the company attempts to gain approval for real estate financing from a bank. At this moment, the design stage is conceptual, and it will take almost one year to be completed. The construction site starts its mobilisation some months after the project release. It is noteworthy that Company E begins the construction at its own risk, namely without bank financing having been approved, or sufficient numbers of apartments being sold. This strategy intends to increase the sales, considering the clients have confidence in the financial health of the project and company. While the company capitalises the project, on-site activities are being developed, such as earth movement and foundations.

4.3.2 Research Process

The study began on 15 June 2015 and was finalised on 18 September 2015. On average, two employees from each area participated in a set of semi-structured interviews during the diagnosis phase. Three tools were used to visualise the flow and wastes between the company's functions: flowchart, DFD and VSM current-state. After one round of data analysis from the tools and interviews, the future-state was proposed with a list of improvements and essential metrics to control. This information was presented for each sector during the *kaizen* meetings, in which participants discussed with the lean consultants if the improvement proposition was feasible in the company. There was also an analysis of software used by each department in order to integrate their processes and avoid rework. This part of the work is not presented in this thesis. At the end of this study, a presentation and a report were delivered to the company's board and main coordinators.

The objectives of this study were to (a) understand the research problem in depth; (b) understand the context in which the solution to the problem was developed; (c) understand how the developed solution integrated company's departments with the design; (d) connect the designed solutions with the theoretical background. The stages of the research and the data collected in each phase are presented in Table 20.

Table 20: Sources of evidence for each phase of the RPS3.

	Aim	Sources	Developed in
1.	**Awareness of the problem**		
a.	Understand the new product development process: who the stakeholders are, the tools used, the difficulties, the information flow	• Semi-structured interviews with design department employees, and more than 20 other company departments • Secondary document analysis: design control sheets, drawings, MS Project files, extranet for drawing exchange	Flowchart, DFD and current-state VSM of design department (new product development process)
2.	**Suggestion of solution for Company**		
a.	Proposition of solution for integration of company's departments	• Data analysis of all interviews and diagnosis tools	Future-state VSM, new concurrent engineering model for PDP (product development process)
3.	**Development and internal evaluation of the study's model for the new product development process**		
a.	Understand the utility of the solution for the company's new product development process	• Interviews in meetings with department's employees about the utility of the proposed solution	Internal evaluation of proposed improvements
b.	Understand the correlation between the solution developed in the department and the literature concepts and tools	• Literature review in Toyota Production System, WIP, PDP, information flow management	Internal evaluation of proposed improvements
c.	Translate the company's solution in a theoretical model	• All study's data and information	Model integrated design and construction systems

4.3.3 Lean Office Phases

The main activities developed in this study were: 1) Map the main processes development in all the company's departments through flowcharts, DFD and VSM; 2) Data analysis to point out the main wastes in processes; 3) Propose improvements through the future value stream map and metrics to control processes inside the units and between them; 4) Elaborate *kaizen* plans; 5) Integrate the company's information systems.

This study occurred in seven phases (Table 21):

Table 21: Study phases and dates. Source: Company C.

		Phase	Start date	Finish date	Duration
1	**Diagnosis**	Devise organisation flowchart Devise data flow diagram Devise current-state value stream map Identify global metrics Identify information systems	15/06/2015	07/08/2015	35 days
2	**Analysis**	Compile data Wastes analysis	10/08/2015	14/08/2015	5 days
3	**Future State**	Future-state proposition Brainstorming Evaluation of information systems	17/08/2015	11/09/2015	20 days
4	**Kaizen**	Kaizen plans			
5	**Metrics**	Metrics proposition			
6	**Software**	Information systems solution			
7	**Report Delivery**			18/09/2015	

The work started with a kick-off meeting to present to the company on how the work should be carried out according to the consultant method for lean office. This took place on 22 June 2015 and lasted two hours. On 26 June, there were four hours of training in VSM with the target participants.

Data were collected through non-structured interviews with the chiefs of each department and employees. In total, 25 interviews were conducted during three months, from June to September 2015 from the following departments: 1) Incorporations; 2) Legal; 3) Commercial; 4) Marketing; 5) Design; 6) Budget; 7) Units Customisation; 8) Production Funding; 9) Purchasing; 10) Construction (2 sites interviewed); 11) Quality; 12) Safety; 13) Maintenance; 14) Clients Funding; 15) Human Resources; 16) Personal; 17) Payments to Receive; 18) Payments to Make; 19) Treasury; 20) Accounting; and 21) Information Technology. The interviews supported the creation of the organogram, flowcharts, DFDs and VSMs tools, as well as the identification of wastes, information system, and current metrics.

Two structured interviews were conducted with the company's directors of finance and production. The latter is also the company's president. The main idea of these interviews was to develop the Importance-Performance Matrix (Slack, 1994), and contrast how the directors think about the company and what they expect for its future.

In parallel to the interviews, there was the diagnosis phase, in which there were data analysis and proposition of improvements and metrics. In the last phase, the focus of work was on the integration of software used by the company's department. All tools and improvement propositions were evaluated by the interviewed participants in the second round of the meeting. At the end of this work, the company's directors and department chiefs attended a final presentation.

4.3.4 The Design Department: Product Development Challenges

In the interviews with the company's employees, it was possible to develop the tools that support the understanding of the design management process. The flowchart was used to visualise the sequence of activities and the inputs and outputs of the department's processes (see Appendix 3 - Figure 172). Below is a description of the product development process:

1. The board of the construction company defines the guidelines of the project.
2. The design department requests to the outsourced designer the topographic study.
3. After receiving the study, it is delivered to the outsourced architectural designer and they are requested to provide the preliminary design of the project.
4. The staff use this design to hire other designers (structure and MEP) and approve the project in the municipality authority through the legal design.
5. The Design division receives the preliminary designs from designers and shares these with the Marketing staff.
6. Clash check between design disciplines.
7. The staff send the structure and MEP legal designs for approval to the local authority.
8. If the preliminary design documents have no interferences, the pre-detailed design stage can start.
9. The study of interferences between pre-detailed designs is outsourced.
10. The pre-detailed design is sent to the Budget division.
11. The detailed design stage begins.
12. The foundation's detailed design is delivered to the construction site.
13. After receiving all detailed designs, their validation is sought.
14. The detailed design should then go to the Residential Customisation office, interior designer and construction site.
15. The design department develops the Owner Manual.

In this product development process, the design department had difficulties in controlling the design flow. The designers began developing design documents in the advance stage without considering the interferences check between disciplines. There was not a clear boundary between one design stage and another; there was not even the information necessary for each stage. As a consequence, many loops, reworks and waits are seen in this process.

The DFD was used to visualise all the documents exchanged by the design unit with external designers and other employees (see Appendix 3 - Figure 173). The design department exchanged information externally with:

1. Topography designer.
2. Soil surveyor.
3. Architectural, structural, MEP/HVAC designers.
4. Foundation designers.
5. Landscape and interior decoration designers.
6. Lift subcontractors.
7. City Hall projects approval department.

Moreover, internally with:

1. Company board.
2. Legal department.
3. Design coordinator.
4. Marketing department.
5. Residential Customisation department.
6. Budget department.
7. Purchase department.
8. Construction site.

Most parts of the information exchange were made by email, during meetings and via the extranet website, especial for design documents. However, not all the participant designers used the extranet, claiming it was confusing and polluted with many files, and claiming that sometimes the documents on this extranet website were out of date, which produced a parallel flow of design documents via emails.

The use of the VSM supported the understanding about the time dimension of the flowchart process, i.e. the visualisation of waits, lead time of each process, reworks, and other participants in the design management process. Through the current-state VSM (Appendix 3 - Figure 174) and the interviews with participants from a construction site and design department, Company C realised that the company's production director would make late design change orders, and many times these changes occurred after execution on-site, causing a lot of rework and loss of money. Adding to this, the design staff spent only 7.3% of their time on adding value activities, i.e. 26 days of a total of 357 days of design development lead time.

The current-state VSM showed that, for most of the time, the design department waits for design documents, even after designers establish their own deadlines. Inside the department, the employees wait for validation or signature from the coordinator and director. The validation is required by the employees due to the lack of transparency of the company's drawings and design documents standardisation.

It became apparent through the VSM the lack of synchronicity/synchronisation between designers, i.e. while the architectural design is in the detailed stage, other designers are still developing in the pre-detailed stage. When the latter find errors and change the design, this impacts the architectural designer, who needs to go back and rework his documents according to the pre-detailed stage.

In summary, the main issues found through these tools were:

- Lack of design changes control;
- Lack of clear deadlines for the design stages of the product development;
- Later design delivery;
- Design errors;
- Lack of company's standard and its transparency for designers;
- Late design change, even during the construction stage;
- Communication difficulties with production director;
- Difficulties in controlling versions of design;
- Difficulties in sharing design through the extranet website;
- Difficulties in checking interferences between different design disciplines;
- The marketing division receives design with interferences problems, which are advertised on the market. It does not guarantee that the design of publicity material is the same as that received by clients, thus decreasing the value generation;
- Lack of collaborative workflow among external designers and the design office;
- Lack of standards of information content for design stages, especially detail stage which is delivered to the Budget and Marketing divisions;
- Lack of standardisation for design documents and its delivery to other company departments.

4.3.5 The Solution Proposed: The Design Department as the Company's Backbone

A set of propositions was developed for the context of the enterprise, but not implemented. The main challenges faced by the design office of the construction company should be partially solved through the implementation of the following actions:

- Design plan containing all the projects to be launched during the year;
- Define the design development stages and deadlines for each phase according to the project's plan;

- Apply LPS in design activities to plan and control the staff activities but also the external designers;
- Define the construction company standards, then elaborate a Manual for Designers explaining how they should meet the company's standards;
- Apply the Stage-Gate method in order to have the design development at the same stage for all designers, avoiding the loss of control of design changes and reworks among the different disciplines at various stages at the same time;
- Promote collaborative meetings during the transition of design stages, namely Gate, using checklists to formalise the achievement of necessary design details, with the participation of designers, production director, and the department manager. As the director is the person who changes the design, his participation is primarily in the Gate meetings. The director should be informed about the design development, and he should propose an improvement for design during these meetings;
- Implement a BIM workflow among the company's designers to facilitate the search for interferences between disciplines, extract quantities for the budget division, and promote the 3D visualisation of the project;
- Define the stages of design development that each area should work with: Marketing – basic design; Legal – legal design; Residential Customisation – detailed design; Budget and Planning – legal and detailed designs.

The future-state VSM was used to propose these solutions and make them transparent. In Figure 91, it is possible to see the *kaizen* boxes for each process, the design stages proposed and the Gate meetings.

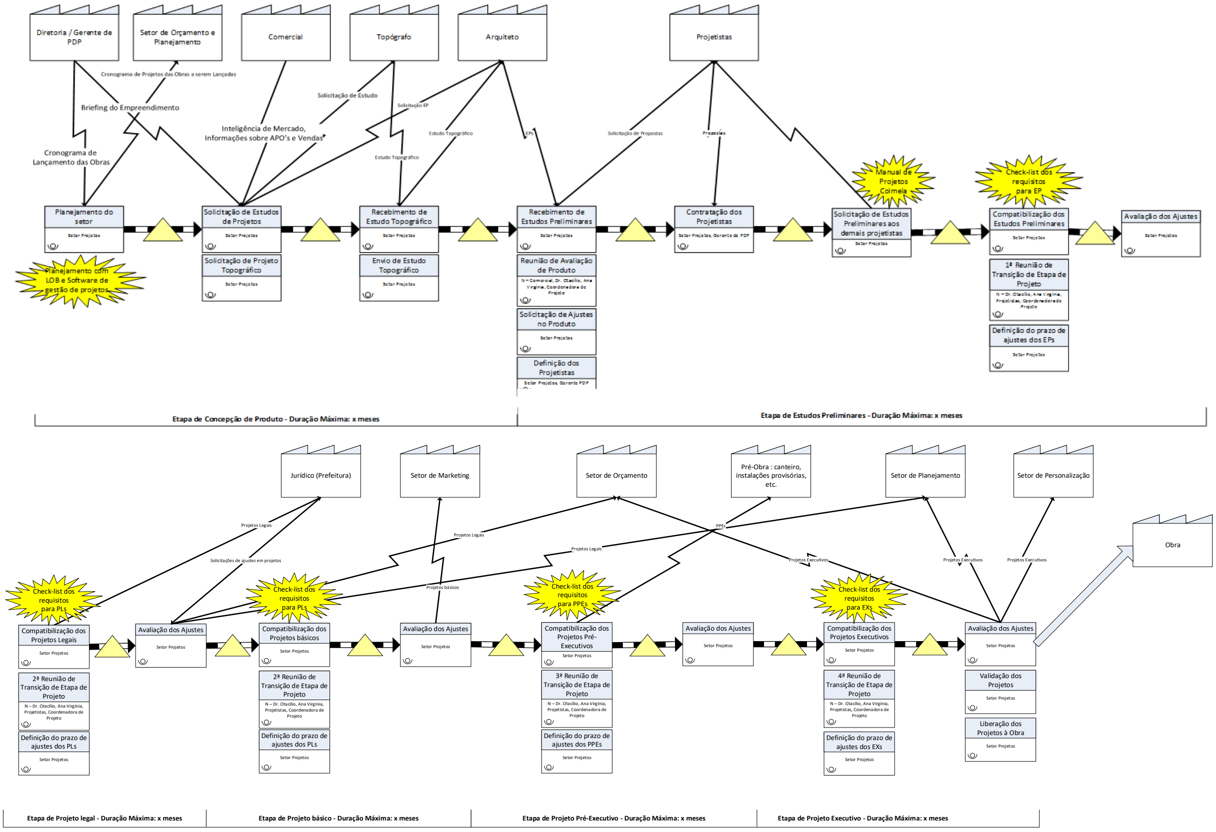


Figure 91: Future-state VSM for the design department. Source: Company C.

However, in order to make these actions real in the company, it is necessary to structure better the design department and its relation to other areas. The latter rely on design information, from the moment of plot land acquisition, passing through the production funding, legal department, purchasing, marketing, commercial, residential customisation, budget, and the construction. These areas use design documents at distinct levels of development. For example, the legal department needs the design for a municipal permit to build. Due to this variety of design information requirements, it was defined, together with the company, the main level/stages of design development:

1. Profitability and conceptual studies.
2. Preliminary study.
3. Legal design.
4. Basic design.
5. Pre-detailed design.
6. Detailed design.

In Figure 92, it is possible to visualise the new product development model for the company, containing the six stages of design (green arrows) adopted by the construction company in parallel with departments that work with the corresponding design stage. Because the company begins the construction without the design completed, the budget and the CSD activities were anticipated. It was proposed for these activities the use of legal design as input for their processes and the work concurrently with the basic design stage development. The preliminary information generated by these activities should be utilised in other areas, such as the purchasing and marketing. The budget and CSD should be reviewed and updated as soon as the detailed design is ready. It noteworthy that the construction sites already use the LOB to design their construction system and master plan.

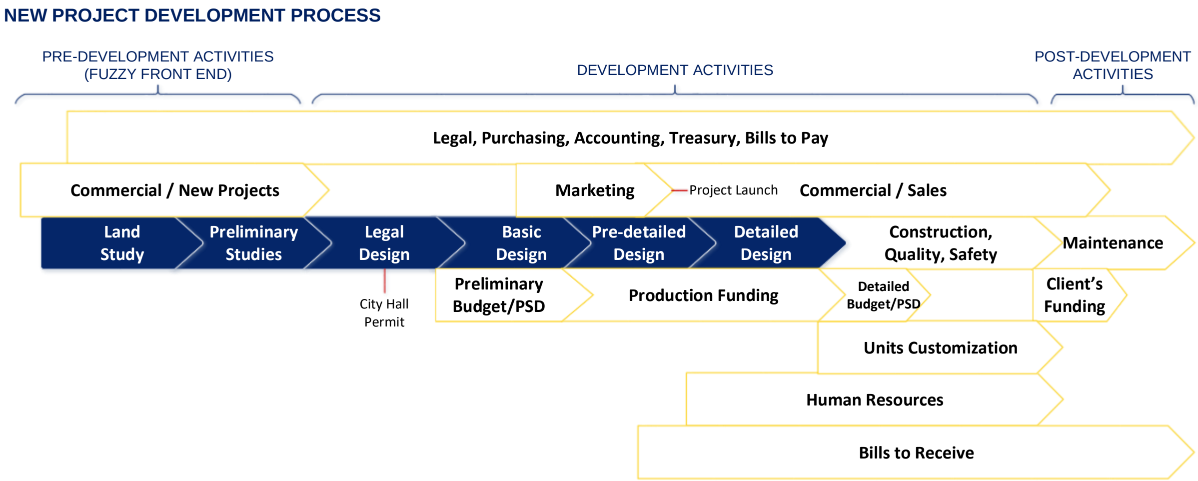


Figure 92: Company's design stages and its relation to other departments through the new project development process. Source: Company C.

In order to keep the departments working with the right design information, it is important to control the design stages. For this, it was proposed to implement the Stage-Gate method, in which documents from each design stage should be sent to the related area after passing through a formal meeting for data check (gate meeting). This decision was made based on a number of employees' complaints about the many design changes throughout the project development, which they were not informed of, or they had not received the most recent version of drawings, which was causing many reworks and loss of information. Moreover, with the definition of each stage duration, it may be easier for the design staff to control and manage the design process.

4.3.6 Analysis and Discussion of RPS3

Study 3 began with a diagnosis of the product development system at Company E. The use of the three tools – flowchart, DFD and VSM – applied in all the company's areas, followed by the interviews, allowed Company C to visualise the relationship among the departments and their workflows. The work was carried by connecting the data collected from the design department with other areas. For instance, Company C detected that the number of stakeholders that rely on design documents was higher than described by the design staff. Furthermore, the tools showed that an extra informal stage of design was occurring (basic design) without any control.

Although the overlap between design and construction was a formal strategy used by the company, the product development was being conducted as traditional projects, i.e. sequential and linear. For this reason, there were complaints from the construction sites about late delivery of design which did not meet the construction company's standards.

Then, the solutions proposed in the RPS3 had the intention to clearly define the design stages throughout the project development; to define the required information into the design drawings through the checklists and the company's manual; to specify all departments that use design information and in which stage, as an activity-stage model; to control the design development through the Stage-Gate method (Cooper, 1990); and, mainly, to promote the collaborative meeting among designers and company's employees.

This solution was not implemented by Company E. However, a positive impact was expected on the construction, mainly because the company overlaps the design and construction stages.

It should be attractive to the company that starts the CSD in parallel with the basic design development to provide feedback to the designers about the constructability and costs. Moreover, the construction sites that already apply lean construction tools should inform the design and planning departments of what information they need according to the LPS. Then, through the phase schedule and the lookahead planning, the construction should pull detailed information from design, budget and planning divisions. Hence, the Construction Managers would not need to: 1) extract quantities from scratch to purchase material, hire manpower and rent equipment; 2) to receive unnecessarily detailed design; instead, to receive the desired detailed design for that construction phase; and 3) to review with the planning staff the production rate for the phase and the crew size.

However, to implement these changes and integrate the design development with other departments, especially construction, the company must make decisions before the project starts, i.e. in the design system design. It comprehends decisions about how many stages a project will have and what information they must contain; decisions about the workflow among stakeholders; definitions on the distribution of design information from the stages to different areas of the company; decisions about software to be used to produce and exchange design documentation; definitions on the design planning and control, as well as others. Figure 93 summarises these descriptions about how an integrated system should be regarding the managerial activities for production systems (Ballard & Koskela, 2009).

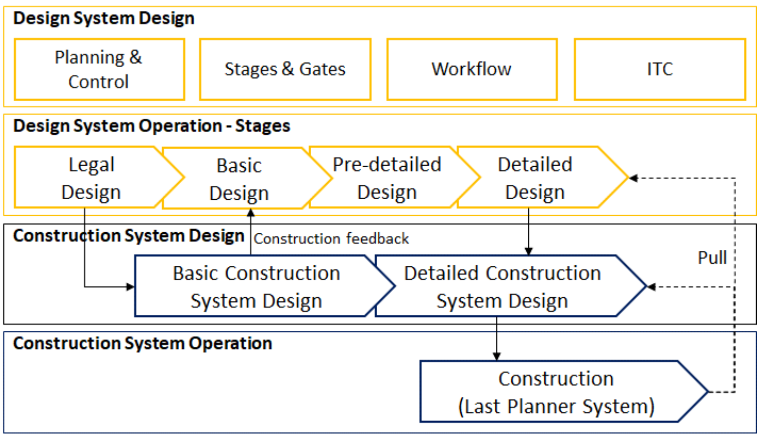


Figure 93: The solution proposed for the design management process to be integrated with others company departments, such as planning and construction.

4.3.7 RPS3 Contributions to the Model

RPS3 presented the problem of integrating design and construction through the perspective of an entire company, and the necessity to expand the relationship to all the departments that somehow depend and contribute to the design and construction progression.

The study contributed to the model by adding the macro view of the product development through the managerial activities of design, operate and improve. It was highlighted the necessity to design the system for design collaboratively at the company. A set of decisions was made, such as to define the production planning and control, the stages and gates, the workflow and the information technologies to develop the design solution.

The definition of the design stages and the level of detail of information in each stage is essentially to connect the design to other company departments, or even to outsourced stakeholders. The role of the gates is to check the right content expected from design at a particular stage, and then disseminate the information when approved. All the disciplines should progress at the same level of detail using BIM to reduce errors. The gate meeting may also be the moment to promote the shared understanding of the project to all involved stakeholders.

The operation of the design overlaps the CSD and operation, which generates opportunities for collaboration between designers and builders. As long as the CSD is progressing, it should always receive and send information for the design development, so the level of detail of both is progressing concurrently. It promotes more assertive decisions for both stages.

Construction should be planned and controlled through the LPS. It should pull design information and decisions about the construction system as well. The model that resulted from the RPS3 is presented in Figure 94. This was combined with the outputs from study 1 and 2 to generate the first version of the model that is presented at the end of this chapter.

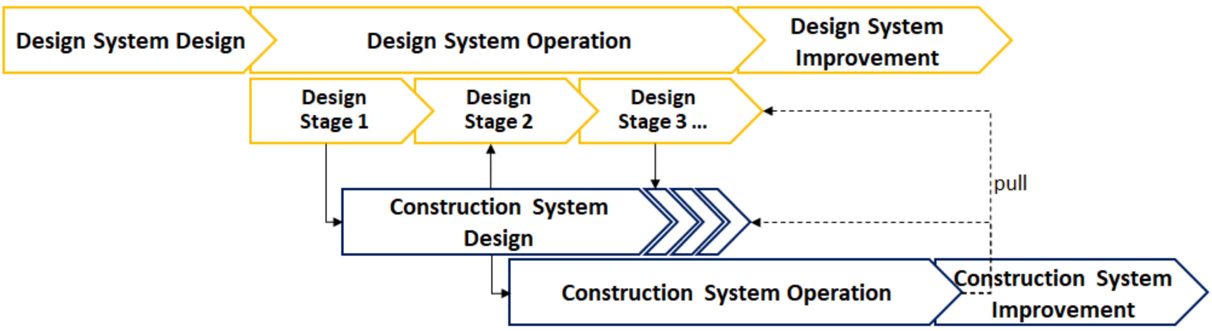


Figure 94: RPS3 contribution to model – integrated design and construction systems.

4.4 RETROSPECTIVE PRACTITIONER STUDIES DISCUSSION

In the retrospective practitioner studies section, the researcher presented three professional practice studies related to the overlap between the design and construction stages. They are studies within different contexts, where principles and tools of lean management were applied to integrate design and construction management.

In the first study, the researcher worked in the context of a complex project, targeting the integration of international suppliers, designers and builders, i.e. different companies. In the RPS2, the context of work was two departments of a lean construction firm: customisation and construction. In the RPS3, the context was all areas of a lean construction company becoming integrated through the design development stages, including the construction. The contexts of each study are represented in Figure 95.

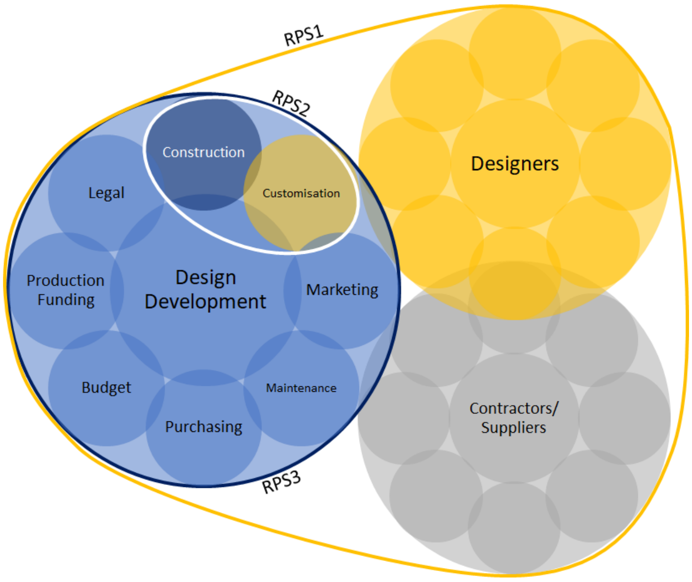


Figure 95: Contexts of the retrospective practitioner studies.

The solutions proposed for these different contexts were developed sequentially, and the solution from RPS1 was applied in RPS2. Moreover, the solution for RPS3 depends on the use of LOB to design-construction systems in the company's projects.

In studies 1 and 2, the location-based tool for planning, namely, the LOB, aligned the production batches, work packages, sequence, pace for different stakeholders to meet construction demands and work integrated through the concepts of JIT.

In study 3, it was established within the construction company the connection points between the design and other departments through the stage-gates, including the CSD at an early stage of design development and, later, using detailed design.

These studies are examples of the benefits of the LOB, or another LBS tool, to unify different stakeholders' plans. Integrated plans are the first step for integrating the project's decisions, pull information/actions and minimise wastes in the construction industry. Studies 1, 2 and 3 also contributed to answering some of the research questions. It can be seen in Table 22.

Table 22: The main contributions of the retrospective practitioner studies for the research aim and objectives.

Aim/Objectives of the Thesis	Studies 1, 2 and 3 Contributions
Devise a **model** to **design, plan and control** the stages of **design and construction** in the context of projects with **overlap** between these stages, using LBS **tools** and other **lean tools to pull** and **align the project production**	The RPS 1, 2 and 3 contributed to the creation of the first version of the model. Study 1 presented the integrated production design for construction, supply and design through the location breakdown structure. Study 2 contributed to the operation of the integrated production system using the LPS, and defining the decoupling point between push and pull flows. Study 3 shed light on the departments' integration using the product development phases as the main structure to connect the production system processes. In study 1 and 2, the LOB was used as an LBS tool.
how to use LBS tools to **structure the work** for design, supply and construction	The LOB used in the studies was used to design the production systems. It represents collaborative decisions regarding the production system and the product design. The future facility in the construction project should be divided into small batches through the location breakdown structure. The definitions of work packages, sequence, dependencies and duration should follow the location structure. The upstream processes should be planned reversely based on the construction LOB.
to **assemble design packages** to meet suppliers' and construction requirements	Design work packages were assembled differently in study 1 and 2. In the first one, a design package was assembled as a collection of detail drawings necessary to be delivered to the supplier. The design package would then contain data from different disciplines and areas of the facility, i.e. be larger than the batch used by the supplier. In study 2, the design for customisation had the same size of the construction, i.e. the apartment.
Determine the **decoupling point of design** development	It is necessary to determine the design decoupling point to conceive the work packages network of the neighbours' production systems as a single production line. Then to mark which work package pulls the upstream processes. The complexity of the production systems varies from project to project, and the system may have more than one decoupling point, highlighting the interface between push and pull flows.
Analyse existing **types of pull production systems**	In construction projects it is very difficult to have a pure pull system. All the studies demonstrated a mixed production system. It was seen the use of pull flow in the strategical levels to devise the reverse master plans based on the construction LOB. Then, in the tactical and operational levels, there was a mix of CONWIP, push and pull flows.
how to measure and manage the **work in progress and buffers**	The WIP was not measured; however, suggestions of how to conduct it emerged: the WIP might be measured through the LBS tool, counting the number of days a work package is waiting to be used by the next activity. Namely, it is the blank days on the LOB. It is noteworthy that the WIP may be purposeful to protect the system against variability, called WIP buffers, or a result of different production paces.
identify the **best tools to control the production system**	The studies 1, 2 and 3 showed that it is important to use the LPS on-site, plus control spreadsheets complemented by dashboards as visual management devices. Also, in the scale of the product development process, Stage-gates are suggested to develop and control the project in shorter cycles.

4.5 FIRST VERSION OF THE MODEL

Figure 96 below is the first version of the model to integrate design and construction systems in the context of overlap projects. It is the product of the combination of the three models presented at the end of each retrospective practitioner study. The first study took place in an aquarium project and included a large international supply chain of engineering to order companies. The second study was carried out in the customisation department of a construction company and focused on the integration of the construction plan and control process with the customisation of apartments. The third study took place at the same construction company of study 2. However, it focused on all departments' relationships with the design function and the product development process.

The model is explained by dividing it into two parts: 1) **The product development process**, and 2) **The pull production system**.

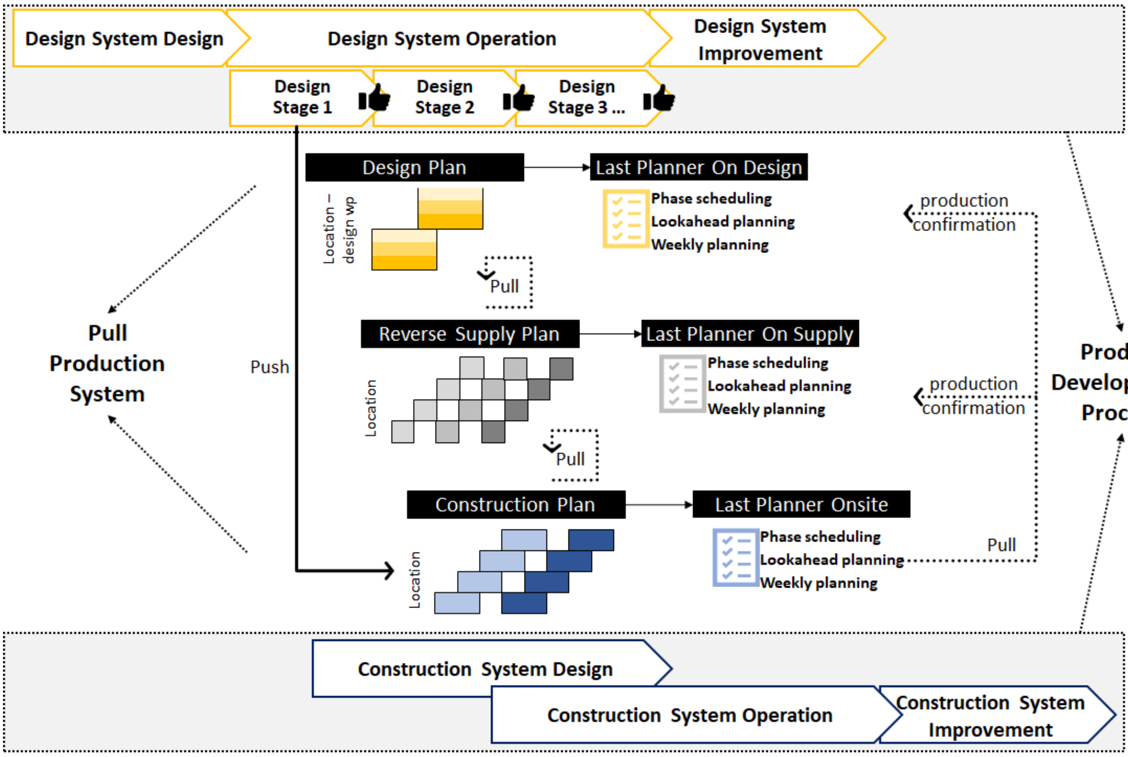


Figure 96: First version of the model to integrate design and construction systems using location-based scheduling tool.

4.5.1 The Product Development Process

The model focuses only on the phases of design development and construction, ignoring other phases of the product lifecycle. Then, it combines the overlap of design and construction systems management. The managerial activities occur in production design, operation and improvements (Koskela & Ballard, 2003). In each phase of management decisions, tools and actions must occur to integrate design and construction planning and control. In the **Design System Design** (DSD), questions proposed by Ballard and Koskela (2009) added to the retrospective studies' findings are:

- How many stages will design development have?

- What is the information content necessary in each stage?
- Information, technology and communication tools. It includes what software to develop the design;
- Standards for data exchange. It includes the files extensions of design documentation; what stakeholders should receive design information from each design stages;
- Design representation (BIM or CAD drawings, for example);
- Contractual relations and incentives;
- Decision-making structure;
- Validation and verification structure;
- Targets (Target value design/cost);
- How will the client be involved in the design process?
- Methods and tools. Will design operation adopt set-based design, choosing by advantages, collaborative planning, LPS, agile?
- Physical layout of designers, especially when co-located.

The number of design stages must follow those proposed by the architect's institutions, such as RIBA (RIBA, 2013), in order to facilitate the chosen procurement route. However, the adoption of the Generic Design and Construction Process Protocol (Kagioglou et al., 2000) is a great tool by which to design the whole NPD process and manage the phases. At the design stage, more stages could be adopted if the project's participant judges it is necessary.

Next, the **Design System Operation** (DSO) should be divided into the stages defined in the DSD. Project teams should use future-state Value Stream Mapping (VSM) (Rother & Shook, 1999) or other process mapping tools to define the workflow of the design development process and indicate the gates each design stage will have. Stage-Gate (Cooper, 2016) is suggested to support the development of the design versions to avoid reworks and to better control the drawings/models versions between stakeholders. Still, the use of the Last Planner System (Ballard, 2000a) to plan and control the designers' activities is recommended, primarily because it will be related to the last planner from the construction site. However, other methods such as Agile can be adapted for the design management (Demir & Theis, 2016), notably to include the client in the design process. In order to quickly change the design solution and check interferences between disciplines, it is also suggested that BIM modelling and the definitions of the LOD be used throughout the design stages (Svalestuen et al., 2018). The design plan for the detailed design stage will be a product of the reverse plan derived from the construction master plan described in the "pull production system" section.

The early participation of construction stakeholders is mandatory for starting the CSD in concurrence with the DSO. The CSD should use drawings/models from a design stage containing more information than the conceptual design, for example geometry, volumes and structural system defined. However, the project team should settle which design stage will be the input to the CSD.

The CSD should be developed using location-based tools such as LOB or flowline, but not the Takt-Time Planning (TTP) because of the high level of uncertainty at this project stage, but also because of the lack of subcontractors' participation in the planning. The main idea of these tools is to break down the work into small batches that are based on location and then to plan the activities, set their sequence and the necessary resources to deliver the project. Location-based tools aim to achieve a unique production pace for activities, which eliminates WIP and reduces the project lead time. These tools have proved to improve project performance, supporting waste reduction and decreasing lead time, costs and risks.

Location-based tools are appropriate for the construction industry, mainly because we can visualise many production characteristics, such as delivery and production paces, crew workflows, cycle time, lead time, buffers, WIP, and so on. These tools are flexible regarding the plan level of detail, which during the CSO will be gradually detailed with construction participants.

During the CSD, the construction team should use 4D BIM models to study the site flows. Herein, construction feedback is expected to designers about constructability, improvements in the product to reduce costs, time for construction, and so on. In the CSD, the constructors and subcontractors (when available) will pull some design decisions in order to study construction strategy, main transport equipment, site layout, flows, and activities duration. They will be able to present to designers the advantages and disadvantages of each design solution from the point of view of construction lead time, costs, risks, procurement and quality. The CSD will evolve according to the design development, and its output is the construction master plan.

In overlapped projects, the CSO occurs in concurrence with the design system operation, which brings many opportunities for design and construction improvements. Then, in the **Design System Improvement** (DSI) and **Construction System Improvement** (CSI), the project participants should gather and analyse data to implement *kaizen* in the next projects. However, the improvements do not necessarily need to be pointed out at the end of the project, but during the system operation by means of tools and techniques for problem-solving, such as the 5WHYs for tasks not completed, A3 to report a problem, and so on.

The operation of design and construction systems is better described in the next section, the pull production system.

4.5.2 The Pull Production System

The lean value stream focuses on client requirements. However, in a project with overlap between the design and construction stages, the latter stage is the final internal client who will dictate how to build the facility, at which pace and lead time, knowing the construction demand is important to structure the work of designers and suppliers. For this reason, the CSD should start early in the project development, as soon as the drawings/models are becoming more mature, and then will be gradually developed following the design/information updates. The CSD is responsible for studying and describing the construction demand that is represented by the LOB or flowline. In the same way that the location-based planning tool is useful for the production planning and control for construction, so it will be useful for design and suppliers.

Then, the design pushes the building information for the CSD. Its output is the construction LOB or flowline that will pull reverse plans for suppliers, that will then pull a reverse plan for designers. The idea of using the construction batch (location) from all suppliers and designers allows the alignment of plans. The suppliers will deliver the material/components to construction following the construction batch and sequence. The same is valid for designers, who must produce the detailed design following the suppliers' production batch and sequence. This idea enables a new way of assembling work packages, and supports the continuous flow by pulling only the necessary information, when necessary, which are concepts of the just-in-time production system.

Thus, the design packages will be composed by a combination of drawings/models of a certain location necessary to be released to the next supplier. The supplier will use this pack of drawings to develop the engineering design (if applicable), and plan the fabrication of components necessary to be delivered to a particular construction location. In order to develop the reverse plan, designers must structure their work and know their production capacity to estimate the duration. On the other hand, suppliers must provide information about engineering design duration, fabrication, delivery time, and so on to produce their reverse plan.

In summary, the construction LOB receives pushed information from design to prepare the construction LOB or flowline. This will settle the milestones for suppliers to develop their reverse plans using the same location breakdown structure. Based on design deadlines from the suppliers' plan, the designers should produce their own reverse plan. However, as construction projects have uncertainty and variability, the whole production planning and control system should be connected. It is suggested that the Last Planner is used on-site, on design and by suppliers.

It is very important to classify the supplier according to their lead time. The time necessary for an ETO company to produce and deliver a component for assemblage is usually longer than an MTO company, which is longer than an MTS company that has components for delivering available in their stock. These lead times or delivery times should be included in each level of the LPS to remove suppliers' constraints and update the supply chain about the construction status. This information is primarily to keep every stakeholder in the same production sequence to deal with the right construction batch.

In **Construction System Operation** (CSO), the LPS starts with the phase scheduling based on LOB or flowline milestones. Major suppliers and subcontractors should be included in this planning process to refine the LOB and update the reverse plans (design and supply). Next, in the lookahead planning, the project participants should focus on removing the constraints, updating the reverse plans and, when necessary, replan the construction. These two LPS levels of planning are critical to confirm with designers and suppliers the right priority of production based on construction status. This idea of confirmation points was suggested by Viana (2015) in her work about integrating the planning and control system in ETO companies. However, the integration of the LPS adopted by designers and builders was suggested by Bolviken et al. (2010).

The adoption of a location-based plan for designers, suppliers and builders is expected to produce an optimal project plan based on the just-in-time principle (Ohno & Mito, 1988). A reduction of project lead time is expected and an increase in design and supply reliability to deliver the right information/material at the right time for builders.

4.5.3 External Model Evaluation

The model was evaluated during a presentation made at the IGLC Summer School on 8-9 July 2017, by the leading researchers in the field of lean construction and with experience in LBS tools. At the event, the researcher interviewed six lean specialists to collect their opinions about the model that was sent to them by email two weeks before the event. One semi-structured interview was applied to focus the data collection on the evaluation of the criterion utility and its decomposition, as presented in the method chapter. An example of the interviews can be seen in Appendix 4.

The general feedback attested that the model is useful to support the integrated planning and control of design and construction. Comments and questions were made surrounding the methods, tools, degree of overlap and pull flow.

Referring to the methods, one of the interviewees declared that the proposition of adopting the Stage-Gate method should be reinforced by replying "*How could this method allow contractors' and suppliers' involvement?*" Moreover, "*How should the gates be defined?*" The interviewee mentioned the use of Choosing by Advantage (CBA) in the design as a method to improve decision-making, and as a possible method to differ an optimal from a satisfactory solution. It was also suggested to use more than the A3 tool to record problems and register learning.

Regarding the use of location-based planning tools, the same interviewee disagreed with using TTP only at the CSO. Other interviewees pointed out how to define the location breakdown structure used on these tools.

Concerning the degree of overlap between design and construction, the interviewees pointed out that it is a matter of overlapping decisions. Moreover, the overlap promotes the opportunity to have early involvement of stakeholders, which creates multilayer interactions between design and construction to clarify the information flow and requirements. This early involvement could support the teams to visualise a unique plan for the whole project. Collaborative decision-making and feedback aspects are also in the overlap between design and construction and should be analysed to infer whether it is possible to go faster.

Regarding the pull production system, the participants agreed it is essential to identify the processes throughout the production stream where the pull flow can be applied. Namely, it is necessary to comprehend the interfaces between push and pull flows. Moreover, in order to pull, it is necessary to define the construction demand. The pull flow described in the model may work for the detailed design stage. If not, is it possible to work with “design assumptions”? It was also pointed out by one of the interviewees how to allocate and size the buffer into the production flow.

Table 23 shows the main outputs of the model evaluation and the actions taken by the researcher to address the issues. Most parts of the comments were tackled in the following studies.

Table 23: External model evaluation outputs and proposed actions from the retrospective studies.

Evaluation Outputs	Actions
Detail how to use Stage-Gate to improve contractors’ and suppliers’ involvement	It is deepened in Case Study 4.
Use of CBA in design development	No occurrence in the studies. Suggested by the literature to use at the negotiation stages of the NPD.
How to define the interface of push and pull flows?	It is depicted in Case Studies 4 and 6.
How to define the construction demand?	By the construction plan. It is deepened in Action Research Study 5.
Adoption of TTP in CSD	It is discussed in Case Studies 4 and 6.
Use of A3 for learning and problems records	It is addressed in Case Study 6.
How to define the location breakdown structure? How to do so when it is not a linear project?	Study 1 defined by the concrete structure sections. More ways are presented in studies 4, 5 and 6.
The overlap between the design and construction stages: how much to overlap?	This thesis does not discuss to which degree both stages can be overlapped. However, when the necessary information from the design is accurate and ready to be pulled by construction.
How to buffer the project?	Different types of buffers were used in studies 1 and 2, such as activity and production capacity buffers.

5 DEVELOPMENT OF THE SECOND VERSION OF THE MODEL

This chapter presents Case Study 4 (CS4), the results of which enabled the refinement of the first version of the model into its second version. The study is the first of two case studies developed in this investigation. It provided insights about how complex projects with overlap between design and construction stages are managed. Although its context is similar to RPS1, i.e. public project, long period for tendering contractors, complex architectural building, the CS4 presents new practices in project management, design management including an extensive use of BIM, and introduces the TTP as a new LBS tool to design the construction system.

Next to the CS4 description, the discussions are presented around the study's findings, the internal evaluation of the case study, and the researcher's recommendations for improvements in the project management. At the end of the chapter, the second version of the model is presented, highlighting the new learnings and contributions from CS4.

5.1 CASE STUDY 4 (CS4): FINE ART, MUSIC AND DESIGN UNIVERSITY BUILDING PROJECT

Case Study 4 (CS4) was conducted in a Norwegian public sector administration company (Company F) responsible for construction and property affairs, building commissioner, property manager and property developer. The organisation has around 930 employees spread across five cities in Norway. The construction project, which is the object of analysis of the study, is a university building.

The study is described in the following sections. Section 5.1.1 concerns the project description, while section 5.1.2 shows the research process. Sections 5.1.3 until 5.1.8 depict the project management practice at CS4, explaining the design, procurement and construction management adopted. Section 5.1.9 analyses and discusses the case study findings. Suggestions for improvement are outlined in section 5.1.10.

5.1.1 Project Description

The project of CS4 is a university building for the courses of art, music and design, located at Bergen, Norway (Figure 97). The new facility accommodates approximately 300 students and 100 employees. It is owned and managed by Company F on behalf of the Ministry of Education (client) of the Norwegian State. The University is the user of the facility. The facility has 14,800 sqm and costs 1,086 billion Norwegian kroner. The project was funded by the national budget.

Figure 97: The university building. Source: Company F.

In 2001, the University started programming the new facility, i.e. defined all the requirements for the new building. In 2005, the educational department of Company F was given the task of building the new facility, which began with the launch of an international design competition for the new building, in which 64 architecture firms participated. The architect firm Company H won the design contest in 2005 with the draft proposal that met the programme and the Bergen city plan. However, the budget available for the construction project was not aligned with the programme requirements. According to the Head of Architects at Company H, the programme was too ambitious and the funding available was not enough to meet the requisites of this project.

The project development was marked by a long and slow development. It took about nine years from the architect design competition results in 2005 to the beginning of construction in 2014. After winning the contest, Company H developed the project programme (similar to the Preparation and Brief stages from RIBA (2013)) and three sketches (similar to Conceptual Design from RIBA (2013)). Between 2007 and 2010, there was much discussion between the architecture office and the owner until the end of 2010, when Company H was invited to reprogramme the project to the targeted cost.

The new preliminary project developed by the architecture office reduced the building area from 17.500m^2 to 14,800m^2 at the cost of NOK 1,114 billion (cost at July 2016). The premises of the new building was to stimulate the sense of belonging to the district community, providing a new identity for them related to art, design and culture, at the same time as being the most important public institution in the area.

In January 2012, the project was sent to Parliament for the approval of funds. For almost 18 months the project lay still. In June 2013, the money was approved for the project construction. However, Company F's participation in the project construction began in 2014. Detailed design, demolition and ground preparations also took place in 2014. The foundation works, framework and enveloping of the building took place in 2015, and the scheduled completion took place in 2017.

The project manager of Company F had previous experience with lean construction and desired a lean project of the new facility. This project began its design system by considering the idea of integration between design and construction, but also the use of lean thinking. During its operation, the project was planned and controlled by hierarchical levels, similar to the LPS. The project manager worked very closely with the Design Manager and the Construction Manager.

5.1.2 Research Process

CS4 had the following aims: (a) understand the context in which the solution to the problem was developed; (b) understand how the solution conceived to design, plan and control the stages of design and construction integrated both stages; (c) connect the solutions with the theoretical background; (d) inform the development of the second version of the model for integrating design and construction stages using location-based planning tools.

In order to understand how the solution used at the project management was promoting the integration between design and construction, the case study also has the next objectives:

- Comprehend the lean design and construction practices in the project;
- Find out how design and construction stages were connected through the production planning and control processes;
- Identify the strength and weakness of techniques used to plan and control design and construction processes.

It is also important to highlight that CS4 also contributed to answering the central questions of the thesis, such as:

- How to use LBS tools to structure the work for design, supply and construction;
- How to assemble design packages to meet supply and construction requirements;
- Determine the decoupling point of design development;
- Analyse existing types of pull production systems;
- How to measure and manage the WIP and buffers;
- Identify the best tools to control the production system.

CS4 was a retrospective study of a construction project delivered in May 2017, with an official opening on 11 October of 2017. The researcher analysed retrospectively the practices, tools, processes and technologies used by participants to design, plan and control the production of the project. The analysis of these practices was connected to managerial activities of: 1) Design System Design (DSD); 2) Design System Operation (DSO); 3) Design System Improvements (DSI); 4) Construction System Design (CSD); 5) Construction System Operation (CSO); and 6) Construction System Improvements (CSI). However, when CS4 took place, the design was concluded and the project was in the handover phase. Hence, the managerial activities taking place at that time were the Design System Improvement and Construction System Improvement.

A number of meetings were conducted during the last week of August 2017. The researcher collected data through semi-structured interviews and documents, such as plans, photos, figures, drawings, and so on. Four companies involved in the project participated in the case study. The interviewees had different managerial roles. However, all of them were actively involved in design and management, and in the PSD. The participants were (Figure 98):

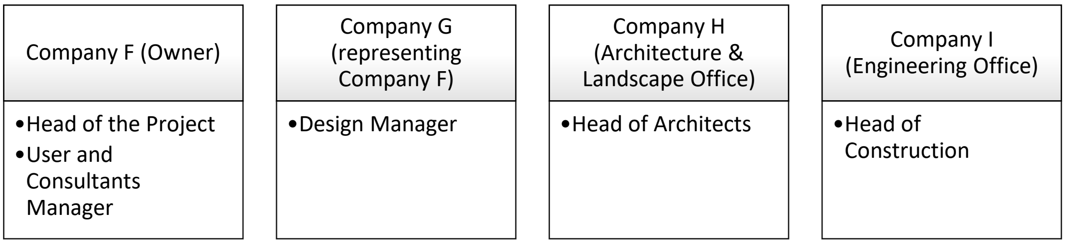


Figure 98: Interviewees in the CS4.

The schedule of meetings and interviews conducted in the case study and their objectives for data collection and model evaluation are described in Table 24.

Table 24: CS4 meetings and objectives.

Date & Time	Participant & Company	Objectives
Mon 28/08/17 10.00 – 12.00	Head of the project (Company F), Design Manager (Company G) and Head of Architects (Company H)	A kick-off meeting to present the research, get to know the participants, the schedule, etc.
Mon 28/08/17 13.00 – 16.00	Head of the project (Company F)	Understand the project management from the point of view of the Head of the Project, who represented the owner and was the one who idealises the lean thinking on the project.
Tue 29/08/17 13.00 – 16.00	Head of Architects (Company H)	Understand the design management regarding the planning and tools used by the architects.
Wed 30/08/17 09.00 – 12.00	User and Consultants Manager (Company F) and Head of Construction (Company I)	Understand how the user of the project was part of the project management. Also, to find out the design management from the point of view of the engineering designers.
Wed 30/08/17 13.00 – 16.00	Design Manager (Company G)	Understand the role of the design manager and the main processes and tools used in planning.
Thu 31/08/17 13.00 – 16.00	Head of the project (Company F), Head of Architects (Company H), User and Consultants Manager (Company F) and Head of Construction (Company I)	Present the researcher's understanding of the project management and confirm this with the participants. Present the 2nd version of the model developed for the thesis and evaluate it together with the participants through a semi-structured interview.

The data collected was internally evaluated according to the criteria explicated in The Studies Evaluation section of the method chapter in order to verify the integration efficiency of the management of the design and construction stages. CS4 has provided new insights into integrated project management. After data collection, new information allowed the researcher to refine the previous version of the model to design, plan and control production systems in the context of overlapped projects using lean practices. The improved version of the model was presented and evaluated externally with the case study participants. The researcher used a set of questions about the model, such as the one described in the section The

Studies Evaluation of the method chapter. The research activities to achieve these objectives, in addition with the sources of evidence, are described in Table 25.

Table 25: Sources of evidence for each phase of the CS4.

	Study Phase / Aim	Sources	Developed in
1.	**Awareness of the problem**		
a.	Understand the project's stakeholders' contractual relationships and responsibilities	• Secondary document analysis: Organisational charts • Semi-structured interview with Head of the project	Organisational chart of the project
b.	Understand the project context, timelines and the overlap between the design and construction stages	• Secondary document analysis: project milestones, project master plan, presentations, pictures, photos • Semi-structured interview with Head of the project	Project timeline of design and construction stages; project's milestones
2.	**Suggestion of solution for project**		
a.	Understand the process to design, plan and control the design stage, the participants, tools used and information exchanged	• Semi-structured interview with Head of architects and Head of construction • Secondary document analysis: design plan, BIM models, pictures, photos, presentations, tool for plan	Diagram of the design planning and control process; IT tools figure
b.	Understand the process to design, plan and control the construction stage, the participants, tools used and information exchanged	• Semi-structured interview with Head of the project and Design Manager • Secondary document analysis: construction plan, BIM models, pictures, photos, presentations, tool for plan	Diagram of the production planning and control process
c.	Understand the mechanisms to integrate the design and construction plans	• Secondary document analysis: design and construction plans, sheets to control production, pictures, photos, presentations. Observe takt-time, the levels of plan and control • Semi-structured interview with all participants	Diagram of project management
3.	**Development and internal evaluation of the study's model to design, plan and control the production system**		
a.	Understand how the solution adopted by the project influenced the stakeholders' work, the main problems faced and suggestion for improvement.	• Semi-structured interview with all participants • Secondary document analysis: information format exchanged, and analysis of WIP, takt-time, batch size, adherence to project plans	Internal evaluation of project's solution
b.	Understand the correlation between the solution developed in the project and the literature concepts and tools	Literature review in TPS, pull production systems, WIP, information flow management, location-based planning tools	Internal evaluation of project's solution
c.	Translate the project's solution in a theoretical model	• All study's data and information	2nd version of the model for project production system
4.	**Evaluation of the 2nd version of the model to design, plan and control the production system**		
a.	Evaluation of the model	• Model presentation and a focus group with all participants	External evaluation of the 2nd version of the model

5.1.3 Project Management

The project followed the traditional phases of construction project development in Norway, i.e. Programming; Conceptual Design; Preliminary Design; Detailed Design; Procurement; and Construction. The lean project management began with the detailed design phase, followed by procurement and finishing with the construction phase.

In 2013, after the funding approval, the mobilisation of the design stage started. At that moment, Company F started the bidding of the engineering design and construction management enterprises. Since 2011, Company G had been participating to support Company F in the project management.

Consultants have been hired to implement the lean thinking in the project. On 21 January 2014, Company I was contracted to develop the engineering design. On 22 January 2014, Company J signed the contract to execute the management of initial site work, such as demolition of the pre-existing building and earthworks. In March 2014, the project began on the detailed design phase. On 14 January 2015, Company J was then selected as site manager for all other construction works. Thus, the project assigned the following responsibilities (Table 26).

Table 26: Main stakeholders in the project management.

Function	Enterprise
Builder and Owner	Company F on behalf of the Ministry of Education
Design Management	Company G
Architecture and Landscape Design	Company H
Engineering Design	Company I
Construction and Site Management	Company J
Lean Construction Consultant	Consultants

During the detailed design development, between 2014 and 2015, there were three waves of procurement for contractors. Then, from August 2014, the demolition services of the pre-existent building and earthworks took place. From June 2015, Company F started the construction. The building was delivered to Company F on 1 May 2017 and to the University on 21 May 2017. It was officially opened on 11 October 2017 after a period of minor works. The timeline in Figure 99 summarises the significant events of design, procurement and construction phases.

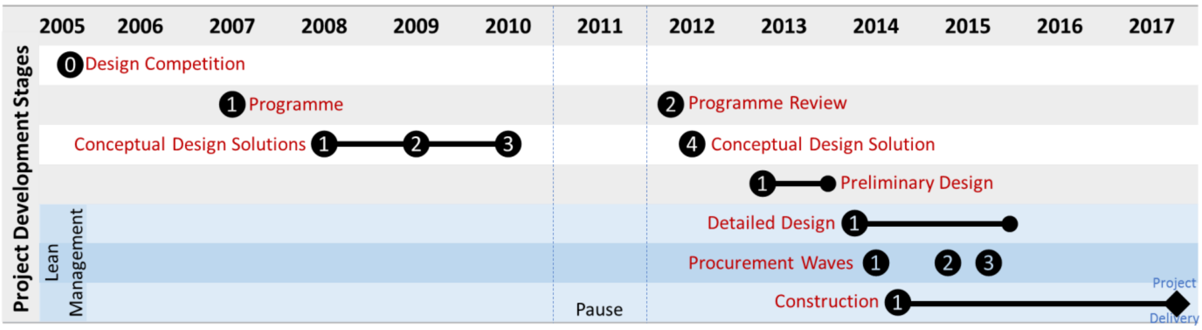


Figure 99: Project timeline.

The main stages of construction are described in Table 27 below.

Table 27: Main project stages.

Project Construction Stages	Dates
Pre-existing building demolition	August 2014 – September 2014
Digging and excavation	October 2014 – January 2015
Piling and foundation	January 2015 - April 2015

Structural work	May 2015 - February 2016
Facade and glass roof	January 2016 - April 2016
Internal works	March 2016 - March 2017
Building occupation	21 May 2017
Start of the academic year	August 2017
Official Opening	11 October 2017
End of 9 months functional trial period	28 January 2018

5.1.4 The Beginning of Lean in the Project Management

The lean thinking in the project management began at the beginning of the detailed design phase. The contract of a Lean Consultant was a prerequisite of the Head of Project at Company F who was appointed to this position in June of 2013. He had previous experience in lean construction and wanted to make the project a pioneer in lean design and lean construction in Norway.

All the main project stakeholders had never used lean before. However, the lean management was required in their contracts. So, in order to create a common ground and understanding about lean thinking for the project participants, the lean consultant introduced the philosophy for the companies through training sessions and activities. They started with a two-day pre-seminar training held in early February 2014, learning lean concepts applied in construction that would then be adapted for the detailed design phase. They focused on: takt-time, Ishikawa diagram, reverse planning and pull information flow. The training was very fruitful for the project participants to become acquainted with each other, think about constructability, and to start the lean culture implementation.

The Head of the Project was concerned with keeping the lean mentality of the participants along the project execution. Following the pre-seminar, the lean thinking implementation continued with two-week lean process planning, held at the end of February and beginning of March 2014. The lean thinking was embedded in the project planning, design and construction stages, which will be described below.

5.1.5 Project System Design

The Project System in the university's building was designed for the stages of design, procurement and construction, plus other processes necessary to keep these three main stages running smoothly.

At the beginning of the detailed design phase, more specifically during February and March 2014, the project participants carried out two sessions of collaborative meetings in order to develop the project process map (Figure 100). The Lean Consultants conducted the meetings with the participation of the leading project roles. The following were present: the Head of the Project and the management staff from Company F (5-7 persons); the Head of Architects and the architects from Company H (5-7 persons); the Head of Engineering and the leading engineers from Company I (5-7 persons); two Site Managers from Company J; and 3-5 external invitees with construction experience. They defined the main project phases, processes, gates, milestones, dependencies and key deliverables of the project.

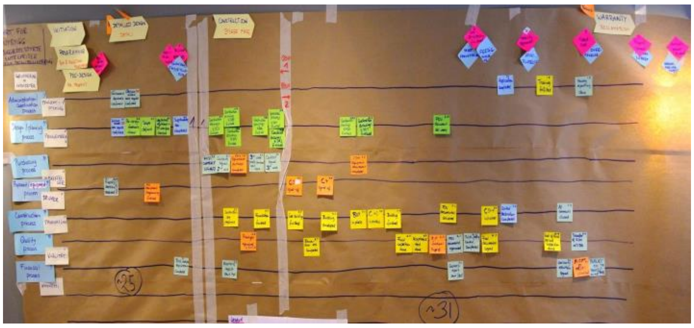


Figure 100: Strategical project map developed and completed after collaborative planning between the owner, leading designers, consultants and site managers. Image courtesy of Company F, 2014.

Although the team did not use the Stage-Gate approach formally for managing the project, they defined the main milestones and deliverables required to pass to the next stage of the project development. If one of them failed to be delivered, the whole project could stop. Besides, the process map supported the project participants to get an overall idea of the project and understand the fundamental connections between the processes that they needed to go through.

The results of the collaborative planning were represented in a digitalised map entitled Product Creation Process (PCP) developed by the lean consultants. This map was populated with dates based on the project's delivery date, becoming the PCP plan – level 1, or the overview project plan. The project team mapped, at the horizontal axis, the main project phases. In order to progress with the project, each phase had its main deliverables at the gates. Because the project restarted from the detailed design, the emphasis was laid especially on this stage and onwards. Earlier stages were not considered further. Each vertical axis of the map specified the eight main processes. The processes had milestones, called key points, coloured according to the person responsible for its completion. Each project participant could have milestones in more than one process. The schematic PCP is presented in Figure 101.

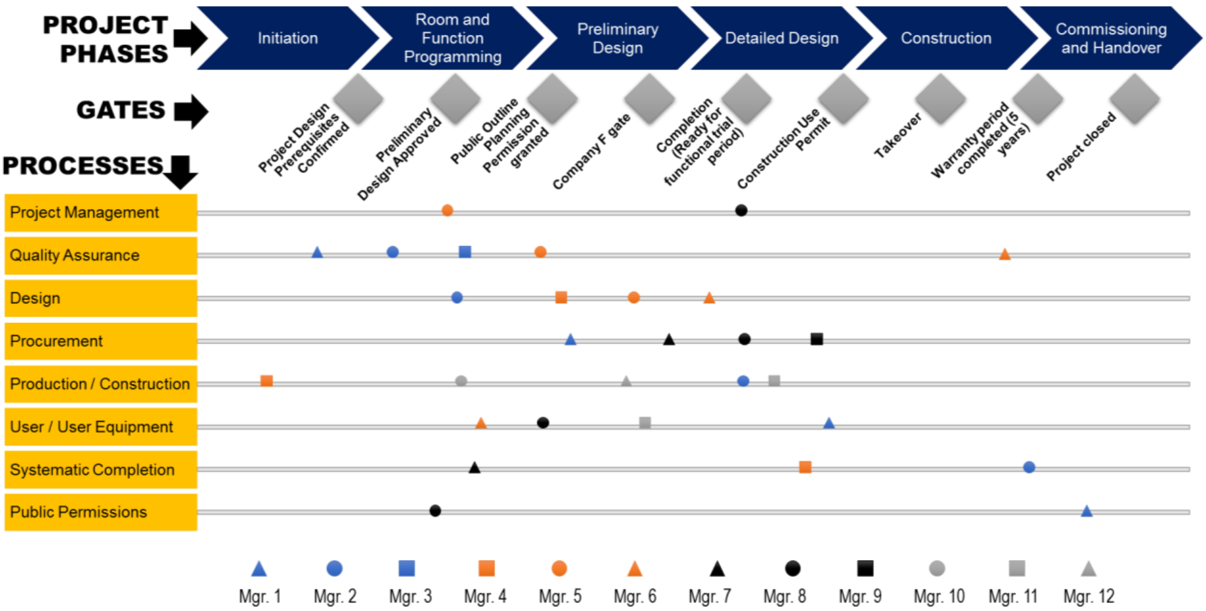


Figure 101: Schematic project creation process (PCP) map developed by the main stakeholders. Source: Based on Company F/Consultants image.

It is worthy highlighting that the project's team was constantly updating the PCP map. The main milestones from the construction plan were the basis on which to set milestones for procurement and design in the PCP plan. Additionally, the PCP planning enabled the project participants to design a shared understanding of the overall processes of the project development. Further, the PCP plan provided the milestones from the Level 1 (project plan) to the main process plans (level 2), such as design, procurement and construction (Figure 102). These plans are described in the following sections.

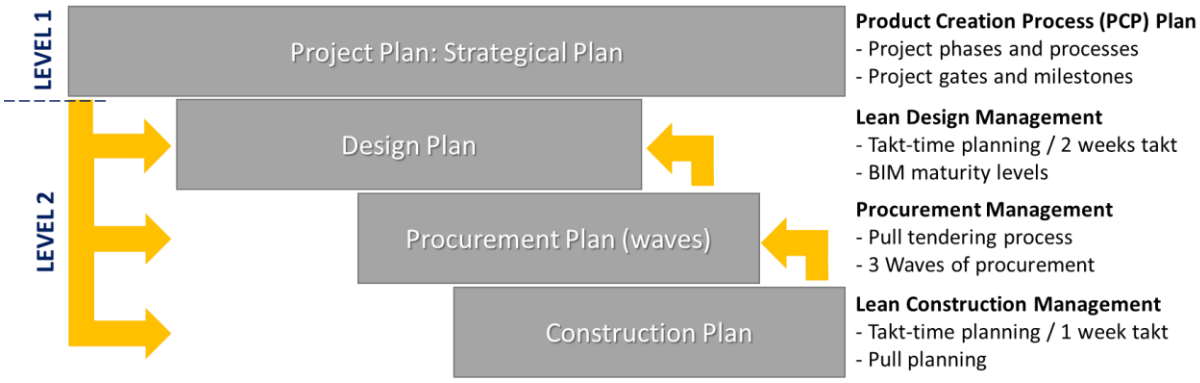


Figure 102: The two levels of planning in the project.

5.1.6 Design System Operation (DSO)

The Design System was operated with the lean philosophy adapted to design peculiarities. The lean design was implemented in the detailed design phase to promote a smooth flow of design production, with the aim to reduce and avoid reworks and negative iterations (Ballard, 2000d). The lean design management was carried out by the triangle comprising: Company F's Design Manager, Company H's Head of Architects, and Company I's Head of Engineers. Under the Head of Architects and Head of Engineers respectively were the managers for all other disciplines. For instance, in Company I there were the Head of Construction, the Head of HVAC, the Head of Electricity, the Head of Acoustics, the Head of Environment, the Head of Fire/Security, etc.

The lean design management was developed based on three core processes, tools and people, which include collaboration among designers, owner, user and Construction Manager. The main items in each core of the lean design management are described in Figure 103.

Process	People	Tools
• Design freezing • Parallel design disciplines development • Design deliveries and development pulled by procurement waves • Takt-Time Planning (2 weeks)	• Design Manager (Company F) • Head of Architects (Company H) • Head of Engineers (Company I) • 3 days of co-location every 2 weeks	• BIM Process • Revit Architecture, MEP and Structure (models development) • BIM 360 Field (document/quality control) • dRofus (model programme/code/rule check) • Solibri Model Check and Viewer (clash detection and visualisation) • MAKS10 (Norwegian building code check)

Figure 103: The three cores of the lean design management at the project.

In order to reduce the negative design iterations, the designers together with the design manager decided to develop the detailed design with all disciplines progressing concurrently. It enabled the team to detect geometrical clashes among disciplines that were at the same level of detail. Otherwise, a discipline detailed and verified later could cause interferences in others that were at an advanced stage of development, provoking a negative iteration, i.e. carrying design disciplines some steps backwards in the design development.

When the design disciplines evolve together, more problems emerge in the process, and their resolutions are more assertive due to the consideration of all the disciplines' requirements and interdependencies. This makes the design development faster and more agile in order to detect and solve interferences. This statement is proved in the chart below (Figure 104), where it is possible to see the number of objects modelled and the number of clashes detected in the BIM models along the time. The number of objects modelled also show the level of detail of the model, i.e. the higher the number of objects, the higher is the level of model detail. Also, the figure shows that there is a moment in the design development when the clashes begin decreasing despite the increasing level of detail.

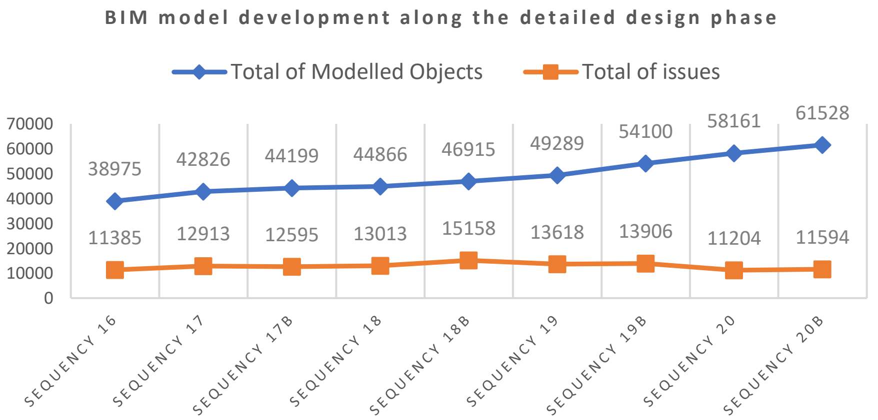


Figure 104: Total sum for general model checks for design disciplines: number of modelled objects (blue) and number of issues (red) per sequence (two weeks takt). Source: Company F.

The parallel development of all design disciplines enabled the team to freeze the design solution after a series of clash detections and reviews. Thus, the design solution would be progressively detailed and improved towards the next delivery.

The BIM models passed through three levels of development in the detailed design phase to accomplish the three procurement waves. Figure 105 exposes this crescent maturity of models in a pulled design development process. It was set up as levels of BIM development:

1. Freeze BIM wave 1: focused on the model/drawings delivered to enable the procurement for the demolition of the pre-existing building and earthworks.
2. Freeze BIM wave 2: focused on the procurement for building foundations, structure, façade and vertical transport (lifts).

3. Freeze BIM wave 3: provided model/drawings for the procurement of all internal works and landscape contractors.

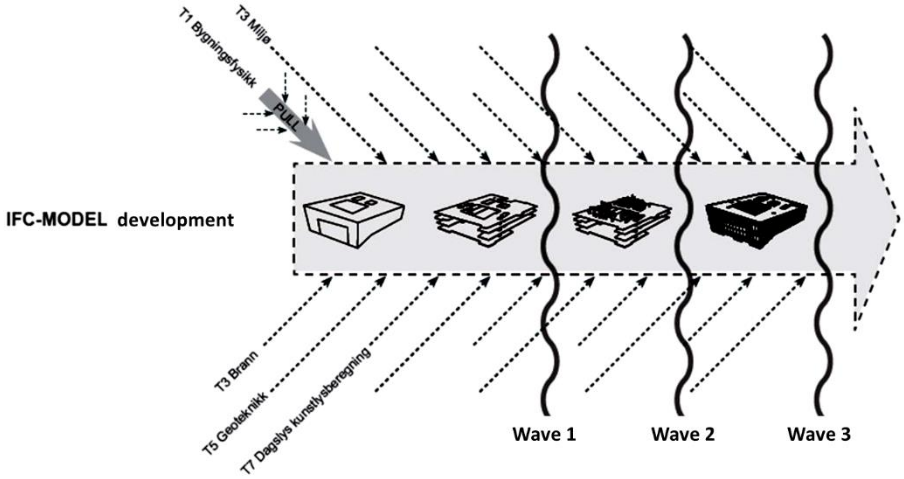


Figure 105: BIM model development along the detailed design phase pulled by the procurement waves. Source: Translated from Company F and Company H.

The procurement wave dates were extracted from a reverse plan based on the construction plan. Because it was a public project, all procurements had to pass through the tendering process, which had a lead time of about three months and two weeks. Due to this project characteristic, the architects and engineers delivered the design for procurement enclosing 80% of the information, and, at the end of the tendering process, they delivered the design to the hired contractor with 100% of the information.

According to the Head of Architects, the different levels of BIM maturity required different ways of working collaboratively. The design development for the freeze BIM waves 1 and 2 required more transdisciplinary work between all disciplines in order to set all the interdependencies, establish the same detailing scale of models/drawings, and run clash detections between the different offices' models. However, the design development for the freeze BIM wave 3 demanded more interdisciplinary work within the offices. After all, the primary design arrangements and interferences were already solved. At this point, the engineers and architects worked more independently to increase the level of model details and produce their deliverables.

Some problems occurred in the process of transdisciplinary design related to modelling the right elements that could impact other disciplines. The design team agreed to put into the BIM model elements that needed clash detections analysis between all disciplines. After solving the clashes, the model was to be frozen for further interdisciplinary detailing. However, due to a lack of integrated design understanding, especially about the engineering interdependencies, some elements were neglected in the transdisciplinary model. These elements were modelled later, in the interdisciplinary model, and interferences were not checked with other building systems. Also, lack of information about major and specialised cross-functional products due to contractors or suppliers who were not yet under contract influenced the completion of the BIM. Finalisation of design had to be put on hold. As a consequence, impacts were perceived only at the construction stage.

In summary, the design team said that there were some difficulties in working with the method of freezing BIM models and progressively detailing all the disciplines concurrently. One difficulty was to identify what information was required to input into the BIM model and exactly when it was needed. It can also be applied to the level of detail of the BIM elements in the model. The clash detections were checking only the modelled elements. A shared understanding of the design development process was necessary among all designers, so then they could discuss what should or should not be in the BIM models and at which level of detail.

On the other hand, the design team felt that the same method of working shortened the design development, avoided reworks caused by negative iterations, and made the design process more agile, producing more assertive design information when needed compared to the traditional design process.

5.1.6.1 Takt-Time Planning in Design

All the design development was managed using the takt-time and pulled flow concepts. In order to set the deliverables, the design phase was planned using the milestones and gates from the PCP plan - level 1. The milestones marked important design deliverables which were, in most part, related to permissions and procurement of construction contractors.

The TTP in design was a collaborative process of designing and planning. It was composed of three main elements: takt, design themes, and co-location of designers and project owner. The takt set by the team was two weeks. They judged that this amount of time was enough to produce deliverables, make decisions, research and prepare the next planning meeting. The design production was organised in themes. Initially, the themes comprised larger, less detailed levels. At later stages, the themes comprised a more detailed level, for instance stairs, windows, and materials.

The themes represented a design subject that needed to be discussed, designed and delivered collaboratively. Each theme was composed of issues which were thought according to necessities of the time, product, quality, method and place (the 5R: Right Material, Right Time, Right Amount, Right Quality, and Right Place). Each theme had a “Theme Owner” who was responsible for gathering people to make decisions together, produce deliverables and list the issues to be solved. Issues could be any activity demanded to deliver the design solution of a specific theme. The pulled design flow occurred through the use of this tool; due to developing the theme issues, the participants should pull all the existent dependencies and constraints to make that design deliverable ready.

At the end of the takt, for three consecutive days the designers and project owner met at the architecture office to work in co-location (Figure 106). On the first day, they defined the meeting plan for the following three days. Next, they presented what they had accomplished during the previous ten days, discussed what was missing in the themes, why, and how to solve it. The designers also made decisions together, besides designing. New themes could be created, and other themes were to be closed during these three days. The themes emerged according to the logical sequence to complete the deliverables for a freeze BIM wave. In total, just over 40 themes were created. The themes had the status controlled by the “Theme

Owner" and Design Manager using an MS Excel spreadsheet (Figure 107). Also, the design plan level 2 was updated during the three days of co-location meetings.

Theme log: _____
Title: ___________________
Responsible: _____________
Established date: _________

Typology	Activity	Input from	Input to	Status	Changes required	32 (Sequence 7)	
						Week 32	Week 33
Xxxxxxx	Xxxxxxxxx	XXX	XXX				
Xxxxxxx	Xxxxxxxxx	XXX	XXX				
Technical room axis 3 to 6	Increase air in façade must be coordinated.	HVAC	ARCH		006		
Xxxxxxx	Xxxxxxxxx	XXX	XXX				
Xxxxxxx	Xxxxxxxxx	XXX	XXX				

Figure 106: Schematic representation of a theme spreadsheet.

OK= Completed 1= In Progress 2= Not Critical Delayed 3= Delayed					Sequence:	18 (Sequence 2)		20 (Sequence 3)		22 (Sequence 4)	
					Key Points n.:	7 (24.04.14)		12 (01.05.14)		10 (06.06.14) 19 (30.05.14)	
					BIM focus area:	Lock the grid		Sketch: Level 4 and 5		Sketch: Level 3	
					Waves:	K202 - FOUNDATION					
					Week:	18	19	20	21	22	23
NR	Responsible discipline	Owner	Activity start	status	THEME	28.apr	05.mai	12.mai	19.mai	26.mai	02.jun
P.x.x					**Design**						
T1	ACO	Xxxx	2014-12	1	Acoustics						
T2	MEP	Xxxx	2014-12	1	Fire						
xx	xxxx	xxxx	xxxxx	2	xxxxxxx						
					Gates:		3	Building Permit			
					Key points description:	1.05.2014 xxxxxxxxxx				06.06.2014 Xxxxxxx 30.05.2014 xxxxxxxx	

Figure 107: Schematic design plan in level 2: Takt-time plan with "key points" and gates, themes, owners and status.

The main idea of the takt is to break down the design production of the themes into small activity batches, called "issues", that could be dealt within two weeks. Some theme issues needed more time to be solved, but not more than three sequences (six weeks). At the beginning of the TTP, the designers faced some difficulties when adjusting the production batch (the number of issues) to fit in two weeks of work. However, over the course of time, they achieved a good knowledge for planning their activities and identifying the project priorities. One of the keys to achieve this was transparency and visual planning using post-it notes with the main design group present.

Figure 108 represents the TTP used at the project, illustrating the timeline of two takts (28 days) with three days of co-location (in orange) and the themes' products as inputs into the BIM model development. In the transdisciplinary control day (in blue), all design deliverables were checked and analysed regarding the project programme compliance and interferences between disciplines.

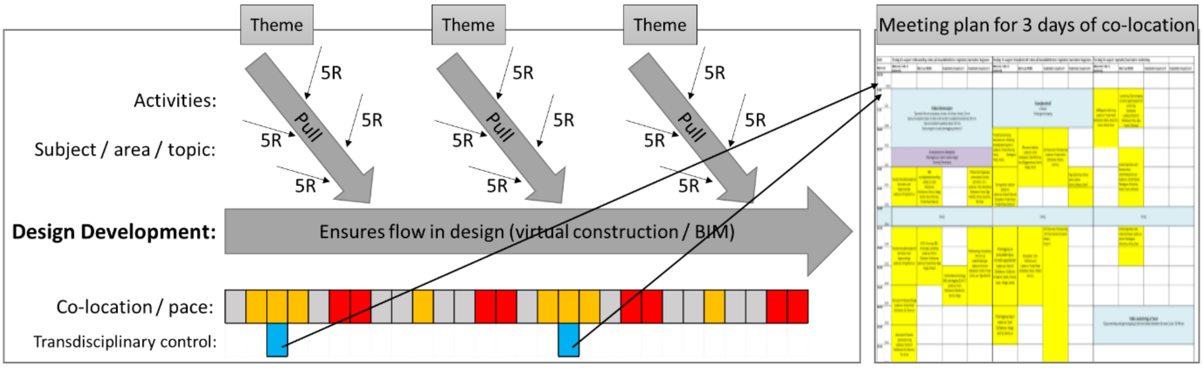


Figure 108: Lean Design Management. Source: Adapted and translated from Company F/Company H/Company I.

The use of TTP and themes helped the team to reduce the batch size of decision and production, as well as the WIP along the design development. Additionally, the use of themes enabled the team to work with shorter lead times, increase their agility in solving problems, and include new user requirements in the design solution. The inclusion of new user requirements was, however, kept at a very low level. Most new change requirements were instead listed and postponed until after the completion of the project. This avoided interference of the original project scope and objectives, and to avoid major technical changes which could have been difficult to keep separated from the original project.

Figure 109 summarises the lean design management of the project, in which the milestones and key points from the PCP plan (level 1) were transferred to the TTP (level 2), defining what themes and issues/activities should be solved in order to increase the BIM level of development and deliver the right information for the freeze BIM waves.

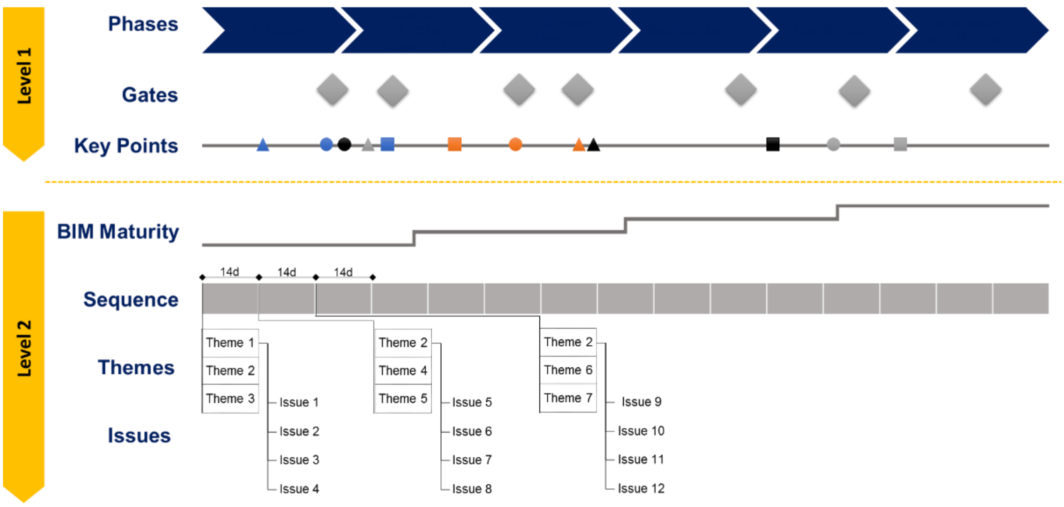


Figure 109: Hierarchical project plan: PCP plan as level 1 and Takt-time plan as level 2. Source: Based on Company F/Consultants image.

5.1.6.2 Building Information Modelling

The Building Information Modelling (BIM) was used by the architecture and engineering offices and was the core of the Agile design development. The BIM models were used in meetings to coordinate activities between the design team, but they were also used actively on-site to ensure shared understanding among contractors and subcontractors.

The architects used the software Autodesk® Revit® Architecture and the engineering designers used the Autodesk Revit Structure and MEP to produce the 3D BIM models. The architecture office also used MAKS10, which is a plug-in developed by the Institute of Norwegian Architects that checks the 3D model according to the Norwegian building codes embedded in the Revit Architecture software.

The designers agreed to use a common server to share the models, which enabled the project team to share the files and models in a single repository hosted on the web providing access to PCs, tablets and smartphones. The service also allowed the team to review the drawings and models, make mark-ups and take pictures on-site.

In the project, there was a dedicated and professional BIM team. During the detailed design, the BIM team consisted of the BIM Coordinator within the architects' company and the BIM Coordinator within the engineering company. They were both supervised by the Design Manager. The BIM Coordinators were responsible for coordinating the model layers, controlling the model versions, and checking updates on the common server. They were further responsible for assembling and reviewing the models in cooperation with the project team and, later on, with the building managers. The models were exported into IFC to clash detections analysis that occurred at the end of the takt, i.e. every two weeks. During the construction phase, there was additionally a dedicated BIM Site Manager teaching workers on-site and following up on the BIM kiosk maintenance and updates.

The studies of all BIM models' compatibility were carried out using two different software packages: dRofus (approximately translated as "data room function program") and Solibri Model Checker. The first one was used by the team to verify whether the design solution complied with the project programme, such as the necessary items/equipment inside each room. The latter was used to check geometrical interferences and conflicts, such as fire routes, rules and project requirements for ceiling heights, opening widths, etc.

The BIM models were distributed digitally to project stakeholders amidst a common BIM server and BIM kiosks on-site. Additionally, BIM360 Field has been used to register deviations and corrections during production. Whether a contractor or subcontractor desired a 2D-drawing from the BIM model, they could order its paper print version. Company F also ensured it would provide training in using the digital tools Solibri Viewer and BIM360 Field to the project stakeholders. Participants could then be better able to use their own tablets and computers, or one of the BIM kiosks located on-site.

The BIM kiosks consisted of a large screen with a PC connected to the internet with Solibri Viewer software installed. The kiosks were distributed to the site office and on each floor of the building. The BIM models could be visualised by the workers that were to perform a task so that they could easily understand the assembled/completed elements (Figure 110). Also on-site, the workers were to use the BIM 360 field to report detected faults, errors or defects during the construction phase. This information was shared through the common server to other project stakeholders, which facilitated the problem-solving.

Figure 110: BIM kiosk on-site for all contractors. Image courtesy of Company F.

The main software and cloud services used by the design team are specified in Figure 111. The use of BIM in this project contemplated the three dimensions of the “M”: 1) M as Model production; 2) M as a Modelling process that involved all the designers from architecture and engineering offices; and 3) M as Management of information that required much planning before the beginning of the detailed design phase and a BIM Coordinator. The use of BIM was primarily to make this project more agile, improve the information flow across the different design offices, and between the design team and the contractors.

3D BIM Modelling	•Autodesk Revit Architecture •Autodesk Revit Structure •Autodesk Revit MEP •MAKS10 Revit Plug-In
Document/Quality Control	•Autodesk BIM 360Field
Model Quality Check	•dRofus •Solibri Model Checker
Model Visualisation	•Solibri Viewer - BIM Kiosks

Figure 111: Main software used in the building information management.

5.1.7 Procurement System

The procurement was planned using information from the PCP plan (level 1) and mainly based on the construction plan. The construction contractors were hired in three main waves of procurement. In total, the new facility was built by 11 contractors (presented in Table 28) and more than 50 subcontractors.[8]

The concern of the project team with the façade execution made them hire this specialist contractor even before the structure contractor. The waves for procurement were defined collaboratively by the project team as a consequence of the reverse planning based on the construction takt-time plan, which will be

[8] The bidding of subcontractors was the responsibility of the contractors, and the right moment to start their procurement was defined along the construction planning processes.

described in the next section. The procurement waves set up the milestones for the design plan; then, the design development was carried out to meet the required deliverables for the procurement process.

Table 28: Main procurement waves of the project.

Procurement Waves	Date	Enterprise
Wave 1	23.May.2014	K 201 (Demolition and Earthworks)
Wave 2	08.Jan.2015	K 202 (Foundation)
	19.Jan.2015	K 204 (Façade)
	09.Mar.2015	K 601 (Lifts)
	08.Apr.2015	K 205 (Structure)
Wave 3	29.Sep.2015	K 301 (Plumbing, Fire, Gas), K 302 (HVAC), K 401 (Electrical), K 501 (Automation/Integrated Control System), K206 (Interior works), K 701 (Landscape).

The design team, jointly with the Site Managers, developed the reverse plan based on the construction plans' starting dates, and then, including the necessary processes, to carry on from the design delivery passing through the procurement activities until the contract signature by the selected contractor (Figure 112). The reverse plan worked as a pull plan that considers the upstream activities necessary to accomplish a downstream construction activity. It will be described thoroughly in the next section.

Figure 112: Reverse plan used in the project.

5.1.8 Construction System Operation (CSO)

Lean thinking was used in the CSO. The lean construction implementation started with the development of the construction plan. The owner, designers and site managers were responsible for designing the production system, i.e. plan the construction strategy, the site logistics, define the production batches, estimate the production duration and crew sizes.

The technique used to do this was the TTP in which the takt was set to five days. The production batch size was defined according to the estimated amount of work the crews perform during one takt, i.e. five days. Because the areas have different amounts of work to be executed, the control or takt areas for the TTP have different sizes. The project is a non-repeatable-area building, and the work had to be calculated thoroughly to make it as repeatable as possible, trade by trade. In the project, the planning team defined different production batches/areas for different activities, namely: structure; façade; roof; interior works; building hall; technical rooms; shafts; lifts; stairs; and outdoor areas.

The definition of the production/control areas was a collaborative process by the team. Their early stage decision is represented in Figure 113, where the control areas and the construction strategy are illustrated from the centre of the building in towards the lifts allocated in the building hall.

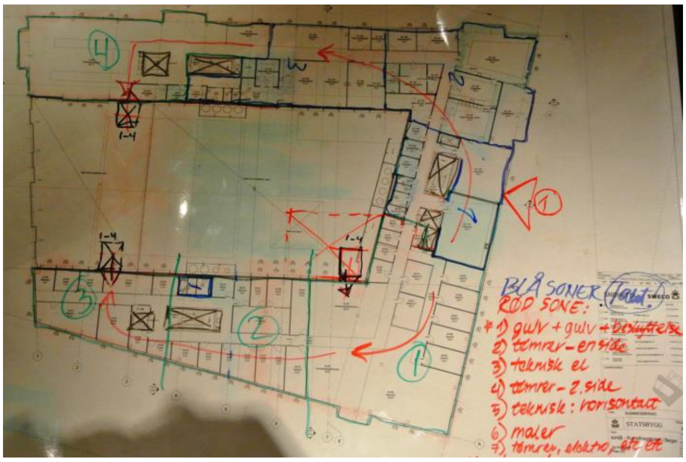


Figure 113: Example of the logistic study in the construction/control areas. Image courtesy of Company F.

The TTP uses the concepts of the production line as a train where each activity is similar to a wagon, and, in order to make the train run correctly, all wagons must run at the same velocity or pace. Thus, each production area in the project is a train, and the activities are the wagons that run at a pace of five days. That means that all crews in the project should follow the same velocity of production, at the same rhythm.

As soon as the takt-time plan was ready, it was used to populate the PCP (level 1) with the milestones. The procurement dates were extracted based on the construction date on the takt-time plan, also giving consideration of the time for tendering, designing for production, production of elements to assemble on-site and delivery, i.e. a reverse plan was developed from construction towards design passing through the procurement process of contractors.

As soon as the contractors were onboard, the team reviewed the takt-time plan with the construction team, which caused the development of more than 80 versions of the construction plan with all minor detail changes. The team also incorporated in the takt-time plan the systems testing through the Systematic Completion process.[9] One of the early TTP versions is presented in Figure 114. Unfortunately, the lack of buffers, flexibility in the plan, and appropriate lookahead resource planning caused some issues with contractors that needed more than one takt to complete their tasks.

[9] Systematic Completion (SC) is a process established at the project that is concerned with enabling early technical system tests as soon as they are built. It avoids the propagation of errors in the total system and ensures the right quality. It includes anticipating at the design stage information about required geometry and function for determined areas of installation and tests. The SC was not the focus of data collection in this study, and for this reason it was not presented in depth.

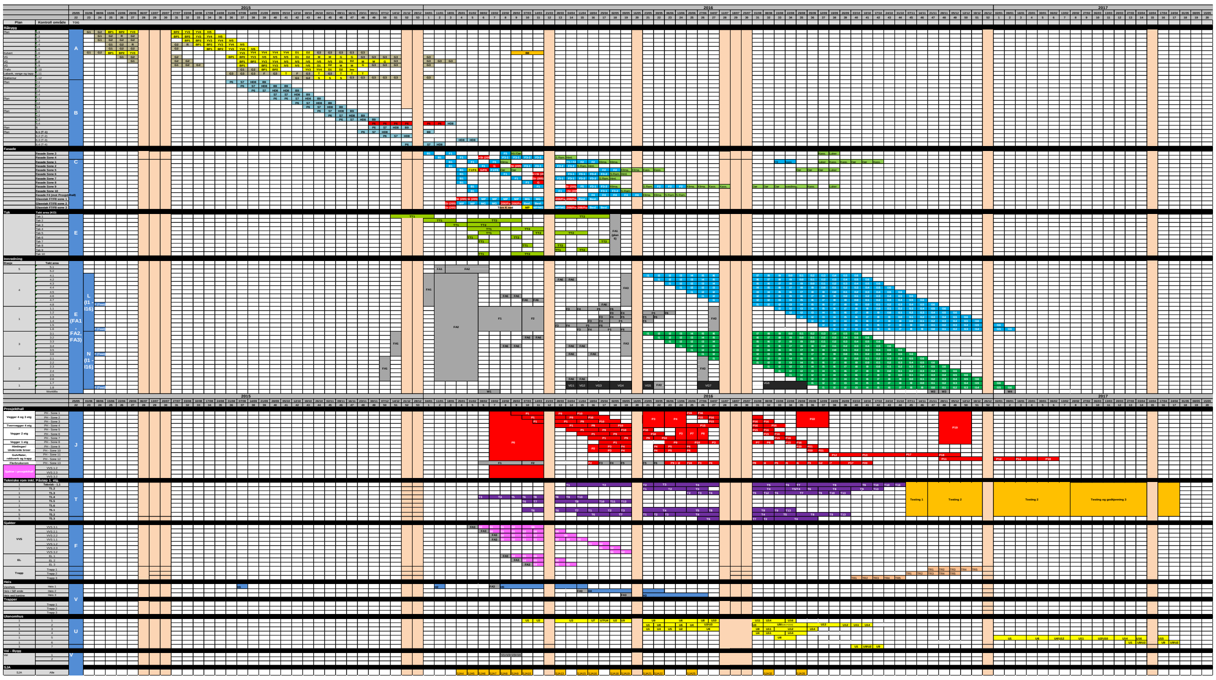


Figure 114: Takt-time plan for the project. Image courtesy of Company F.

The takt-time plan was a very transparent and visual tool for the construction contractors. They could easily understand what should be done, where and when, principally due to each wagon having colours and the label of the crew. There were several visual panels on-site, the takt-boards, one for each takt control area, containing the primary information about the production necessary for the crews (Figure 115). The takt-time plan was also used by some subcontractors to plan their weekly work according to the control areas (Figure 116).

Figure 115: Visual management takt-board on-site. Image courtesy of Company F, 2016.

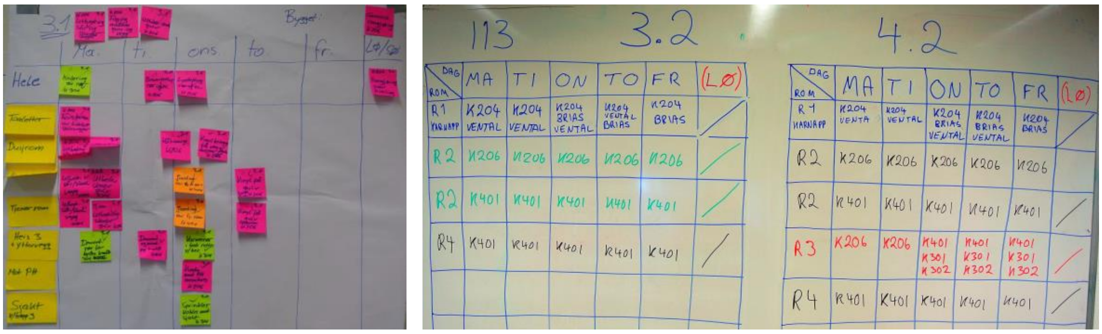


Figure 116: Transparent weekly plan based on production batches/control areas. Image courtesy of Company F, 2016.

During the construction, one of the leading contractors brought to the project the collaborative planning. They introduced the same lean practices they used to carry on across the company's projects. It is noteworthy to mention that this company is the same one referred to in CS6, i.e. Company L. The collaborative planning of the project consisted of three levels of planning: a) "14-10 weeks"; b) "6-4 weeks"; and, c) "1 week". The first one was a tactical planning conducted by Company F jointly with designers, contractors, subcontractors and specialised suppliers. In the meetings, the participants discussed the design interdependencies and its challenges, and also decided the solutions, scheduled the activities, and focused on planning the long lead time items.

In the second level of planning, the "6-4 weeks", the participants focused their efforts on tactical and operational decisions. The purpose of the planning meetings was to clarify any pendant issues from the "14-10 weeks" planning, discuss and coordinate the dependencies, and solve technical and practical issues around a control area. Herein, the horizon of planning is short. Thus, the level of detail is higher compared to the previous planning. The meetings were led by Company F's site manager with the participation of contractors, subcontractors and specialised suppliers.

The "1-week" meeting is an operational planning session carried out by the contractor's foremen jointly with the crews in order to plan the forthcoming week of work, starting on Monday morning. The crews reviewed all the preconditions to initialise a task in a determined control area based on the issues from the "6-4 weeks" plan. Some contractors and subcontractors carried out daily planning meetings as well, in order to clarify the work to be performed on the day and verify the progression from the previous day.

5.1.9 Analysis and Discussion of CS4

This research focuses on projects with overlap between the design and construction stages. As mentioned in the research method chapter of this thesis, the case study should be assessed according to some criteria that the researcher judged essential in order to integrate the design and construction planning.

The project is a complex building regarding design and construction. Part of its success of on-time delivery for the University is due to the integrated use of lean design and construction, added to the common use of BIM and the high focus on the Systematic Completion process by all the designers and construction teams.

The integration of teams and the promotion of shared understanding began at the meetings to devise the PCP, which gave the participants a big picture of logic sequences among the main project processes (design, procurement, construction, quality, testing, etc.). The PCP represented the design of the project systems, or, as Young (2008) called it, the design of context.

The PCP is very similar to the Generic Design and Construction Process Protocol (Kagioglou et al., 2000), which includes the Stage-Gate method (Cooper, 1994), with very clearly defined soft gates (key points) and hard gates (phases gates). The relationship between the deliverables was also planned and studied in the process map. These milestones were pushed for the second level of planning, i.e. the master plan for design and construction. At this level, the team was designing the context (Young, 2008), and the PCP map performed the role of a boundary object.

The **collaborative and integrated PDS** in the project was enabled by the early inclusion of the enterprise responsible for managing construction. They were essential to provide constructability feedback to designers and facilitated the PDS. However, an earlier inclusion of major contractors could be more beneficial for the construction design and execution. Unfortunately, the contractual arrangement in this project hampered this possibility. The procurement route adopted in the project also fragmented the subcontractor's communication. In CS4, the suppliers and subcontractors were responsibilities of the contractors. It was not necessary to develop a supply system, because each contractor controlled their suppliers. The contractors participated in the Collaborative Planning on-site, and constraints were removed in the 14-10 weeks planning.

Focusing on the design process, the team made important decisions about the detailed design development before it began. Architects, engineers and the design manager decided how the BIM models should be shared, in each extension, what software should be used to model, detect clashes and assure the programme accomplishment. They also decided that the BIM level of development should be focused on design deliverables, and this latter should follow the procurement waves. This idea is very similar to the one highlighted by Kiiras and Kruus (2005) of pushing design into design packages for procurement, and then pulling according to construction needs.

As there were three procurement waves, there were also three BIM freezing waves, in which the primary structures of each design discipline were developed concurrently and all the interferences before freezing the model were checked. Herein, the LOD was determined based on deliverables for procurement, which was very similar to the work developed by (Svalestuen et al., 2018), with the only difference being in the procurement route adopted in CS4 that focused on public bidding. With all these procedures in the design stage, the team avoided many negative iterations, saving time, resources and money.

The design development was a collaborative process, in which architects, engineers and owner had a shared understanding of negotiation, decision-making, solving problems and analysing impacts on the project performance. The use of takt-time for design planning adapted perfectly to the context of the project and made the design development more agile in order to adjust to user's requirements and other variabilities. The fact of combining in the design master plan both strategical and tactical activities enabled the teams to focus on removing constraints (similar to the "make ready" of LPS) and pull information and decision to deliver the design to the dependent activity. It was enhanced by the 3-day co-location work with all designers and owners of the themes. This adaptation in the design planning made it easier to plan and control the design production because it reduced the design production batches, WIP, cycle time and facilitated the problem-solving.

The design planning also adapted to the different stages of the design development: from negotiation about strategical decisions of design solutions for the project (known in the study as transdisciplinary work) at the early stage of detail design phase, to coordination of design detailing at the end of the design stage (known as interdisciplinary work). Progressive design fixity (procurement waves in the study) enabled the designers to pass through the negotiation to coordination management in a smooth manner. At the final stages of design, the 3-day co-located meetings became scarce, and the designers could work independently.

In summary, the design planning system had two levels of hierarchical planning: the strategical, represented by the Product Creation Process Map (level 1), and the tactical, represented by the Takt-time plan (level 2).

Then, in order to meet the deadlines, the project designers (architects and engineers) set up the BIM Models for all disciplines to progress concurrently followed by the clash detections. The BIM maturity is related to the level of detail in the drawings to achieve the milestones planned in the PCP level 1.

As opposed to design, in which the takt-time was two weeks and the control areas were building themes, the construction TTP used 1-week takt and the control areas were building locations. Although they are different, these plans were integrated by the procurement waves. Because the designers participated in the CSD decisions, they were aware of the complexity of the construction. It facilitated the definition of contractors for each procurement waves, and the alignment of the BIM models' LOB with the procurement necessities. The designers also prepared 80% of the design information for the procurement waves, and then the spare 20% in the next four months concurrently with the procurement process. At the end of this process, when the selected contractor is hired, it receives 100% of the design information.

As opposed to the design, the construction planning used four levels of detailing: the strategical (PCP level 1); the master plan expressed by means of TTP (level 2); the lookahead plans, such as "14-10 weeks" and "6-4 weeks" (level 3) and the "1-week" plans (level 4).

The use of a transparent location-based planning tool for construction, such as the TTP, was primarily to protect the production against stoppages, avoid interferences between trades, and detect constraints. It also facilitated the visualisation of cross-functional dependencies and gave all parties an overview of construction activities. This technique also improved the construction lead time by the buffers removal, enabled a smoother workflow for crews, easier control and predictability of resources required every week, increased the transparency of plan, facilitated the planning for long and medium lead time resources, and the devising of the weekly plans.

Summarising, the **collaborative and integrated production plan and control** in the project was boosted by the takt-time plan for the design. At this stage, the collaboration for negotiation and integration of decision was higher than in construction because all designers were already hired in the project, as opposed to the construction contractors and subcontractors. However, as soon as the contractors were onboard the project, they were invited to review the construction takt-time plan. Because of the lack of buffers in the construction plan, there were some issues related to crews achieving the 5-day takt, construction sequence, and so on.

The WIP in the design was not measured, but it was possible to visualise how many days one theme remained open in the TTP sheet. As the design production batch was related to the theme, the WIP should be measured on the same basis. The spreadsheets used by the design project team did not measure the WIP and percentage of concluded packages.

Regarding the use of the **transparent plan**, the takt-time plan for design had three days of co-location with many meetings using post-it notes to plan the next takt theme activities. Also, the team had access to a shared web-based server to visualise the themes, theme owners, activities, and other information. Moreover, the spreadsheets used in the project, instead to plan design or construction, were transparent and straightforward tools to communicate and coordinate the work of participants.

At the strategical and tactical levels, **the pulled and integrated production** in the project occurred in three moments: 1) In the design themes, when the theme's owner was responsible for pulling the decisions to be made, the design to be produced, and the activities to be carried on in order to complete the theme; 2) In the development of the design milestones, which used a reverse plan from construction TTP and also included the procurement processes; and 3) In the lookahead planning deployed by the construction contractors and subcontractors on-site.

CS4 also contributed to answering some of the research questions. These can be seen in Table 29.

Table 29: The main contributions of the CS4 for the research aim and objectives.

Aim/ Objective of the Thesis	**Case Study 4 Contributions**
Devise a **model** to **design, plan and control** the stages of **design and construction** in the context of projects with **overlap** between these stages, using **location-based tools** and other **lean tools to pull** and **align the project production**	A second version of the model was devised based on the case study. The model was improved considering the design of the project as a whole, its operation and improvement. Other improvements were made related to the techniques to plan design, including the takt-time plan, the use of themes, BIM development of all disciplines concurrently, and BIM freezing waves connected to the procurement waves.
how to use location-based tools to **structure the work** for design, suppliers and construction	The location was used mainly for the construction stage, but its reverse plan enables the milestones definition for procurement waves, which were followed by the design production. Designers explained during the evaluation of the model that the design produced during the interdisciplinary phase could be done based on construction location, as well as the contractors' deliverables. Also, the designers got involved in the CSD, understanding the construction strategy, production batches, complexities, etc.
how to **assemble design packages** to meet suppliers' and construction requirements	The design packages were assembled according to the themes created during the takt-time plan in order to meet the procurement waves requirements. The design packages include more than the design production, but also the decisions to be made collectively in the project.
determine the **decoupling point of design** development	The decoupling point of the design is the end of transdisciplinary and beginning of the interdisciplinary stages of design development, i.e. after freezing the

	main building design disciplines, the architects and engineers can develop their work relatively independently without running clash detections.
analyse existing **types of pull production systems**	In the project, there was a central pulled flow from construction to design. The construction takt-time plan pulled the procurement process that pulled the design deliverables. However, the design takt-time plan had the deadlines pushed from the PCP level 1. On the other hand, the completion of the design themes required a pulled flow of production, information, activities and decisions by the theme owner.
how to measure and manage the **work in progress and buffers**	The WIP could be measured based on the sum of days a design theme is open (unsolved) in the takt-time plan. The WIP should also be measured from design through procurement until the construction stage. The buffers should be estimated during the CSD, and controlled during the system operation.
identify the **best tools to control the production system**	The production system can be planned and controlled for design using the TTP with some crucial metrics for WIP, issues solved on time, etc. For construction, the LBS tools combined with the last planner is still an excellent system to plan and control resources, remove constraints and learn. For the project as a whole, the Project Plan should use Process Map and be tracked.

5.1.10 Suggestions for Improvements

The researcher suggested some improvements for the next project that will be managed by Company F using lean design, BIM and lean construction. The suggestions were:

- Use of target costing for Company F's projects, considering the company works with taxpayers' money and the projects should always be on budget;
- Use of IPD (Integrated Project Delivery) which enables the early participation of stakeholders in the project, benefiting it to meet the budget and share the risks and profits among the participant enterprises;
- Use of lean metrics to control project performance:
- Control the executed design master plan;
- Measure the adherence of dates and information of design deliverables;
- Measure the WIP in the design takt-time plan;
- Metrics for design themes, such as the number of issues solved on time.
- An easier way to track decisions made in the design themes:
- Suggestion: tag decisions by disciplines, floor and area.
- Collaborative Construction Plan with contractors and subcontractors:
- TTP should consider buffers: less deterministic and rigid, but more flexible for contractors and subcontractors – flexible for negotiation.

- Register the suggestions for the project improvements along its execution, and select the feasible actions;
- Use the PCP more extensively for other project areas from the first stages of the new product development;
- Extend the consideration of the Systematic Completion process into the PCP;
- Still, in the Systematic Completion, align the testing batches with design and construction batches.

5.2 SECOND VERSION OF THE MODEL

In the second version of the model, the Project System managerial activities of design, operation and improvement were added. Moreover, new practices to manage design deploying BIM were embedded in the model. The CS4 also provided new insights into the use of TTP for CSD. The second version is depicted in Figure 117 and will be explained in the following paragraphs.

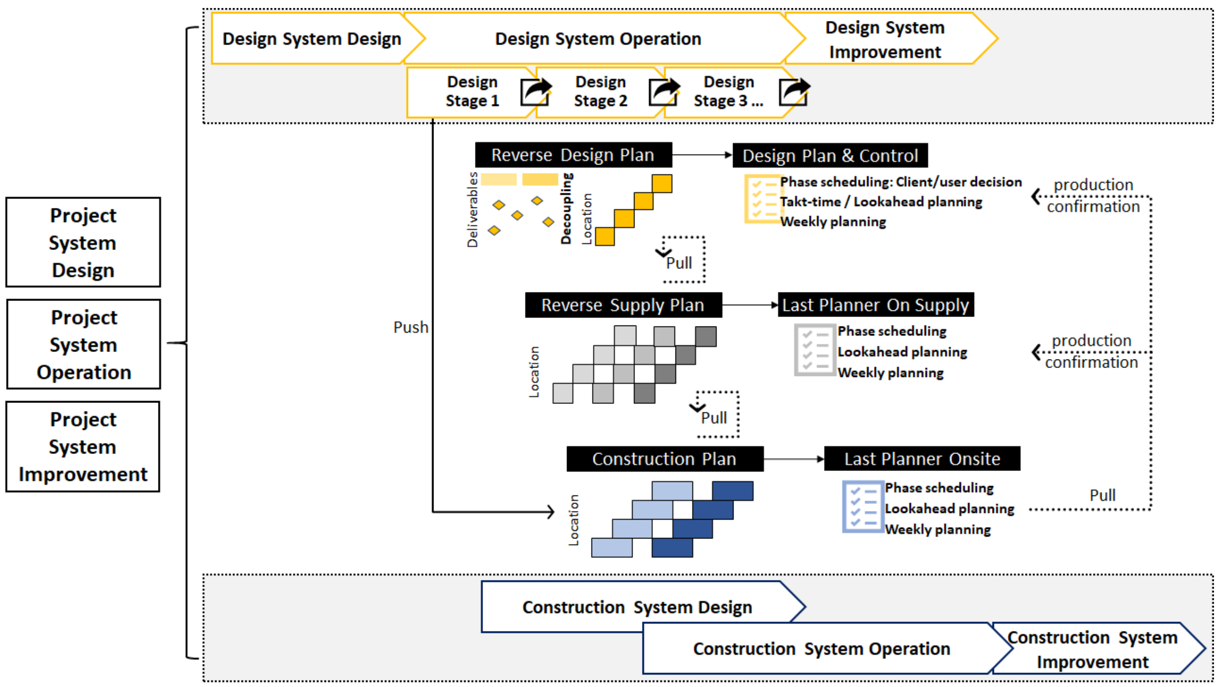


Figure 117: Second version of the model to integrate the design and construction stages resulting from case study 4.

The part of the model concerned with the product development process gained the project management activities. Following the three actions of production management, it also should incorporate the design, operation and improvements activities.

The **Project System Design** should define the structure and workflow of the whole project, and how different functions and stakeholders will communicate and make joint decisions. The project team, including designers, builders, client and owner, should:

- Define the main functions of the project, such as Design, Procurement, Construction, Quality, Health & Safety, and so on;
- Define the stages of the project development, not only the ones required by law;
- Define the main milestones for each function inside the stages of project development;
- Create a logical sequence of milestones through the functions and stages;
- Define the lead time of each main stage based on the following:
- project delivery date;
- complexity of the project (longer design development and construction);
- type of tendering (public projects have longer lead time for procurement).
- Develop a strategical plan with the major milestones for each function.

With these definitions, the dependencies among different project functions are clarified, and the sequence of work settled. In order to keep the project adhered to the strategical plan previously defined, the **Project System Operation** should: a) plan and control the progression of all functions' activities; and b) use metrics to control the strategical plan by deliverables from other levels of plans and functions.

To enhance the performance of the project management along with its execution, in the **Project System Improvement**, the team should:

- Gather information of suggested improvements from the Design and Construction, but also from other project functions;
- Have frequent *kaizen* meetings with project stakeholders to collect more suggestions and develop action plans to implement the improvements across project functions;
- Document the *kaizens* on A3 sheets;
- Distribute the knowledge acquired among the company's employees.

With these actions, the project participants can be assured that the ideas of improvement can be applied during the project operation. Otherwise, the ideas will emerge only at the end of the project as lessons learnt for future projects if the knowledge is retained and distributed across the companies.

Previously, at the beginning of the design stage, the main participants should carry on the **Design System Design**, in which they decide how the design should operate regarding the design goals, workflow, processes, tools and people. One contribution of the CS4 was related to the BIM The participants should then:

- Define the main BIM and IT tools that will be used for the design development, the file extension for exchanging information, documentation to record clashes, use of common server;

- Define number design development stages that the project will have and what level information/geometry detail is necessary for each one;
- The stages should be related to the design deliverables (procurements, public permission, construction, etc.);
- Define which and how the disciplines will be developed for each BIM model freezing, and how many freezing waves they will have;
- Define the verification and validation process of the models. Include the client/user on it;
- Based on the strategical project plan, prepare the master plan for design;
- Define how the master plan will be controlled: through the LPS, Agile design management, TTP, or other.

Based on the previous definitions, the **Design System Operation** should:

- Control the master plan using information from other levels of plans;
- Metrics for completion of design packages are essential to help people to learn how to plan their work better;
- Hierarchical levels for design planning and control:
- Design Master Plan (milestones/stages/relation with other project areas). Meetings to close the gates with the client/user, validate design solution and review deliverables;
- Metric: adherence to the plan = time and information deviation of deliverables;
- Takt-time Plan (tactical plan for the next two weeks of work) – similar to the lookahead plan of the LPS: the main idea is to remove constraints;
- A3 sheets: record the central decisions made and make them accessible and transparent;
- Kanban cards: request decision/information accurately from other designers;
- Metric: percentage of issues solved vs opened on time and by the person;
- Root causes should be recorded on the plan sheet.
- Weekly Plan for designers: every designer should control its takt-time plan by planning their work along the weeks. It is a personal plan.
- Metric: PPCb and root causes for non-completion of tasks.
- Apply the decoupling point between Transdisciplinary and Interdisciplinary design development.
- Design specification developed for building areas looking at downstream processes necessities (e.g. construction sequence).

Design System Improvement:

- Stakeholders should have in mind the *kaizen* principle for continuous improvement;
- Common project database to record *kaizen* suggestions for design process;
- Use of A3 sheet to make it transparent and easy to understand how the *kaizen* should be and why;
- Regular meetings to discuss the *kaizen* implementations (maybe every three months);
- Metric: control the number of *kaizen* implemented versus open.

At the **Construction System Design**:

- CSD using a location-based planning tool (Flowline or Line of Balance);
- Decisions about: production batch size, systems testing batch size, work packages, construction sequence, resources capacities and duration, logistic flow, critical processes, and buffers to shield the production against variability;
- Use of BIM for 4D simulation and 5D quantities take-off;
- The CSD should be a collaborative process;
- Designers should understand the impact of design solutions for production;
- Production of reverse plans for suppliers and designers.

The **Construction System Operation**:

- The Line of Balance or Flowline should be redeveloped collaboratively with the subcontractor;
- Ownership of the plan is essential;
- The takt-time plan is a technique that requires collaboration, accurate information, which is why it is better to be used when there is an engaged subcontractor;
- Last Planner System:
- Phase Scheduling with TTP
- Lookahead Planning to remove constraints – Make ready plan
- Designers and Suppliers should be included as responsible
- Metric: ICR (Index of Constraints Removed)
- Commitment Planning to operationalise the plan and control its deviations
- Metric: PPCb (Percentage of Plan Concluded). PPCT (Percentage of Plan Concluded and Tested)

- Kanban to request information/drawings/decision
- Tools for construction control: *kanban / andon / heijunka*

In the **Construction System Improvement**:

- Kaizen to improve the system while it is in operation;
- Common project database to record kaizen suggestions for the design process;
- Use of A3 sheet to make it transparent and easy to understand how the kaizen should be and why;
- Regular meetings to discuss the kaizen implementations (maybe every three months);
- Metric: control the number of kaizen implemented versus opened;
- Send kaizen for designers and suppliers.

5.2.1 External Model Evaluation

When the model was presented, the new insight from CS4 was the managerial activities around the whole project: Project System Design, Operation and Improvement.

In the **Project System Design**, in order to design the project, it is necessary to select how many areas will participate in the new product development process. The word “area” was used to refer to “functions” or “sub-systems”, such as the construction, design, procurement, quality, health and safety, public permissions, etc. The CS4 participants, maybe due to language differences, pointed out that the word “area” refers to space or physical location, and it may be confusing. They also suggested using the word “processes”, because they are part of a chain. So, the researcher decided to use “sub-systems”.

The participants also understand “process” as the highest level of the planning, the sum of “activities”. This is different from the VSM vocabulary, in which process is the lowest level of production, where the cycle time can be measured. The participants suggested using the conventional terminology for process, activity and system. They pointed out that the terminology used in the literature is confusing, and the words should be used with care.

At the **Project System Operation**, the model suggested the use of metrics for the quality and milestones. The participants agreed with this and added that they used to change colours for green when the gate was crossed. The Head of the Project highlighted that they controlled the progress in lower levels of planning that needed to be transferred to the highest level. He also added that they could have done the metrics, but that, as it was their first Lean Project, they were focused on making it happen. This improvement idea should be applied in a second project.

Project System Improvement suggested promoting kaizen, or continuous improvements, based on the stakeholders’ ideas, and use the root causes detected in the LPS used by designers and builders. The Head of Architects pointed out that kaizen should be analysed because they have different purposes and levels of application: some may be applied in operational, on strategical levels, or transferred to other projects. The tools suggested in the model, the use of A3 for instance, how they can be applied effectively. At the end of the discussion, the group agreed to use the model suggestions for the project system improvements.

The project participants have an “allergy” to theory. They believe if the theory is followed, it may hamper the productivity on the operational level. They got into defensive arguments because they were discovering how to make the project system work, rather than following the theory. The HoP exemplified that they use Agile in Design, but they did not want to mix Scrum vocabulary with the Lean vocabulary.

In **Design System Design**, the Head of the Architects highlighted that all of the parallel progression of design, from transdisciplinary to interdisciplinary, is related to BIM only. Moreover, the most critical concern is the “I” of the BIM - the information: what information is needed and when to avoid overload of the models.

At the **Design System Operation**, two-week takt-time was ideal for the project, but it may be different from project to project, according to the complexity of the design. For complex projects, it is good to have 2-week takt, and 3-day co-location works among designers. To improve it, it is checked for whether the chunks have the size for two weeks. It is a combination of sharing and developing the BIM model. Finding a balance between external work and internal work is important.

The model suggested deploying the “make ready plan”, i.e. to remove constraints to execute the design activities smoothly. In the model, it was also suggested to collect root causes from the design TTP. The HoA said she is not familiar with the LPS. The researcher explained the difference between the LPS in design and the TTP. In the CS4 project, the latter was used based on the design deliverables for procurements and to achieve the maturity levels.

The decoupling point between the transdisciplinary and interdisciplinary point is crucial to define the pull and push flows and solve all the building’s interferences between disciplines before conducting the interdisciplinary phase.

In **Design System Improvement** and **Construction System Design** there were no comments.

In **Construction System Operation** the participants claimed that the subcontractors need to meet with the takt-time, that their logistic and production capacity is their problem. The HoP added that the TTP should have buffer areas in the master plan. The HoA explained that the TTP of façade has that face because the subcontractor wanted to work with the same amount of workers during the project execution, independently of the workload. HoP pointed out the balance between takt and areas and capacity. The HoA added that, if everybody understands the concept of TTP and his or her own capacity, he or she can plan comfortably ahead along the horizon. Then, the HoP added that 80% of the construction projects could be pre-planned because they have the same work packages’ sequence and duration. Then, when the contractors are onboard, it is possible to confirm the production plan and adjust the TTP.

The researcher and the study participants discussed the differences between LOB and TTP. It was highlighted that the wagons of the takt-time could be composed by more than one crew to keep the 1-week takt. However, sometimes the wagon can have more than 1-week takt, as happened in the project, with 2-week takt.

During the model explanation, the participants were unfamiliar with some Japanese words, such as *kanban*, *andon*, *heijunka*. The researcher therefore explained the words to them and the context of use. As the information was new for the participants, they did not mention anything about it. Around the **Construction System Improvement,** there were no comments.

When replying to the questions in the semi-structured interview, the participants had solid opinions. They said that the Stage-Gate is extensively used in Norway, and that the MAKS10 contains all the requirements for each design stage. The Stage-Gate is a good practice but should be flexible regarding the number of stages, due to different project characteristics. The HoA said there is a first layer in the stage driven by law and regulations. Other project layers include decision-making and design deliverables for procurements. The participants agreed that it should have formal gates and keep all discipline developments concurrently.

The participants agreed that all projects should be managed as Agile. They understand that their project was Agile, but they prefer not to mix the vocabularies between Agile and Lean. They were concerned about making the project management simple and effective.

The participants were asked about using a less mature design to produce the CSD, and mainly the location-based schedule tools. They said that it is feasible due to the fact that the design will not change too much from design for public permissions and a detailed design. They explained that it is good to start developing the CSD earlier in order to understand the complexity of construction. One of the participants was concerned about not having the contractors available so early. However, they agreed it could be overcome by the inclusion of the site manager or someone else knowledgeable in the collaborative design meetings with the designers. The participants said that, for the CSD, it is not necessary to know about the size of the construction crews.

Regarding the TTP, the interviewees agreed that it could be used to optimise the resources and flow efficiency of construction. A mode to make this LBS tool more adaptable to variability in the planning process is to adopt a buffers zone. This could guarantee the TTP use at the CSD.

The interviewees also highlighted that the use of a location breakdown structure (LBS) derived from construction applied to the design is not the answer when aligning design and construction. They explain that design has a different focus throughout its development. It is possible to apply the same LBS to the pull design only in the specifications phase, i.e. in the interdisciplinary design development, where negotiation is no longer required. The design does not need to be developed in the same control areas adopted by construction. The study interviewees believe that, when the design is 80% completed, the spare 20% can be produced by pull flow from construction. According to the HoP, using the LBS is possible, but it is tricky because design needs to think about the test of technical systems on-site. Geometry and function need to be developed together.

The case study participants expanded the different characteristics of the design development. According to them, the design develops in a different way along the stages. First, one entire floor can be drawn to a certain level, then the level of detail is increased in small areas, and then special meetings are needed to clarify the design solution for specific rooms. Afterwards, one room is completed, the design solution can be replicated and checked for the remaining similar rooms at the building. However, the adoption of this rationality to develop design relies on the building's complexity.

In the HoP's view, the design is an iterative process, in which the team needs to ensure that they are advancing five steps forward and only one step backwards, rather than four steps. It is challenging to control a positive design iteration because it is not always clear where the final stage is, and backwards steps are necessary to meet the client's requirements. In construction, however, a backward step almost always means rework.

When questioned about progressive design fixity, the participants pointed out that freeze design is important to avoid project over-costs and higher risks. In order to decide when the design development is ready to be frozen, it is crucial to define all the expected requirements for all disciplines to that stage of design. Before freezing, it is mandatory to cross-check the transdisciplinary BIM model. Unfortunately, it is not accurate and straightforward to decide when exactly the design should be frozen. The interviewees believe it is a team decision, as the team members should know when the design is ready to freeze.

The user participation seems not to be very desirable for the project team. They agreed that it is necessary throughout the project development. However, the users should be prohibited from changing their orders too late in the project in order to keep the project on budget.

In conclusion, the project team, and mainly the HoP, were very keen to try an IPD project. They understand the benefits of IPD to check and ensure design buildability with suppliers involved earlier in the NPD process. Table 30 presents the main outcomes from the second version of the model evaluation.

Table 30: External model evaluation outputs, and proposed actions from the CS4.

Issues pointed	Actions
Word "areas"	Word "sub-systems" or systems.
Define the word "process" and "activities"	The words used follow the literature review.
Word "system" is confusing	
Takt Planning Design vs. Last Planner System in Design	The Takt Planning defines the takt, and in its operational level it pulls the work that can be done in one takt. In the operational level of LPS, it pushes the tasks to be completed in one week. These differences will be discussed in the Discussion chapter.
Takt-time Planning vs Line of Balance	These differences will be discussed in the Discussion chapter.

6 DEVELOPMENT OF THE THIRD VERSION OF THE MODEL

This chapter presents the development of the third version of the model. The third version was created based on findings from the Action Research Study 5 and CS 6. In the ARS5, the researcher implemented part of the model in a construction project to field test it. While in CS6, there is new data about how another company integrates the design and construction stages through the production planning and control process. The context in which the CS6 was developed is also in a construction project led by two partner companies: K (the construction company) and N (the real estate company). The complexity of the architectural design is low in both studies.

The chapter is structured in the following way: first, the presentation of the work developed at ARS5, and finally the CS6 description. The next section describes the third version of the model, focusing on the enhancements made from the second version to the third. The third version was externally evaluated by the CS6 participants and is included at the end of the chapter.

6.1 ACTION RESEARCH STUDY 5 (ARS5): HIGHWAYS DEPOT AREA

In ARS5, part of the thesis developed model was implemented in order to be field tested. Following the action research steps of diagnosis (section 6.1.3), planning the action (section 6.1.4), taking action (section 6.1.5), evaluation (section 6.1.6) and learning (section 6.1.7), the ARS5 not only provided findings about the utility of part of the model, but also how to implement it in the context of a construction company. The ARS5 had limitations regarding the client changing its orders, which prevented the use of all the practices developed and their further evaluation.

6.1.1 Project Description

ARS5 was conducted at Company J, which “is one of the world’s foremost support services and construction companies”. The company offers “advice, design, construction, equipment, facilities management and frontline public services”. The gross revenue is around £3.6 billion and it employs 80,000 labourers worldwide.

The ARS5 occurred at the construction project of a depot for maintenance of highways. It is located on 2.0 hectares of land adjacent to the A1(M) motorway, in North Allerton, UK. The works comprised the detailed design and construction of the depot. The contractual arrangement was the NEC3 – option C, which is a “target cost contract with an activity schedule where the out-turn financial risks are shared between the client and the contractor in an agreed proportion” (NEC, 2013).

The construction activities were scheduled to start in February 2018 and take overall 30 weeks, i.e. finalised at the beginning of September 2018. The major building at the depot project was the salt barn, which was programmed to take 16 weeks. The construction of the depot consisted of the following:

- Site preparation;

- A timber-framed dome storage building (with a capacity of 7500 tonnes of salt) measuring 36.1m in diameter with a maximum height of 15.5m;
- A 30m x 30m garage to house salt spreaders, workshop and stores;
- External vehicle wash down area;
- Office space to accommodate approximately 20 staff and messing facilities;
- Internal access road and adequate parking spaces to be provided for both office staff and highway maintenance operatives;
- Fuel tanks with a 20,000-litre capacity;
- Some other ancillary facilities including, but not limited to, hardstanding and stores for traffic management and incident response equipment up to 1500 square meters;
- An oil separator or series of oil separators that will be determined during detailed design, in line with the planning conditions;
- Car park with dimensions – 100m x 200m plus 50m x 50m.

6.1.2 Research Process

The aim of ARS5 was to field test the model. In order to enable this, the study followed the action research activities proposed by Susman and Evered (1978): (a) diagnosing; (b) action planning; (c) action taking; (d) evaluating; and (e) specifying learning. The diagnosis was conducted on 19 July 2017 at the site office by means of semi-structured interviews with the company's members, with the aim to understand which were the project management practices deployed by Company J. The action planning consisted of defining what parts of the model were feasible to implement and what the process should be. It was decided to deliver three workshops and, in between them, the researcher conducted the development of the tools (recommended in the model) collaboratively with the project's participants.

The workshops were run by three lean specialists from the industry and academia. The workshops focused on the fundamental topics of lean production management and supported Company J in the implementation of the lean construction practices and tools. The workshops totalled 24 hours of teaching and exercises.

The workshops were designed with an action-based approach to learning. Hence, existing lean approaches and tools were presented and discussed in the workshop. Participants were then expected to implement specific tools in the project jointly with the researcher. Finally, implementation results were shared across all participants during workshop discussions.

The implementations took place for two months. The researcher implemented the tools throughout eight weekly meetings at the site office. When the meetings concluded, the project participants were able to continue using the tools for project management. In January 2018, they were required to reply to an online interview evaluating the overall process. The participants wrote down testimonials about their experiences and the relevance of the tools for their practice. The final step of the ARS5 was the learning, which requested the participants to reflect on the practice and connections with theoretical background.

The timeline of the activities developed at the ARS5 is presented in Figure 118, followed by the evidence sources in Table 31.

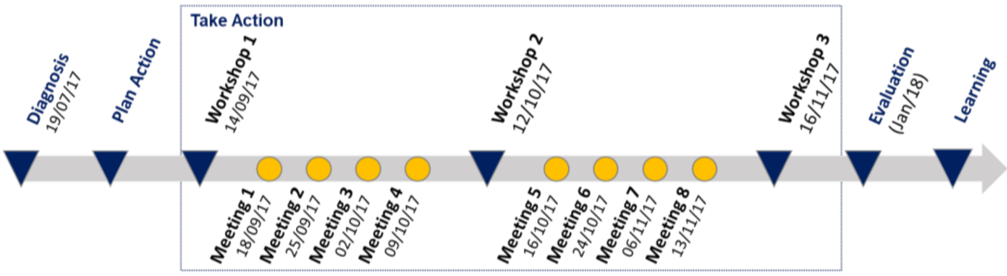


Figure 118: Timeline of activities developed at the ARS5.

Table 31: Sources of evidence for each phase of the ARS5.

	Aim	Sources	Developed in
1.	**Awareness of the problem – Diagnosis**		
a.	Understand the project management at Company J	• Semi-structured interviews with employees • Direct observations: planning and controlling spreadsheets in the site office	List of lean practices to deploy at the company and the project management
2.	**Suggestion – Plan the Action**		
a.	Proposition of instantiation of part of the model through action research study	• Data analysis of interviews	Workshops 1, 2 & 3; Structure of model instantiation; Tools development jointly with project's participants
3.	**Development and internal evaluation – Model Instantiation**		
a. b. c.	Workshop 1 Workshop 2 Workshop 3	• Classes and exercises about Lean Construction, Wastes, Production System Design, Line of Balance, Last Planner System, Visual Management, etc.	Basis for tools development and part of the model instantiation
d.	Weekly Instantiation	• Researcher participation jointly with project members	Tools: Line of Balance, Supply System for design and
4.	**Evaluation of the process of model instantiation**		
a.	Evaluation of the process of model instantiation, including tools and practical relevance	• Online interview with all participants (Quantity Surveyor, Contracts Planner, Design Manager, Project Manager, Sub-Agent)	External evaluation of the process
5.	**Learning**		
a.	Learning about process and model practical relevance	• Participant observation of tools development and use • Documental analysis of tools developed	Internal evaluation of the study

6.1.3 Diagnosis

For the diagnosis conducted on 19 July 2017, the researcher interviewed the company's employees about their general practices for project management. Open questions about the project organisation, software used, the processes and people involved were made. Data from the site office observations were also used to understand the project's visual management.

The owner and client of the project is a public enterprise that "operates, maintains and improves England's motorways and major A roads". They work with the Department for Transport. In the project, Company J was selected by the client in an NEC3, or Option C contract, which means they have a target cost for the project development sharing risks with the client.

Company J was in charge of the design and construction activities. The design was outsourced with a specialist enterprise in a traditional contract. They were invited to get involved in the study, but Company J did not want to change the contractual arrangement. Then, the part of the model about design production planning and control was not deployed in the study.

Company J had used collaborative planning in some projects and intended to use it in the Depot project as part of a list of lean practices required by the client. However, the team assigned to the project have never used lean tools and practices. The construction plan was developed in MS Project, using the traditional CPM.

In summary, the project was a vast field to explore the lean practices in supply and construction management, but with limitation to look into design management due to the lack of designers' participation. Thus, with Company J's participation, the focus of the study was to deploy part of the model applicable to the CSD and operation, and to the pull flow from construction to supply and design, as shown in Figure 119.

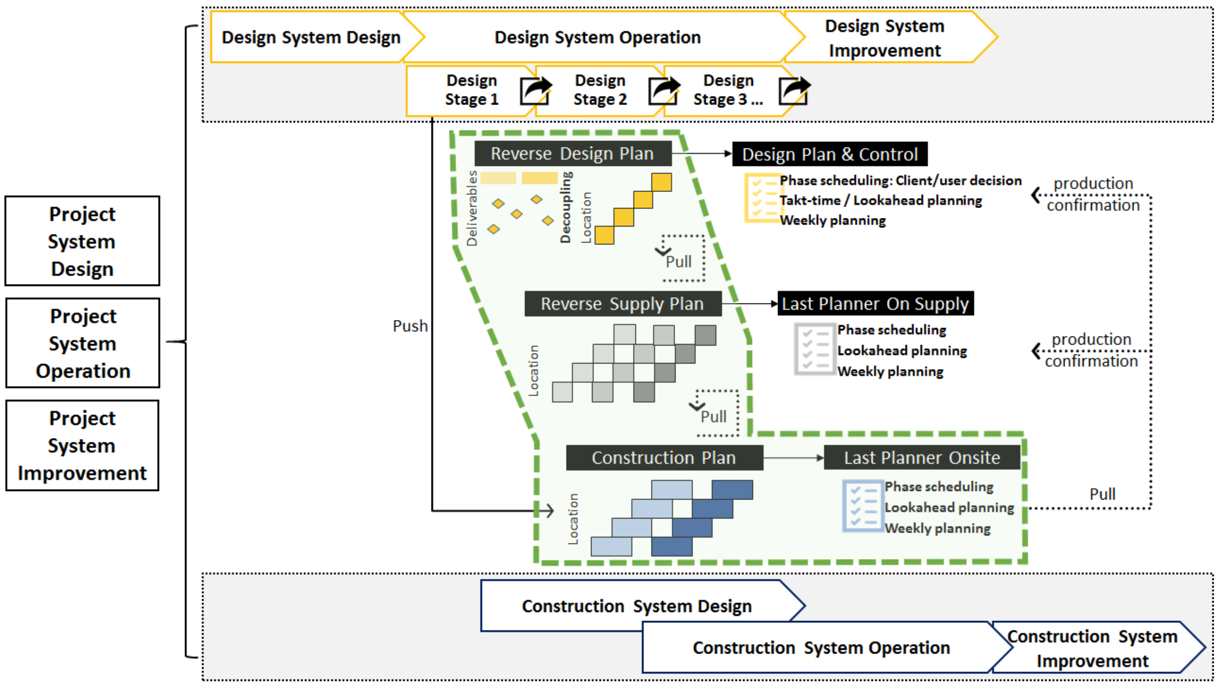


Figure 119: Part of the model implemented in the ARS5.

6.1.4 Planning the Action

In order to implement part of the model, some lean theory needed to be taught to the participants. The model required knowledge about lean concepts, the PDS, LBS tool, LPS, visual management, and so on.

The professional experience of the researcher in implementing lean construction was crucial when deciding the method to embed the model in Company J. It was estimated, based on the complexity of the project, that two months was enough to prepare the tools of the PDS and the LPS. In order to dilute the content along the months and facilitate the learning and tools development, three workshops were planned mixed with implementations. The project's participants should deploy the tools with the support of the researcher who visited the site every week, and then present the progress of the implementation in the workshops to promote discussion – see Figure 120.

Figure 120: Planned action to embed the model in the ARS5.

Due to the variety of topics, three lecturers were invited: one specialised in PDS, one in the LPS, and the other in visual management. The workshops were planned from 9:00 to 17:00 and occurred at the University's facilities.

In the first workshop, the basic concepts of lean construction were introduced, namely CSD and LOB. This theoretical background was used by the researcher and Company J's participants to deploy the tools. In the second workshop, the participants presented all the work developed in the previous weeks. The content of the second workshop was LPS and continuous improvements. In the following weeks, the participants should deploy the lookahead and weekly plans. At the third workshop, the project team learnt about visual management, 5S and SMED (Single Minute Exchange of Die) and also presented the tools realised. The content planned for the workshops is described in Table 32. At the end of the workshops, the participants evaluated the content and the lecturers.

Table 32: Workshops content in the ARS5.

Workshop 1	**Workshop 2**	**Workshop 3**
▪ Lean Construction ▪ 9 Wastes in Construction ▪ Construction System Design ▪ Line of Balance	▪ Production Planning and Control: Last Planner System ▪ Continuous Improvement	▪ Visual Management ▪ 5S ▪ SMED

The researcher asked to Company J the participation in the ARS5 of key players in the project management, namely the project manager, planner, sub-agent, quantity surveyor, graduate engineer and design manager.

6.1.5 Taking Action

The workshops were attended by ten people of Company J. The researcher and the lecturer of the first workshop prepared MS Excel templates for the participants to develop the LOB and LPS.

6.1.5.1 Workshop 1

The workshop 1 occurred on 14 September 2017 from 09:00 to 17:00 at the University of Huddersfield. The participants learnt about the Toyota Production System, Lean Construction theory of Transformation, Flow and Value, Wastes, Production System Design and Line of Balance; they also did exercises in groups to understand the balancing process in the LOB – see Figure 121. At the end, the programme was shown of the implementation of the tools for the next four weeks, as depicted in Table 33. The participants were invited by the researcher to start drawing the work packages sequence for each production batch.

Figure 121: LOB exercise in the workshop 1.

Table 33: Programme of activities in the ARS5 for the first four meetings.

Period	Activities
Week 1 (15/09 – 22/09)	Definition of the production batches, work packages and the tasks, and sequence network
Week 2 (25/09 – 29/09)	Resources production capacity: duration of work packages, crews and responsible contractors
Week 3 (02/10 – 06/10)	LOB, balancing delivery rates and buffers allocation
Week 4 (09/10 – 11/10)	Finalise the LOB and prepare a presentation for the next workshop
Workshop 2 (12/10)	15 minutes presentation + 15 minutes discussion

6.1.5.2 Instantiations

The instantiation of part of the model was begun by the company’s participants after the first workshop. The first meeting on-site occurred on 18 September 2017, with six company’s employees participating. They were requested to start the work packages sequence network for each production batch of the project. However, they had done this for the whole project as a single batch. Then, the researcher requested them to break down the project into small batches, i.e. in zones and buildings, so that they could create specifics work package sequences. This task was made during the meeting collaboratively. Also, the team had prepared a preview of the construction sequence of the site zones and, after much discussion about physical flows, was defined as shown in Figure 122.

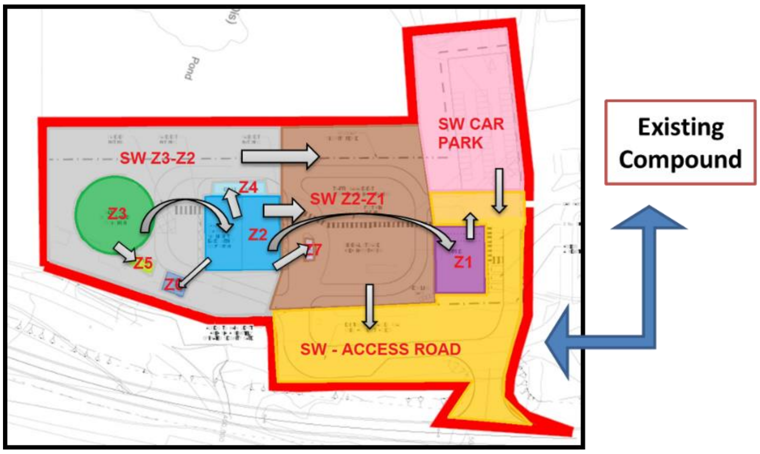


Figure 122: Site zones and construction sequence defined in the ARS5.

As homework for the next meeting, the project team was in charge of reviewing the construction zones sequence and the work packages sequence, and to make a list of the tasks in each work package. The final version of the work packages network is demonstrated in Figure 123, while the list of tasks is in Figure 124.

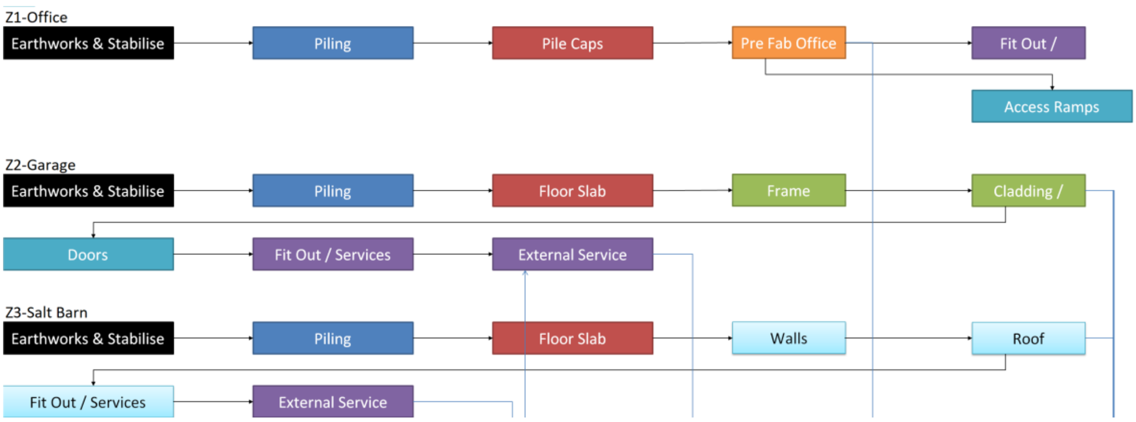


Figure 123: Work packages sequence-net developed collaboratively for the depot project in ARS5.

Piling	Floor Slab	Walls	Pile Caps	Frame
Piling Mat Set up Rig* Drive Pile*	Excavation* Blinding* Formwork* Reinforcement* Concrete Pour Strip formwork*	Reinforcement* Formwork* Concrete Pour Strip Formwork*	Pile cut to level* Reinforcement* Formwork* Concrete Pour Strip Formwork*	Set Up Crane Superstructure (Colum Bracing Beams*

Figure 124: Example of work packages task content in ARS5.

At the second meeting on 25 September 2017, the project team had accomplished the tasks requested. Then, collaboratively, the team and the researcher started the logistic plan of the construction site, marking the main routes for lorries, unloading areas and lay down (stock). For the next meeting, Company J's participants were to prepare the production capacity sheet, on which they should list for each work package the quantities, the gangs and their productivity in order to estimate the duration.

In the third meeting, on 2 October 2017, the team prepared the production capacity sheet for all the zones, with information about the duration, buffer, transfer batch, quantities and crew tag (Figure 125). Based on this, which was added to the construction zones sequence, the LOB was devised collaboratively. For the next week, the researcher requested that the team finalise the LOB and balance the rates, insert the buffers, check interferences and review the work packages sequence-net once again.

Z1-Office

WORK PACKAGE (wp)		S/C	RESOURCES		Qty	Unit	Rate / day	CYCLE TIME	LOB
		CREW TAG	PROFESSIONALS	EQUIPMENTS					
1	Piling	P1	1 Supervisor, 2 Operatives	1 Piling Rig, 1 Lorry, 1 Excavator	56	No	15	3.73 days	5
2	Breakdown Piles	C1	1 Plant Op, 1 Operative	1 Excavator, 1 Pile Crusher	56	No	15	3.73 days	5
3	Pile Caps	F1	1 Steel Fixer, 2 Joiners	Hand Tools, 1 Concrete Pump	400	m2	30	13.33 days	15
4	Pre Fabricatied Offices	E1	3 Installers, 1 Crane Op	Crane, Lorry	14	No	3	4.67 days	5
5	Fit Out / Services	E2	2 Skilled, 1 Operative	Hand Tools	1	item	0.067	14.93 days	15
6	External Service Connections	I1	2 Skilled	Hand Tools	1	item	0.2	5.00 days	5
7	Access Ramps	F1	1 Steel Fixer, 2 Joiners	Hand Tools	4	No	0.75	5.33 days	5

Figure 125: Example of one production capacity sheet for one of the construction batches in ARS5.

On 9 October 2017, at meeting number 4, the project team completed the LOB and inserted a third in-house crew in order to keep the continuity of crews flows. The final version of the LOB is shown in Figure 126. In the latter, the construction zones and buildings are the locations represented in the vertical axis of the tool in the order of execution.

For workshop 2, the researcher requested that the team make final adjustments at the LOB in order to improve the physical flow on the construction site for the paving work package.

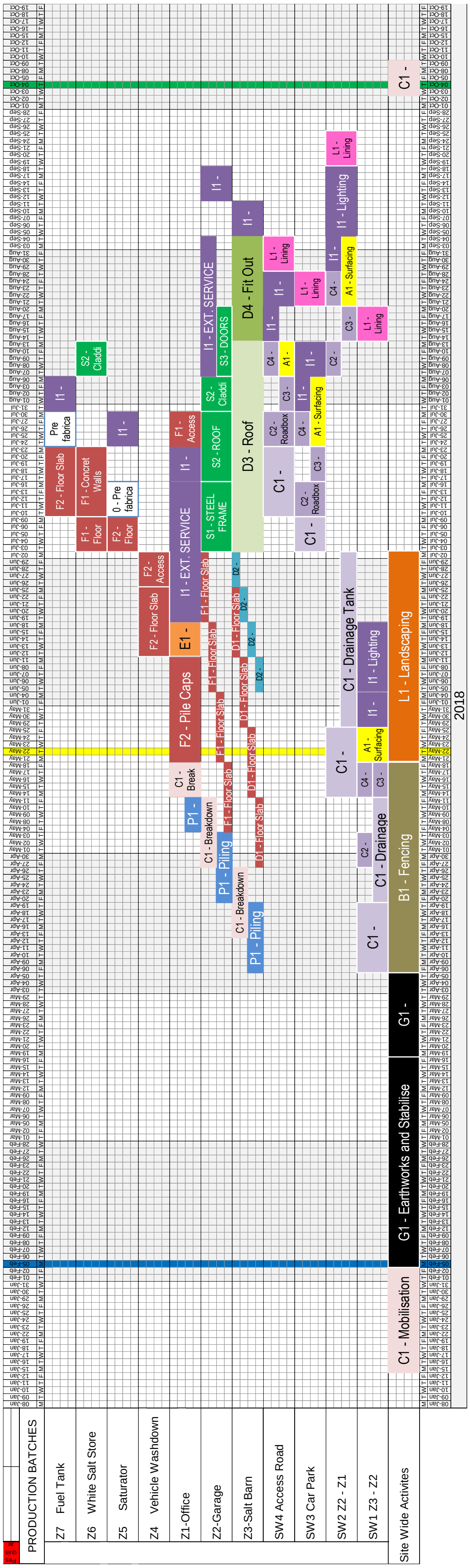


Figure 126: Line of balance of the depot project in ARS5.

6.1.5.3 Workshop 2

At workshop 2, held on 12 October from 09:00 to 17:00, the staff involved in ARS5 presented the work done along the four weeks. They started with the construction site sequence, the work packages sequence, then the production resources capacity. The LOB was presented in detail. During the discussions, the staff pointed out that the LOB as a planning tool is more straightforward to understand compared to the Gantt chart and CPM used in the Ms Project. They also highlighted that it is easier to understand the resources allocation, interferences and use buffers without speeding up the production. The project team added that the duration of the tasks was rounded up, but the project lead time was kept the same compared to the Ms Project plan.

After the presentation, the invited lecturer began the workshop, teaching the following topics: Lean Planning vs Traditional Planning and Overview Last Planner System; Master Plan and Lookahead Plan; Short-term plan and Continuous Improvement; and Lean in practice. During the workshop, the project team did a pull plan exercise to understand all the activities involved from the design to construction. Also, in another exercise, the participants were invited to develop the lookahead planning based on the LOB of the project and the pull plan activities, as shown in Figure 127.

Figure 127: Last Planner System exercise in the workshop 2.

At the end of the workshop, the researcher specified the activities and tools to be developed in the next four weeks. Before starting the LPS, the project team should classify the suppliers according to the lead time to produce and deliver the products. The classification was essential to know which supplier should be planned in the long, medium and short terms, as well as to define the time horizon of the lookahead plan. The programme of activities is described in Table 34 below.

Table 34: Programme of activities in the ARS5 for the last four meetings.

Period	Activities
Week 5 (16/10 – 20/10)	Develop the workforce histogram. Studies for the Master Plan: Site layout and flows (print it). Planning of C1 suppliers.
Week 6 (23/10 – 27/10)	Studies for the Lookahead Plan: Workstation layout and flows for the next work packages (print it). Make ready meeting 1: constraints studies and removals (C2/3 supply). Costs per packages, quantities, suppliers, deliveries

Week 7 (30/10 – 03/11)	Studies for the Commitment Plan meeting 1: tasks according to zones, check resources, C3/4 supply.
Week 8 (06/11 – 10/11)	Make ready meeting 2: IRR. Commitment Plan meeting 2: PPCb, causes for non-compliance.
Week 9 (13/11 – 15/11)	Prepare presentation for next workshop
Workshop 3 (16/11)	15 minutes presentation + 15 minutes discussion

6.1.5.4 Instantiations

The instantiation of the practices learnt in the second workshop started with the team developing the Supply System, including the processes for procurement and design, just as in the workshop exercise as demonstrated in Figure 128. The batch for procurement is the work package, rather than the location as specified in the LOB. This decision was made because the contractors are responsible for components present in many buildings or zones of the construction site, and their priority is to keep a continuous flow of crews across the zones. Thus, the reference to pull the supply system was the date of the first work package where the component is needed. The design followed the same idea of work package batches rather than location, due to the fact that the drawings are used in the procurement process, so both processes have the same batch.

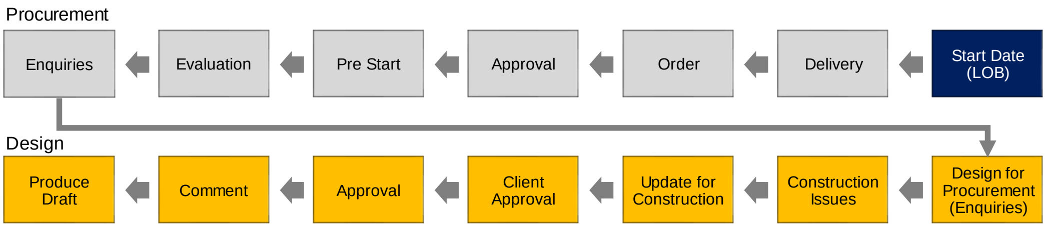


Figure 128: Processes for procurement and design.

At meeting 5, on 16 October 2017, the researcher provided the MS Excel template file, and Company J's staff fulfilled it with the durations for each process on the right-hand side of the spreadsheet, including buffers between the delivery date and the start of the work package on the construction site. The size of the buffers was decided based on the reliability of the supplier and the criticality of the task for the project lead time. The supply system represents the pull plan from the LOB dates, marking the milestones for each process necessary to complete the procurement and design. The supply system spreadsheet is shown in Figure 129. All the spreadsheets use colours to represent the number of days remaining of the deadlines, e.g. green means the task was completed on time; yellow represents less than 10 days; and, red means the task is delayed.

Work Package	Item	Enquires	x	Evaluation	x	Pre Start	x	Approval	x	Order	x	Mobilisation / Delivery	x	Buffer	x	Start date (LOB)	End date (LOB)	Enquires	Evaluation	Pre Start	Approval	Order	Mobilisation / Delivery	Buffer	Total Lead Time
Earthworks	Stabilisation of Ground & Hardstanding	22/11/2017		06/12/2017		13/12/2017		20/12/2017		10/01/2018		17/01/2018		31/01/2018		05/02/2018		14	7	7	21	7	14	5	75
Piling		17/01/2018		31/01/2018		07/02/2018		14/02/2018		21/02/2018		28/02/2018		21/03/2018		26/03/2018		14	7	7	7	7	21	5	68
Civils		02/02/2018		16/02/2018		23/02/2018		02/03/2018		09/03/2018		16/03/2018		30/03/2018		04/04/2018		14	7	7	7	7	14	5	61
Drainage Tanks		17/03/2018		31/03/2018		07/04/2018		07/04/2018		07/04/2018		14/04/2018		12/05/2018		17/05/2018		14	7	0	0	7	28	5	61
FRC Works		16/02/2018		02/03/2018		09/03/2018		16/03/2018		23/03/2018		30/03/2018		20/04/2018		25/04/2018		14	7	7	7	7	21	5	68
Saltbarn	Roof	21/01/2018	x	04/02/2018	x	11/02/2018	x	18/02/2018		25/02/2018		04/03/2018		17/06/2018		22/06/2018		14	7	7	7	7	105	5	152
Pre Fab Offices		24/01/2018		07/02/2018		14/02/2018		21/02/2018		28/02/2018		07/03/2018		30/05/2018		04/06/2018		14	7	7	7	7	84	5	131
Steelwork		20/03/2018		03/04/2018		10/04/2018		17/04/2018		24/04/2018		01/05/2018		12/06/2018		22/06/2018		14	7	7	7	7	42	10	94
Cladding	Walls & Roof	08/04/2018		22/04/2018		29/04/2018		06/05/2018		13/05/2018		20/05/2018		01/07/2018		06/07/2018		14	7	7	7	7	42	5	89
Doors		24/04/2018		08/05/2018		15/05/2018		22/05/2018		29/05/2018		05/06/2018		17/07/2018		27/07/2018		14	7	7	7	7	42	10	94
Surfacing		25/04/2018		09/05/2018		16/05/2018		23/05/2018		30/05/2018		06/06/2018		20/06/2018		25/06/2018		14	7	7	7	7	14	5	61
IES		18/04/2018		02/05/2018		09/05/2018		09/05/2018		09/05/2018		16/05/2018		27/06/2018		02/07/2018		14	7	0	0	7	42	5	75
Lining		30/05/2018		13/06/2018		20/06/2018		27/06/2018		04/07/2018		11/07/2018		18/07/2018		23/07/2018		14	7	7	7	7	7	5	54
Fencing		09/05/2018		23/05/2018		30/05/2018		06/06/2018		13/06/2018		20/06/2018		27/06/2018		02/07/2018		14	7	7	7	7	7	5	54
Landscaping		20/04/2018		04/05/2018		11/05/2018		18/05/2018		25/05/2018		01/06/2018		13/07/2018		18/07/2018		14	7	7	7	7	42	5	89
Fuel Tanks		18/05/2018		01/06/2018		08/06/2018		08/06/2018		08/06/2018		15/06/2018		27/07/2018		01/08/2018		14	7	0	0	7	42	5	75

Work Package	Item	Produce Draft	x	Comment	x	Approval	x	Client Approval	x	Update for Construction	x	Construction Issue	x	Buffer	x	Design for Procurement	End date (LOB)	Produce Draft	Comment	Approval	Client Approval	Update for Construction	Construction Issue	Buffer	Total Lead Time
Design																									
Earthworks		10/10/2017	x	17/10/2017	x	24/10/2017		31/10/2017		07/11/2017		14/11/2017		17/11/2017		22/11/2017		7	7	7	7	7	3	5	43
Piling		14/11/2017	x	28/11/2017	x	05/12/2017	x	12/12/2017		19/12/2017		09/01/2018		12/01/2018		17/01/2018		14	7	7	7	21	3	5	64
Civils		14/12/2017	x	28/12/2017	x	04/01/2018		11/01/2018		18/01/2018		25/01/2018		28/01/2018		02/02/2018		14	7	7	7	7	3	5	50
Drainage Tanks		02/02/2018	x	09/02/2018	x	16/02/2018		23/02/2018		02/03/2018		09/03/2018		12/03/2018		17/03/2018		7	7	7	7	7	3	5	43
FRC Works		21/12/2017		11/01/2018		18/01/2018		25/01/2018		01/02/2018		08/02/2018		11/02/2018		16/02/2018		21	7	7	7	7	3	5	57
Saltbarn		12/11/2017	x	03/12/2017		10/12/2017		17/12/2017		24/12/2017		14/01/2018		17/01/2018		22/01/2018		21	7	7	7	21	3	5	71
Pre Fab Offices		21/11/2017	x	19/12/2017	x	26/12/2017		02/01/2018		09/01/2018		16/01/2018		19/01/2018		24/01/2018		28	7	7	7	7	3	5	64
Steelwork		22/01/2018	x	12/02/2018		19/02/2018		26/02/2018		05/03/2018		12/03/2018		15/03/2018		20/03/2018		21	7	7	7	7	3	5	57
Cladding		17/02/2018		03/03/2018		10/03/2018		17/03/2018		24/03/2018		31/03/2018		03/04/2018		08/04/2018		14	7	7	7	7	3	5	50
Doors		05/03/2018		19/03/2018		26/03/2018		02/04/2018		09/04/2018		16/04/2018		19/04/2018		24/04/2018		14	7	7	7	7	3	5	50
Surfacing		06/03/2018	x	20/03/2018	x	27/03/2018		03/04/2018		10/04/2018		17/04/2018		20/04/2018		25/04/2018		14	7	7	7	7	3	5	50
IES		13/02/2018	x	13/03/2018		20/03/2018		27/03/2018		03/04/2018		10/04/2018		13/04/2018		18/04/2018		28	7	7	7	7	3	5	64
Lining		17/04/2018	x	24/04/2018	x	01/05/2018		08/05/2018		15/05/2018		22/05/2018		25/05/2018		30/05/2018		7	7	7	7	7	3	5	43
Fencing		20/03/2018		03/04/2018		10/04/2018		17/04/2018		24/04/2018		01/05/2018		04/05/2018		09/05/2018		14	7	7	7	7	3	5	50
Landscaping		22/02/2018		15/03/2018		22/03/2018		29/03/2018		05/04/2018		12/04/2018		15/04/2018		20/04/2018		21	7	7	7	7	3	5	57
Fuel Tanks		22/03/2018	x	12/04/2018		19/04/2018		26/04/2018		03/05/2018		10/05/2018		13/05/2018		18/05/2018		21	7	7	7	7	3	5	57

Figure 129: The supply system devised to control the procurement and design processes.

For the next meeting, the project team took charge of starting the lookahead planning, mainly for the design activities and the construction site mobilisation. Then, on 24 October 2017, at meeting 6, the researcher asked the team to expand the constraints, thinking about the preconditions for a sound task: 1) Manpower; 2) Equipment; 3) Construction Design; 4) Components and materials; 5) Space; 6) Connecting works; 7) External Conditions, and 8) Safety. The lookahead was planned in combination with the make ready plan at the meeting and finalised by the team within two weeks. The horizon of planning was 12 weeks, and the constraint was assigned per person responsible, classified by category and controlled by the deadline to remove it. One of its initial versions is presented in Figure 130.

ITEM	DESCRIPTION OF THE SERVICES	DATES				February 2018				March 2018				April 2018					CONSTRAINS						
		START PLANNED	START EXECUTED	FINISH PLANNED	FINISH EXECUTED	05/02	12/02	19/02	26/02	05/03	12/03	19/03	26/03	02/04	09/04	16/04	23/04	30/04	TYPE	DESCRIPTION	RESPONSIBLE	DEADLINE	REMOVED IN	STATUS	OBS
1	**Site Wide**																								
1.1	**Earthworks and Stabilise**	05/02/2018		02/03/2018		x	x	x	x										DESIGN	Receive Design for procurement	ICL Design Mgr	22/11/2017		Not Removed	
1.1.1	Excavate																		H&S REQUIREMENT	Prepare Rams	Subcontractor01	17/01/2018		Not Removed	
1.1.2	Fill																		H&S REQUIREMENT	Approve RAMS	ICL Site Agent	29/01/2018		Not Removed	
1.1.3	Lime Treatment																		EQUIP. AND TOOLS	Confirm availability Stablisation Equipment	Subcontractor01	22/01/2018		Not Removed	
1.1.4	Compact																		COMMERCIAL	Let Sub-Contract order	ICL QS	10/01/2018		Not Removed	
1.1.5	Trim to profile*																		DESIGN	Request models and specifications	ICL Site Agent	22/01/2018		Not Removed	
																			DESIGN	Request final design drafts	ICL Design Mgr	10/10/2017	09/10/2017	Removed On Time	
																			DESIGN	Collect the design drafts comments and issue	ICL Design Mgr	17/10/2017	10/10/2017	Removed On Time	
																			DESIGN	Approve the final design	ICL Design Mgr	24/10/2017		Not Removed	
																			DESIGN	Final sign off	HE Andrew Brown	31/10/2017		Not Removed	
																			DESIGN	Update for construction	Atkins	07/11/2017		Not Removed	
																			DESIGN	Request for construction issue	ICL Design Mgr	14/11/2017		Not Removed	
																			COMMERCIAL	Pre-let meeting	ICL QS	01/12/2017		Not Removed	
																			COMMERCIAL	Approve Subcontractor	ICL PM	20/12/2017		Not Removed	
																			COMMERCIAL	Approve Subcontractor	ICL Commercial	22/12/2017		Not Removed	
																			COMMERCIAL	Approve Subcontractor	ICL Commercial	22/12/2017		Not Removed	
																			COMMERCIAL	Approve Subcontractor	ICL BUM	22/12/2017		Not Removed	
																			SPACE	Plan the site logistic	ICL Sub-Agent	22/01/2018		Not Removed	
																			OTHERS	Prepare ITP	ICL Sub-Agent	22/01/2018		Not Removed	
																			OTHERS	Prepare construction records	ICL Sub-Agent	29/01/2018		Not Removed	
																			H&S REQUIREMENT	Carry out the Induction of the Subcontractor	ICL Works Manager	05/02/2018		Not Removed	

Figure 130: Make ready planning prepared for construction stage in ARS5.

The dashboard used to visualise the make ready metrics was developed in meetings 7 and 8, and it is demonstrated in Figure 131. The categories for constraints were adapted to the project context and included: material, services, design, equipment and tools, operatives, H&S requirements, commercial, space and others. The professionals assigned to remove constraints were: designers, client, commercial director, commercial manager, design manager, project manager, quantitative surveyor, site agent, site sub-agent, works manager, and subcontractors.

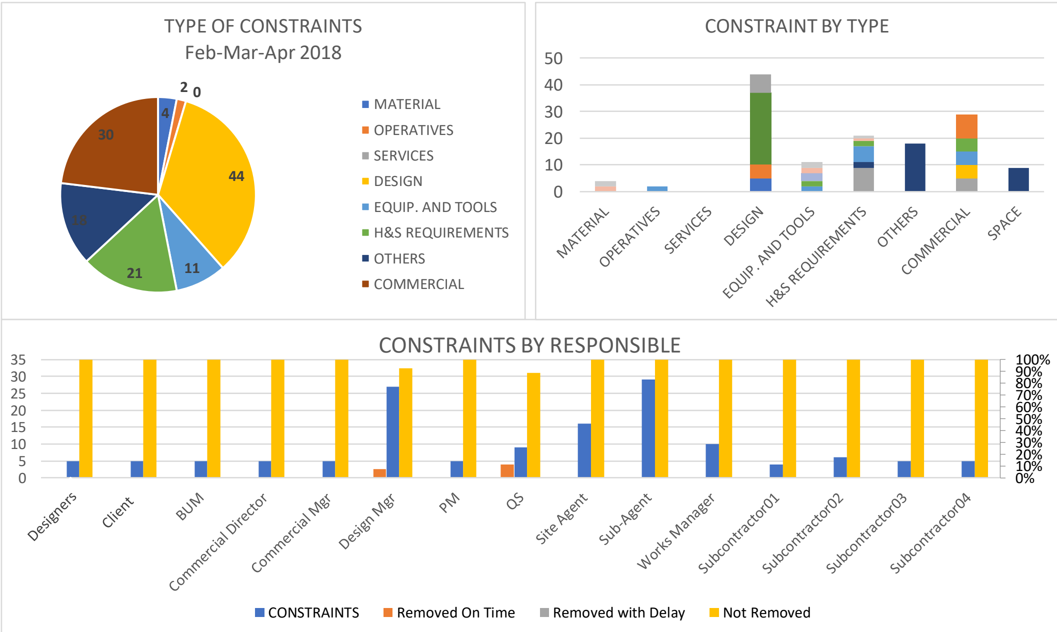
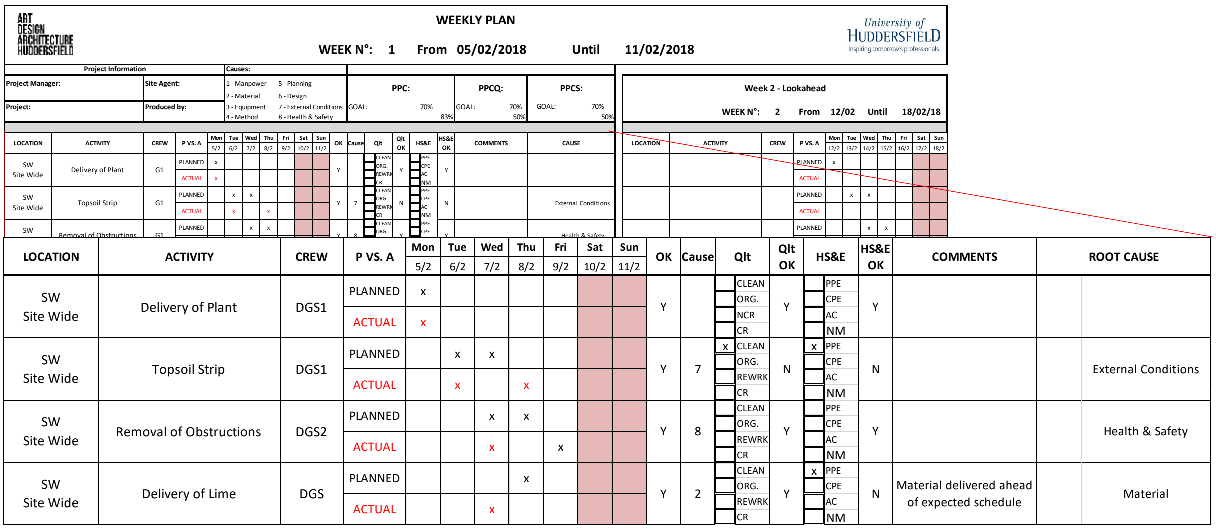


Figure 131: Dashboard of metrics for the lookahead planning prepared for the construction stage.

In meeting 7, on 6 November 2017, the team and the researcher began preparing the weekly plan for the first two weeks of the construction stage in order to simulate the planning. The project team defined that the weekly meetings should occur every Thursday morning and that the following week's plan should be visible on the spreadsheet, as shown in Figure 132. The researcher introduced the possibility of controlling not only the conclusion of the planned tasks, but also whether they were executed by accomplishing the correct quality and safety requirements. The PPCb (percentage of plan concluded) gained a further two versions to measure the quality, PPCQ (percentage of plan concluded with quality), and safety, PPCS (percentage of plan concluded with safety).

The non-concluded tasks had the causes for non-compliance categorised in: 1) Manpower; 2) Material; 3) Equipment; 4) Method; 5) Planning; 6) Design; 7) External Conditions; and 8) Health and Safety. However, the team could write down comments to specify the root cause for non-compliance.

In PPCQ, the items controlled were: 1) Work Area Clean; 2) Work Area Organised; 3) Non-Conformance Issued; and 4) Construction Record up to Date. As such, Company J measured in PPCS: 1) Personal Protective Equipment in Order; 2) Collective Protection in Order; 3) Accident Occurred; and 4) Near Misses Reported by Others.



WEEKLY PLAN

WEEK N°: 1 From 05/02/2018 Until 11/02/2018

Week 2 - Lookahead

WEEK N°: 2 From 12/02 Until 18/02/18

LOCATION	ACTIVITY	CREW	P VS. A	Mon 5/2	Tue 6/2	Wed 7/2	Thu 8/2	Fri 9/2	Sat 10/2	Sun 11/2	OK	Cause	Qlt	Qlt OK	HS&E	HS&E OK	COMMENTS	ROOT CAUSE
SW Site Wide	Delivery of Plant	DGS1	PLANNED	x							Y		CLEAN ORG. NCR CR	Y	PPE CPE AC NM	Y		
			ACTUAL	x														
SW Site Wide	Topsoil Strip	DGS1	PLANNED		x	x					Y	7	x CLEAN ORG. REWRK CR	N	x PPE CPE AC NM	N		External Conditions
			ACTUAL		x		x											
SW Site Wide	Removal of Obstructions	DGS2	PLANNED			x	x				Y	8	CLEAN ORG. REWRK CR	Y	PPE CPE AC NM	Y		Health & Safety
			ACTUAL			x		x										
SW Site Wide	Delivery of Lime	DGS	PLANNED				x				Y	2	CLEAN ORG. REWRK CR	Y	x PPE CPE AC NM	N	Material delivered ahead of expected schedule	Material
			ACTUAL			x												

Figure 132: Weekly plan prepared for the construction stage in ARS5.

For meeting 8, on 13 November 2017, the ARS5 participants should finalise the dashboard tab in the lookahead and weekly plans; set up the lookahead plan meeting; prepare the site logistic plan for the first work packages according to the lookahead plan; prepare the LOB for histogram; and insert the milestones call outs in the LOB.

Shortly afterwards, the researcher received the LOB file from the team and created the crews' histogram in the MS Excel. The histogram showed the use of the same crew in two different locations on the same day. Then, adjustments were made in the LOB at the meeting. One example of the histogram is presented in Figure 133.

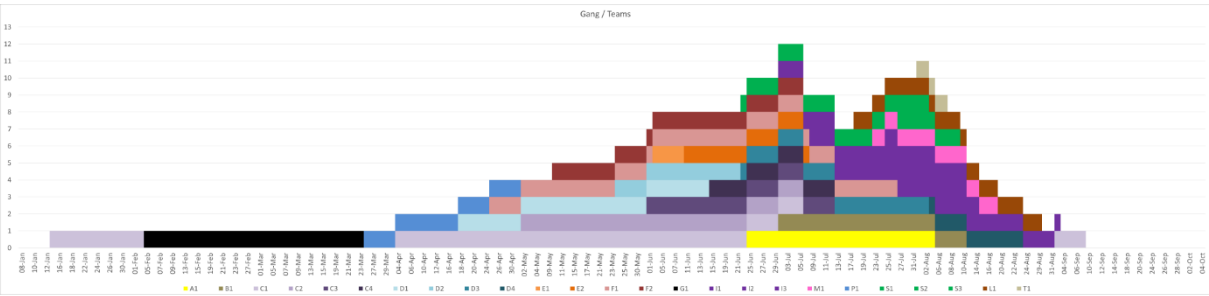


Figure 133: Histogram of workforce created based on the LOB.

The team decided to measure the contractors' and in-house crews' performance by the PPCb, PPCQ and PPCS. Then, the dashboard for the weekly plan was updated with a total number of gangs, as shown in Figure 134.

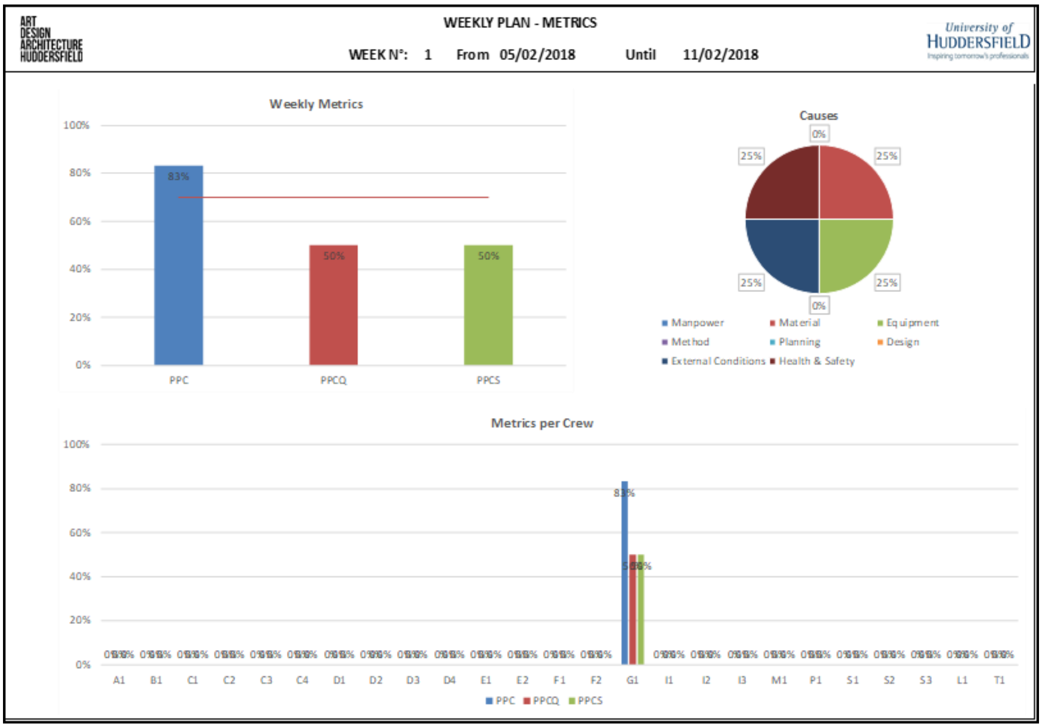


Figure 134: Dashboard of the weekly planning for ARS5.

The first lookahead planning meeting was set up for 15 December 2017. The participants invited were designers, client, some contractors, the quantitative surveyor, planner, project manager, and site agent.

For workshop 3, Company J was in charge of preparing the slides presentation, including the supply system for procurement and design; the lookahead plan and its dashboard; the weekly plan and its dashboard; and the crews' histogram.

Meeting 8 was the last day that the researcher visited the site office and support the team to deploy the lean practices. Due to the fact that the implementation occurred two months previously at the beginning of the construction stage, the weekly plan was only simulated for the first week of work. Plus, due to a contractual arrangement, Company J decided not to change the delivery dates of design after realising the supply system. The latter showed that some drawings were already delayed and others would be delivered earlier than necessary.

6.1.5.5 Workshop 3

On 16 November 2017 the last workshop took place to teach to the project participants the topics of: Visual Management (VM) Theory; Conventional and IT-based VM in Construction; Examples of VM; and SMED in Construction (Figure 135). Throughout the course, the invited lecturer promoted a discussion about VM solutions for the depot project, where new ideas to apply VM within the planning and control emerged. The team decided to create in the site office a large room, where they should display:

1. A Last Planner System Board:

   - Master plan: a glass board over the LOB, and two vertical rulers to mark the lookahead horizon in the LOB. The metrics proposed were the days to complete the project and activities' adherence to the plan. Thermometer and X-Ray.

   - Lookahead plan: make ready and lookahead plans displayed, constraints removed metrics, construction site plan on a magnetic board.

   - Weekly plan: weekly plan exposed, metrics PPCb, PPCQ and PPCS, and continuous improvement ideas.

2. Design metrics of changes and drawings.

3. 5S Board with Audits, Implementation plan, explanation, photos, league table, responsible/champions.

At the end of the workshop, Company J presented the tools and practices deployed between workshops 1 and 3 (Figure 136). The lecturer of the first workshop participated in promoting discussions about the benefits and difficulties of the tools and the process of implementation.

Figure 135: Workshop 3 held at the university in ARS5.

Figure 136: Company J's presentation.

In order to celebrate the conclusion of the work, the university delivered certificates and took photos with the participants. Workshop 3 was not followed by implementations supported by the researcher. Before closing this thesis, the researcher checked with the project team about how the practices were being applied. Unfortunately, the client had put the project on hold in order to change the programme and design requirements.

6.1.6 Evaluation

The practices implemented represented part of the model developed until CS4. The participants in the workshops were invited to write a testimonial about the content of the workshops and tools deployed, as well as the method used to implement the practices.

Regarding the method of implementation, the participants of Company J stated that it was "extremely useful for the current project… and also for future projects". Plus, the implementations were "very worthwhile". The workshops were also considered useful by the participants who stated "I would recommend anyone involved in construction" and "to anyone starting on their Lean Journey in the Industry", it was "very informative and helpful in a number of ways".

Regarding the tools, the participants approved the LOB technique, as they claimed that it "can lead to cost and programme saving on future projects", and "proved very worthwhile implementing on our project showing clearly where we had waste in our current programme".

About the LPS implementation, they said "we created several spreadsheets to clearly show where we need to be at each stage of a new project", plus "using lean planning highlighted the hidden constraints within workflows, and I will look to use this methodology going forward to remove variability in project planning".

Regarding the Visual Management, the participants stated that it promoted "many ways in which to improve what we already do".

Based on Company J's opinions, the method to partially implement the model was effective. The participants thought the content was useful for their project and they intend to use it in future projects. The lean tools promoted transparency in the production planning and control activities. The LOB was considered a useful technique to save costs and visualise the master plan, crew allocation, and so on.

The limitations of the ARS5 depend on the contractual arrangements with the outsourced design firm and distant relation with the client. As such, the tools and practices were useful to understand the impacts of design in procurement and construction and were used to reduce the variability, but not to promote stakeholders' collaboration. Also, due to the client's decision to change the project programme, the LPS was limited only to the lookahead planning.

Due to the ARS5 taking place for only two months, there proved to be time enough to design the production system, and prepare the tools and spreadsheets before the beginning of the construction stage. Two months was considered a short duration in which to implement the model partially. If the study could have been extended, and occurred during the construction stage, the model could be tested regarding the supply and construction systems operation. Moreover, if the study could have included the designers, the model could be tested regarding the Design System Design and operation.

As an action research study, the ARS5 also had limitations regarding the iterative cycles of implementation, evaluating, learning, improving, planning and implementing. Due to the short duration of the study, only one cycle of the action research took place.

6.1.7 Learning

Some learnings emerged from the ARS5 evaluation and reflection on the implementation process. First, in order to implement and field test the whole model, it is necessary to expand the model instantiation for the suppliers and designers. The participation of project stakeholders in the study was limited by two factors: the contractual arrangement with the design enterprise, and the lack of contractors hired at the moment of the implementation. The first factor could be overcome if Company J had developed the supply system before the agreement of the delivery dates and specified in the contract collaboration of designers in the production planning and control. Namely, if designers had the real delivery dates from the supply system pulled by construction, they could have changed their work sequence and efforts to produce what was needed at the right time, rather than delivering all the drawings at once. Plus, they could have participated in the ARS5, in which the researcher could have applied lean design and LPS to support them in the design production. Then, although it is entirely known in the lean literature, the ARS5 showed that contractual arrangements might hamper project collaboration.

The second factor is related to the lack of contractors' participation in the ARS5. However, it is not a real limitation of the study, but for the complete model implementation and evaluation. As soon as a contractor was hired by Company J, it could have been possible to develop an operational pull plan of their production, using the same location breakdown structure from the construction LOB.

Analysing the production batch for the supply system (procurement and design) in the long-term plan, it is possible to note that it was the work package, i.e. it is different from the LOB location breakdown structure. It is due to the fact that, at this level of planning, the construction plan had to pull the procurement of contractors, and the design must be delivered to enable this process. Then, the first work package in the LOB to be executed by the contractors is responsible for pulling all the production flow.

The location breakdown structure could have been used to generate the medium-term plan to pull the operational level of components and design production. However, due to the lack of stakeholders' participation, it was not possible to develop it. This characteristic of using large batches in the long-term plan is a consequence of the type of construction company as well. Namely, in a context of a high number of outsourced enterprises, added to the traditional contractual arrangements, the participation of contractors is delayed to after the procurement process, which delays some important decisions and collaboration surrounding the PDS.

The same fact occurs with the design. In the early stages of the design development, the deliverables are to apply for public permissions, planning, and procurement, which make its production batch large: the whole project. However, through its development and transdisciplinary decisions, the level of uncertainty in design solution decreases. Then, when the design becomes an interdisciplinary production of details, its production can be planned using the location breakdown structure adopted in the construction LOB. The interface between transdisciplinary and interdisciplinary is the real decoupling point between push and pull production flow, which corroborates with the CS4 findings.

Regarding the method to implement the model for the construction stage, the structure of mixing workshops with the deployment of the tools seemed smooth and effective to the staff learning and adoption of the lean practices. Company J's participants recognised the utility of the practices and tools for the project management.

To achieve a complete model instantiation on a construction project, it is advisable to do so directly with the owner or client as they have power enough to require the adoption of lean practices and collaboration along the value chain, from design until construction, including the contractors and subcontractors.

For further guidance on the model implementation, see Appendix 7.

6.2 CASE STUDY 6 (CS6): RESIDENTIAL PROJECT

This section presents case study 6 (CS6), the results of which enabled the refinement of the second version of the model into its third version. The main learning brought by this study regards the design management and how it was pulled by the procurement process. Next, is presented the discussions, the internal evaluation of the case study and the researcher's recommendations for improvements in the project management. The new data provided by the study created the third version of the model.

CS6 was carried out in Company K, which is the largest Norwegian construction and civil engineering company. They have business in construction and engineering operations, rehabilitation work, heavy construction, asphalt operations, maintenance of public roads and dwellings development for private and public sectors. The company was founded in 1936 and currently has operations in Sweden as well.

6.2.1 Project Description

The project of the study is in a residential development in Trondheim, Norway. A total of 1,100 residential units were planned across 100 acres. The project comprises both townhouses and apartment blocks surrounded by 38 acres of green space, car-free and communal outdoor areas. The development is divided into three phases. The first one began in 2015, and it is expected to finish in 2019. The second phase is planned from 2019 to 2026, and the third from 2026 to 2028.

The first phase has 11 buildings that are being built through nine construction stages, and one of them is the object of the CS6. In total, the phase has a contract amount of approximately 1 billion NOK (Norwegian Kroner) (VAT excluded) to build 478 residential units. The case study was focused on the building project MP2, which is a 5-storey apartment building with apartments of different sizes: studios of 29.2 m^2, 1-bedroom and 2-bedroom apartments of 85 m^2. Moreover, the construction Company K offers to their clients the mass customisation of the residential units.

6.2.2 Research Process

CS6 took place during December 2017, and the head of design management of the company went along with the researcher in the project with a design-construction overlap that he chose. It was known that the company develops within their projects a collaborative planning with designers and other project stakeholders. This collaborative planning is similar to the LPS, although it is applied during the stages of design and construction simultaneously. In this study, it was indispensable to understand how this mechanism works and how it connects the project's participation from the construction to design, but also what the other tools are that support the collaborative plan.

CS6 has a number of objectives: (a) understand the context in which the solution to the problem was developed; (b) understand how the solution was developed to design, plan and control the stages of design and construction, and how both stages were integrated; (c) connect the solutions with the theoretical background; (d) devise the third version of the model for integrating the design and construction stages using location-based planning tools.

CS6 aimed to understand how the participant companies managed the project to promote the integration between design and construction. As objectives, this case study intended to:

- Comprehend the lean design and construction practices in the project;
- Find out how design and construction stages were connected through the production planning and control processes;
- Identify the strength and weakness of techniques used to plan and control design and construction processes.

With these outcomes, it is expected that the study will support the researcher in the major objectives of the thesis, such as:

- Determine how to use location-based tools to structure the work of designers, suppliers and builders in alignment with their production sequences and batches;
- Find out how to assemble design packages to meet suppliers' and construction requirements;
- Determine the decoupling point of design development to apply pull production;
- Identify and analyse the pros and cons of existing types of pull production systems that suit better the context of overlapped projects;
- Explore how to measure and manage the work in progress and buffers in an integrated project system;
- Identify the best tools to control the production system, and to ensure that downstream information is informing upstream processes.

In this case study, the researcher analysed the practices, tools, processes and technologies used by participants to design, plan and control the production of the project. The analysis of these practices was connected to the managerial activities of 1) Design System Design (DSD); 2) Design System Operation (DSO); 3) Design System Improvements (DSI); 4) Construction System Design (CSD); 5) Construction System Operation (CSO); and 6) Construction System Improvements (CSI). However, when CS6 took place, the design was finalising the detailed stage, and the project was under construction. Hence, the managerial activities taking place at that time were the Design System Operation and Construction System Operation.

A set of meetings took place between 4 and 8 December 2017. The researcher collected data through semi-structured interviews and documents, such as plans, photos, figures, drawings, and so on. The interviewees had different managerial roles and were representing four different entities: 1) The construction Company K; 2) The architecture office (Company L); 3) The engineering design office (Company M); and 4) The client (Company N). However, all of them were actively involved in design and construction management. The participants were (Figure 137):

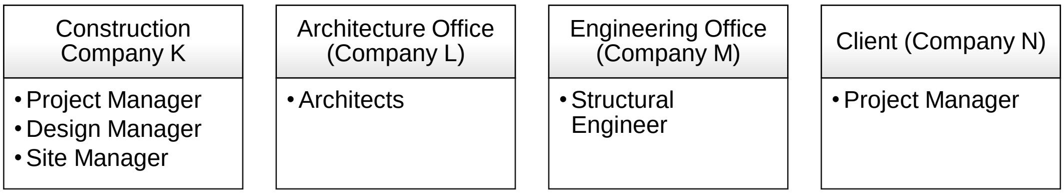


Figure 137: Interviewees in the CS6.

The case study began with a kick-off meeting, in which the researcher presented her research background, aims and objectives. Next, a set of interviews was conducted with each manager (client, design, construction) who were involved in the Collaborative Design Management. At the end of the case study, the researcher presented to the participants her understandings about the project management and the third version of the model for evaluation. The schedule of meetings and interviews conducted in the case study, and their objectives for data collection and model evaluation, is set out in Table 35.

Table 35: CS6 meetings and objectives.

Date & Time	Participant & Company	Objective
Mon 04/12/2017 10.00 – 12.00	All case study participants	A kick-off meeting to present the research, get to know the participants, the schedule, etc.
Mon 04/12/2017 13.00 – 16.00	Project Manager, Company K	Understand the project management from the point of view of the construction Company K.
Tue 05/12/2017 09.00 – 12.00	Design Manager (Company K)	Understand the role of the design manager and the main processes and tools used in planning and controlling. Seek for integration aspects between the design and construction stages.
Tue 05/12/2017 13.00 – 16.00	Architects (Company L)	Understand the design management regarding the planning and tools used by the architects to produce models/drawings and deliver it to other project's stakeholders.
Wed 06/12/17 09.00 – 12.00	Structural Engineer (Company M)	Understand the design management regarding the planning and tools used by the engineering designers to produce models/drawings and deliver it to other project's stakeholders.
Wed 06/12/17 13.00 – 16.00	Project Manager Client (Company N)	Understand how the client of the project is included in the project management, and how decisions are made.
Thu 07/12/17 13.00 – 16.00	Site Manager (Company K)	Understand how the construction production is planned and controlled. Seek for integration aspects between the design and construction stages.
Fri 08/12/2017 09.00 – 12.00	All case study participants	Present the researcher's understanding of the project management and confirm it with the participants. Present the 3rd version of the model developed for the thesis and evaluate it together with the participants through a semi-structured interview. Case study closing remarks.

The research activities to achieve these objectives, in addition to the sources of evidence, are described in Table 36.

Table 36: Sources of evidence for each phase of the CS6.

	Study Phase / Aim	Sources	Developed in
1.	**Awareness of the problem**		
a.	Understand the project's stakeholders' contractual relationships and responsibilities	• Secondary document analysis: Organisational charts • Semi-structured interview with project managers from companies K and N	Organisational chart of the project
b.	Understand the project context, timelines and the overlap between design and construction stages	• Secondary document analysis: project milestones, project master plan, presentations, pictures, photos • Semi-structured interview with project managers from companies K and N	Project timeline of design and construction stages
2.	**Company's solution development**		
a.	Understand the process to design, plan and control the design stage, the participants, tools used and information exchanged	• Semi-structured interview with design manager, architects and engineer • Secondary document analysis: design plan, BIM models, pictures, photos, presentations, tool for plan • Direct observations of transparent plans at the site office	Diagram of the design planning and control process
b.	Understand the process to design, plan and control the construction stage, the participants, tools used and information exchanged	• Semi-structured interview with Construction Manager • Secondary document analysis: construction plan, BIM models, pictures, photos, presentations, tool for plan • Direct observations of transparent plans at the site office, construction site visit	Diagram of the production planning and control process
c.	Understand the mechanisms to integrate the design and construction plans	• Secondary document analysis: design and construction plans, sheets to control production, pictures, photos, presentations. Observe production pace, the levels of plan and control, the collaborative planning • Semi-structured interview with project manager, design manager, Construction Manager, engineering design manager	Diagram of project management
3.	**Discussions and study's model to design, plan and control the production system**		
a.	Understand how the solution adopted by the project influenced the stakeholders' work, the main problems faced and suggestion for improvement.	• Semi-structured interview with project, design and construction managers • Secondary document analysis: information format exchanged, and analysis of WIP, takt-time, batch size, adherence to project plans	Internal evaluation of project's solution
b.	Understand the correlation between the solution developed in the project and the literature concepts and tools	Literature review in TPS, pull production systems, WIP, information flow management, LPS, location-based planning tools	Internal evaluation of project's solution
c.	Translate the project's solution in a theoretical model	• All study's data and information	3rd version of the model for project production system
4.	**Evaluation of the 3rd version of the model to design, plan and control the production system**		
a.	Evaluation of the model	• Model presentation and a focus group with all participants	External evaluation of the 3rd version of the model

CS6 provided new insights into the integrated project management. After data collection, new information allowed the researcher to refine the previous version of the model to design, plan and control production systems in the context of overlapped projects using lean practices. The improved version of the model was presented and evaluated externally with the case study participants. The researcher used a set of questions about the model, such as the one described in the method chapter.

6.2.3 Case Study 6 Development

MP2 (Figure 138 and Figure 139) was designed by Company L, an architecture office from Trondheim, Norway. The office has been established in the city since 1993 and employs 24 professionals to develop mostly public and private buildings such as schools, kindergartens, universities, care centres, commercial buildings and housing projects.

Previously to their participation in the project, MP2 was conceptualised by another architecture office as a larger building, including the residential area of MP3 (another building in the project). The owners decided to split the building and change the construction system of MP3 from the traditional concrete and steel structures to solid wood. For this reason, both buildings were planned together and had the same handover deadline.

Figure 138: Illustration of MP2. Source: Courtesy of Companies K and N.

Figure 139: Ground floor plan of MP2. Source: Courtesy of Companies K and N.

MP2 is a 5-storey building which contains different-sized apartments, from studios of 29.2 m^2, 1-bedroom apartments of 42.7 m^2 and 2-bedroom apartments of 57 m^2, 57.7 m^2, 58.5 m^2, 70.2 m^2 and 85 m^2. The residential units have an open-plan kitchen integrated with the living room; terraces; one prefabricated bathroom; and wardrobes. The apartments on the ground floor have access to the garden.

6.2.4 Mass Customisation Options

In the project, clients could change specifications for their apartments following some available options and the construction schedule. At the time of the apartment purchase, the client became aware of the items that he/she could customise. The client received a customisation leaflet of the apartment which showed all the customisation options available, costs and time limit. Then, Company N charged an administration fee of 10% on all options. The customisation work was executed only by Company K, and no other suppliers or contractors were allowed into the building during the construction period.

The client could change the following items:

- Parquet;
- Paint colour on internal walls (entire room only, non-contrasting walls);
- Painted/plastered mouldings;
- Fronts, worktops, fittings and appliances in the kitchen;
- Selection of mixer in the kitchen;
- Tiles over kitchen worktop;
- Cloakroom;
- Upgraded pack for electrical;
- Additional option of electrical point for several TV appliances;
- Optional bath installation (depending on the cabin size);
- Additional rooms with lightweight walls and interior doors where extra rooms are dotted on sales plans. The construction of additional rooms also requires technical installations adapted to the new room;
- Battery charging point for electric car, including an internal meter.

As the construction project was planned as a mass production, the customisation option order is time-limited according to how the construction and purchase progresses. The right to additions/changes was nevertheless limited to a value of 15% of the total purchase price of the property.

6.2.5 The Project Management

MP2 is the fifth stage of building construction in the project. The conceptual design of the building started in January of 2016 and was completed in May 2016. In the following month, the architecture office started the design development which ended in September 2016, just before the beginning of the apartment sales in October of the same year. MP3 sales began in January 2017. When half of the residential units of MP2 were sold, the detailed design phase began in April 2017 and was at its end in December of 2017. In August, the construction work began with the earthworks activities. At the time the researcher interviewed the project team in December 2017, the detailed design phase for MP3 had come to an end.

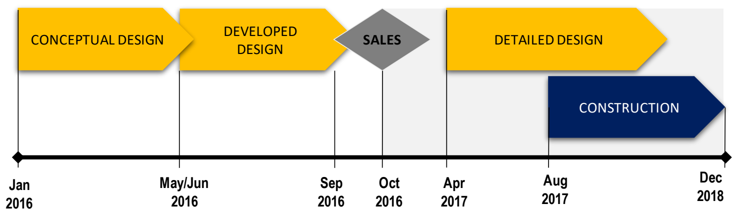


Figure 140: MP2 timeline.

6.2.6 Project Management – Collaborative Planning (CP)

In Company K's projects, the project development comprised three stages: 1) Pre-design; 2) Delivery Stage; and 3) Facility Management. The first stage encompassed a) Idea Phase and b) Concept Phase, whereas the second stage comprised a) Design; b) Detail/Engineering Design; c) Construction; and d) Commissioning. The third stage is for Operation and Maintenance. The schematic illustration of the project development is explicated in Figure 141. The Lean Project Management took place during the design and construction stages, but mainly in the detailed design phase and construction.

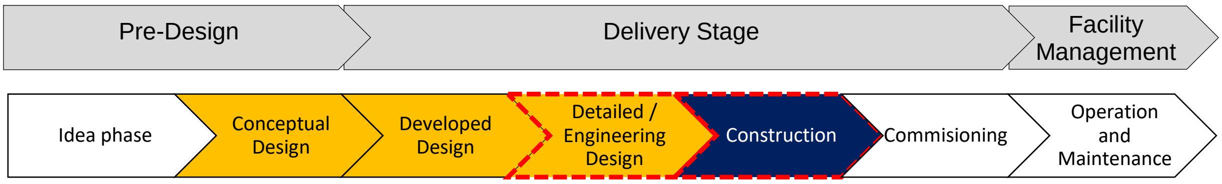


Figure 141: Company K's project development and situation of Collaborative Planning (red dots) in the design and construction stages. Source: adapted from Company K.

All the managerial activities developed by Company K's teams and their designers were applied not only for MP2, but for MP3 as well. The Collaborative Planning presented in this study was applied in both the design and construction stages of the project development. It was an Agile project delivery system because:

- It quickly responded to owners' (Company N) demands;
- It quickly responded to clients' (apartment buyer) customisation demands and simultaneously respected the production;
- Design (architecture and engineering offices) responded quickly to construction's demands (Company K and subcontractors/suppliers).

In Company K, the projects have a master schedule controlled by the Project Manager that describes the major stages of the project, such as design phases and construction. It is developed jointly by the Project Manager, Construction Manager, Design Manager and Owner as part of the contract, and is the basis for further planning of the design and construction stages.

The MP2 project had five levels of planning and control: 1) the Project Master Plan, where strategical decisions were made for the whole product development process; 2) this was divided into the Design Plan, Construction Plan and Purchasing Plan, which represented strategical decisions about design, construction, procurement and supply systems, respectively; 3) the tactical levels of design planning, i.e.

decision plan and lookahead plan; 4) the lookahead plans used by construction stakeholders; 5) their operational level composed of the weekly plans. The operational level carried out by the construction crews on-site also mixed tactical planning activities and included a daily basis plan. Figure 142 outlines the Project Plan and Control System deployed in MP2.

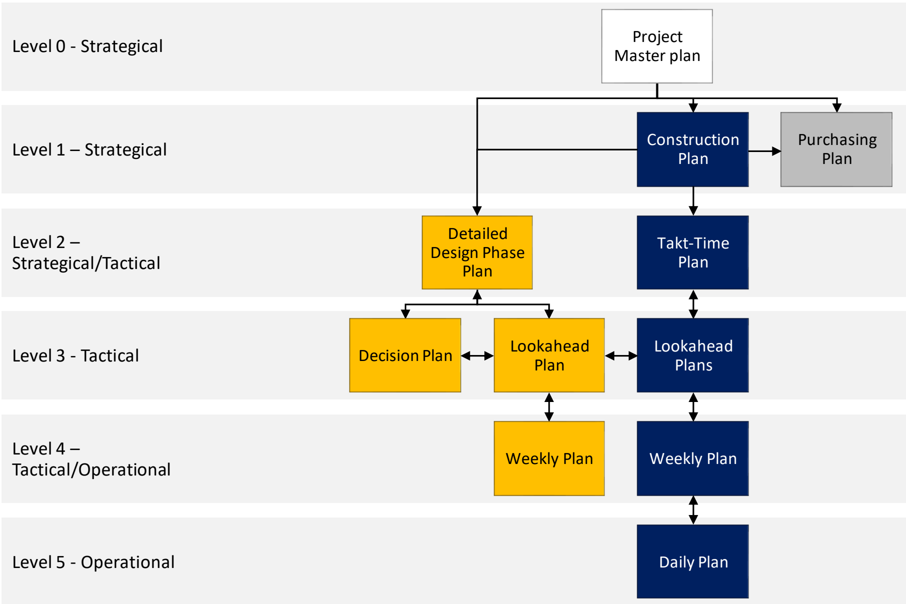


Figure 142: Levels of the project planning and control system deployed in MP2.

6.2.7 Design Management – Collaborative Planning in Design (CPD)

In Company K, the team that managed the design development used the Collaborative Planning (CP) to plan and control the design process, called Collaborative Planning in Design (CPD). Its purpose was to create a smooth design flow through the collaborative planning of designers' activities, which promoted their engagement and ownership of everyday work. While making the design workflow run smoothly, Company K intended to reduce the costs of the design and construction processes and increase the value of its final product by meeting the client's needs. Also, the CPD reduced the time in which designers handle information, which increases the time they spend designing.

The use and development of the CPD are more recently been compared to the Collaborative Planning in Production (CPP). For both uses, the conceptual basis is the same. Nevertheless, the CPD required some adaptations to the design context that is described in this section.

The CPD was used by Company K, mainly by their Design Managers in order to lead and control the design progress. It was applied in the detailed design phase, and it was tightly integrated within the construction stage. The role of the Design Manager was to coordinate efforts of all designers, ensuring that they have the right information at the right time to produce the optimal design solution for the client, and, not less important, for the construction teams on-site.

In MP2 and MP3, the Design Manager was responsible for coordinating the work of the following design disciplines (Figure 143):

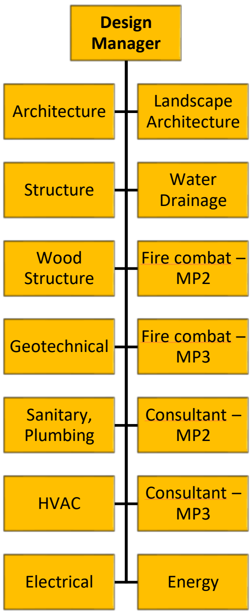


Figure 143: Structural organisation for design development for MP2 and MP3. Source: Company K.

According to the company's documents about the collaborative planning, the conceptual core of the CPD is the triad of deciding-processing-informing. Company K believes that a successful design management occurs when design decisions are made collaboratively by designers and then processed jointly. Therefore, new information about the impacts on budget and time can be continuously evaluated. Another critical aspect of decisions is their proper information distribution across the organisation, production responsible, client, public authorities, and other stakeholders. It should be done using the right means, such as drawings, models, written documents and illustrations of the product. This triad is a cyclic process of making decisions based on available information, then informing of the decision and processing it, which creates more relevant information for the project development that should be considered in further decisions.

The CPD was supported by two approaches: 1) a hierarchical planning and control system; and 2) weekly collaborative meetings among project teams. The second item is where the integration between design and construction is fed by the project participants through a well-established information flow between the meetings.

The hierarchical planning and control system had different managerial levels, namely strategical, tactical and operational, and the detailing level of design activities increased throughout these levels, which also has different horizons of planning. Figure 144 presents the hierarchical levels of planning in the CPD applied in MP2 and MP3.

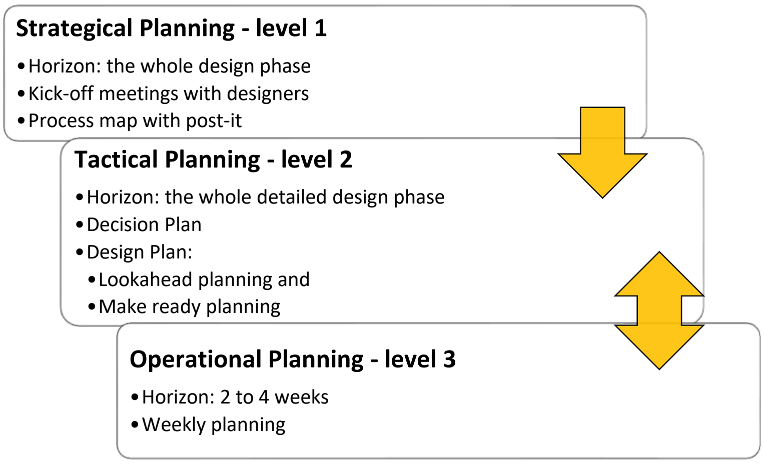


Figure 144: The three levels of planning in the Collaborative Planning in Design.

Some projects at Company K have other planning activities rather than the ones presented in Figure 144. However, this study concerns only the managerial activities seen at MP2. Company K's CPD Guide specified the development of a Master Schedule for all the project stages. However, in the MP2 project, the master schedule was a plan showing the construction period of all buildings in the development area.

6.2.7.1 Strategical Planning – Level 1

The strategical planning occurred at the beginning of the detailed design stage when the leading designers and subcontractors were hired. Jointly with the owner, consultants, Company K's Design Manager (DM), Project Manager (PM), Construction Manager (CM) and foremen, they developed a Strategical Plan for Design collaboratively at the kick-off meeting. In this meeting, the participants understood the goals of the design phase, got to know each other, created communication and trust, and clarified the demands and expectations. Moreover, the participants defined the dependencies among design disciplines and activities; and, through a pull planning, they set deadlines for deliverables based on the Construction Master Plan provided in an MS Project file. The Design Manager was responsible for setting up the meeting and inviting the participants, besides being the owner of the Design Plan. The strategical design plan in MP2 and MP3 was devised using post-it notes on a wall in the site office during all the weeks of the detailed design phase.

In other Company K's projects, the DMs use the CP for earlier design phases as well. However, as in the MP2 and MP3 projects, the conceptual design phase was developed by another architecture office, and the CPD was applied only in the **detailed design phase**, after hiring the new architecture office.

The objective of the detailed design phase planning was to ensure that all designers could visualise their dependencies, detail feasible deliverables, ensure the main project purchases could be performed at the right time, and that design information could be provided for construction at the right time and level of detail according to the construction plan.

To plan the detailed design phase, the designers used the start dates of major activities from the construction plan as milestones, such as the beginning of the earthworks, concrete structure, wood structure (MP3), bath cabins ordering, and so on. Based on these milestones, backward design work was planned among the architecture and engineering offices, and Company K. Figure 145 shows the final design strategical plan after the kick-off meeting for the detailed design phase.

Figure 145: Strategical Collaborative Planning for Design. Source: Courtesy of Company K.

6.2.7.2 *Tactical Planning – Level 2*

When the strategical plan was completed, all the information from the post-it notes was digitalised and put into the Design plan in the MS Excel spreadsheet (Figure 146). Herein, the project team fed the plan with more detailed information and design deliverables as tactical planning. The Design plan aimed to select resources and the means to enable the execution of a design task.

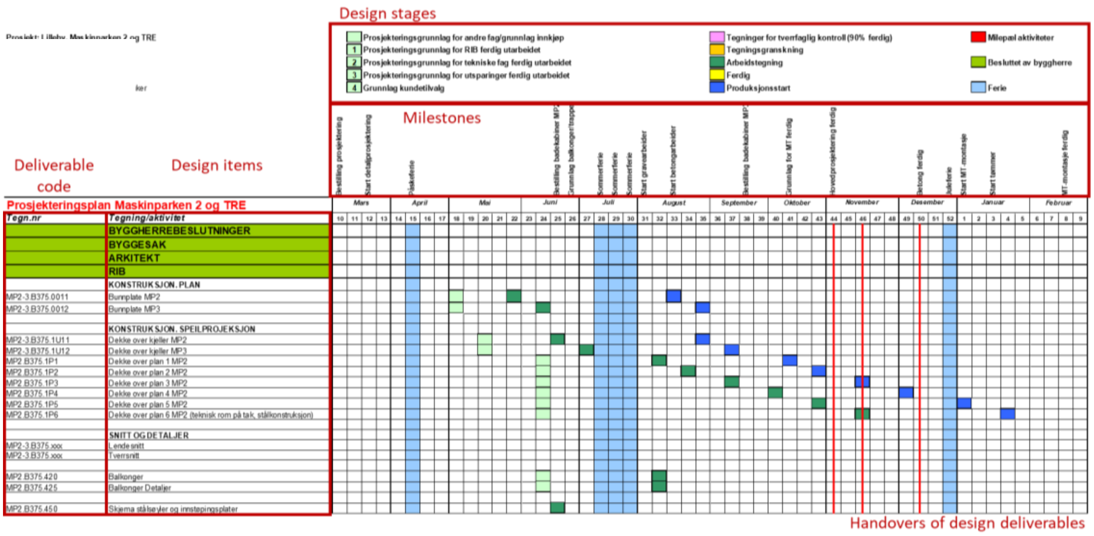


Figure 146: Design Plan for MP2 and MP3. Source: Courtesy of Company K.

The Design plan was made up of a list of all the main items per design disciplines, such as: owners' decisions; building matters; architecture; structure; mechanical; electrical; plumbing; heating; ventilation; safety; energy; landscape; prefabricated concrete; bath cabins, among others. The deliverables have a drawing code and also handover dates with colour codes that represented the purpose of the drawing. The colour codes described the stage or purpose of drawing, such as:

- Design for another subject/foundation procurement;
- Design for structure completed;
- Design for technical subjects completed;
- Design for savings completed;

- Design for customers' choice;
- Drawings for interdisciplinary control (90% complete);
- Drawing review;
- Drawing for construction;
- Done;
- Beginning of construction;
- Milestone activities;
- Decided by the builder.

At the top of the design plan sheet, the design team highlighted the handover milestones for the design phase based on the construction plan. They were:

- Hiring designers;
- Beginning of the detailed design phase;
- Ordering bathing cabins MP2;
- Design for balconies/stairs;
- Start earthworks;
- Start concrete work;
- Ordering bathing cabins MP3;
- Design for wood structure completed;
- The main project completed;
- Concrete finished;
- Start the wood structure assembly;
- Start timber;
- Wood structure assembly completed.

The Design plan was reviewed and updated every Wednesday morning in the design meetings on-site. Its primary function was to identify the drawings and documents that should be delivered to other designers, construction, purchasing, clients, and other stakeholders in the subsequent weeks (around 10 to 15 weeks). This level of planning also ensured that all constraints to produce the design documents were removed, making the design flow more reliable and smooth.

The design project team analysed six types of constraints, or preconditions, to process a design activity. Based on Koskela's (2000) model of preconditions for construction tasks and its illustration by Bertelsen

(2003), Company K has created their own model for preconditions for a sound design task, which was described in the literature review of this thesis: 1) Clearly define the client's expectations and requirements; 2) Dialogue; 3) Decisions; 4) Team; 5) Methods and tools; and 6) Previous design task.

The six preconditions analysed at the design meeting are as follows (Bolviken et al., 2010):

1. **Design basis**: the previous design activities must be completed according to the required quality.
2. **Expectations and requirements:** the design must comply with the client's expectation, contractual requirements, constructability, government rules and regulations.
3. **Dialogue:** it must have forums for discussion among designers and stakeholders to ensure that a problem can be solved with consensus and shared understanding.
4. **Decisions:** decisions must be made, added to the decision log list, or added to the unsolved list.
5. **Team:** consultants, in-house staff and designers must have the capacity and competence to perform a task. Also, the owner of a design activity should have the authority to make decisions and be solution oriented.
6. **Methods and tools:** must be adapted to the project context and be used by the project participants in harmony.

Decision is an essential precondition that must be solved in order to enable a design activity to be performed in the operational level. Decisions must be recorded in a **Decision log** tab of the Design Plan spreadsheet in order to make it transparent for all designers who may use that information in the future. Also, if a designer detected that a specific problem was hampering the right progress of design activities, he/she recorded it in the **Unresolved issues list** tab for further action.

The Decision log was a table tab containing data about: the identification number of the decision; the meeting number in which meeting it was made; the date decision was made; the issue it was solving; description of decision; who made it; and who was responsible for its implementation.

Similar data was used in the Unresolved issues tab, such as the number of the issue, the meeting number, the date, the related design disciplines, the description of the issue unsolved, the status and the history of steps to solve the issue, comments, deadline, the responsible person to lead the issue solution, and if the issue was solved.

6.2.7.3 Operational Planning – Level 3

When the design activities planned in the Design Plan were completed, i.e. all the six preconditions solved, the design team pulled these activities to the weekly plan. The Design Manager and designers still looked four weeks ahead of the Design Plan, while detailing more of the activities in an operational level for the next two weeks. At the weekly design meetings, they reviewed the activities executed in the past week and plan one week further.

The weekly collaborative meetings had the task of controlling the planned design activities, confirming the production sequence according to changes in the owners' decisions, construction demands, manufacturers' and designers' requirements. A set of meetings between different project teams allowed the short cycle of control of project activities, as well as the Agile distribution of information and mutual decisions generated in these meetings to those project stakeholders who were impacted.

Figure 147 represents the weekly plan, in which the design activities are detailed according to the related disciplines, including data about the responsible design discipline to execute the task, to whom the handoff should be sent, the day of the week the handoff should be delivered, if it was or not delivered, the cause for non-compliance with the deadline, and comments. The causes for non-compliance with the plan were: lack of planning, lack of information, lack of decision, lack of resources, and incorrect method/tool. Although the document presents the possibility of marking the causes for non-completion of the tasks, the design team of MP2 did not use it.

Project: MP2 and MP3
Phase: Detailed design

Tasks	To be developed by	To be delivered to	Week 1					Week 2					Week 3					Week 4					Yes	No	Causes					Obs
			M	T	W	T	F	M	T	W	T	F	M	T	W	T	F	M	T	W	T	F			Cause 1	Cause 2	Cause 3	Cause 4	Cause 5	
Area/Discipline																														
Task 1	ARQ				x																		x							
Task 2	HVAC	ARQ			x					x			x										x							....
Task 3	ELET	STRUC			x																			x						
...	...	...																												

Figure 147: Schematic weekly plan of MP2 and MP3.

The weekly plan was a "live" document that enabled the design team to improve their work by planning more certain tasks, understand their production capacity and the interdependencies among design tasks.

6.2.7.4 *Design Meetings*

In the CPD at MP2 and MP3, there were three types of meetings with different purposes: 1) The kick-off meeting; 2) The design meetings; and 3) The special meetings.

6.2.7.4.1 Kick-off Meeting

As described at the beginning of this study section, the kick-off meeting was the first one to occur at the strategical level of planning as part of the CPD. It set the goals of the design development and aligned it with the project goals.

In order to set up the meeting, the Design Manager gathered project documents and information, such as the project master plan, drawings, models, owner's requirements, and so on. Previous to the meeting, Company K's project team prepared a strategy for interactions between design and construction regarding information exchange and team communication. The project team also set up a BIM Design Plan document for the MP2 and MP3 project to define the different uses and levels of detail of the BIM models.

Then, all documents prepared for the design development process were distributed to the project participants. The kick-off meeting in MP2 and MP3 occurred on 22 March 2017, hosted by the Design Manager at Company K's site office. The meeting started at 09:00 and finished at 14:30.

In the meeting, the participants:

- Got familiar with the project and project team;
- Set up the project design team;
- Got familiar with the CPD and the importance of sound designing and the ownership of the activities;
- Understood the project's requirements;
- Set up joint goals, and agreed on the priorities and progress for further work;
- Planned the design phase collaboratively with post-it notes;
- Clearly defined the working methods;
- Clarified the roles and expectations of each participant;
- Built the communication channels;
- Allocated responsibilities and tasks to the project team.

The agenda covered the following:

- Organisational chart presentation;
- Owner's presentation (Company N);
- Project presentation focusing on architecture discipline, and then technical, landscape and infrastructure disciplines;
- Presentation of drawing basis for the further development of the detailed design;
- Presentation of the Construction Master Plan and Meeting Schedule;
- Presentation of routines in the project management;
- The upcoming activities;
- A roundtable for discussions and clarifications, and;
- Discussions around solid wood fireproof, architecture, wood structure, building structure, ventilation systems, etc..

The Design Manager presented the organisational chart of the project team, with an emphasis on the construction team, and then the design team under his coordination. Next, the Project Manager presented the project context, with information on the construction stage that included the construction of MP2 and MP3. On the same day, 22 apartments of 31 were sold in MP2 and 33 of 47 apartments in MP3.

The kick-off meeting continued with the presentation of MP2 and MP3 drawings, such as the basement area, technical areas and installations, building floor plans, outdoor areas and facilities (bicycle parking, firefighters), infrastructure facilities, and the challenges for designing the project.

Another explanation in the kick-off meeting was about the information exchange in terms of information technologies and rules to name files. The main design disciplines had a specific folder in SharePoint, for instance: planning regulations; sales prospectus; business description; technical description; framework application; architectural drawings, including IFC; and landscape plans, among others.

The routines of dialogue and information exchange were also specified by the Design Manager. The BIM workflow was also explained to the designers. Regarding information flow, the DM advised the team of the following:

- Communication with Company K related to engineering must be sent to the DM;
- Communication between consultants must be sent with a copy to the DM;
- Appointments by phone must be confirmed per email;
- Changes made to drawings affecting others must be sent a notification email, and modifications uploaded in the cloud server;
- Meetings minutes, drawings and documents of the project are distributed via SharePoint (instructions on how to use it and the rules to name the files were explained).

At the kick-off meeting, designers reviewed the objective and application of BIM in the project; defined null point and the structure of the BIM models; defined the level of detail of model elements; confirmed the software to be used and the file format for model delivery.

Next, regarding the activities related to planning, the Design Manager presented the construction milestones, such as the beginning of earthworks, concrete structure, wood structure and construction phases permit. The following were highlighted: the routine of planning, the design meetings, special design meetings, design verification, and design delivery before construction. The designers understood that their planned deadlines were based on the construction master plan milestones.

The DM highlighted the main characteristics that make the design management a success. The designers and participants developed a design plan following the CPD method, which means lapping the plan along the lowers levels of planning. They should have clarification of their assignments and interfaces with other disciplines, get involved in developing the plan, and have ownership of the plans. Designers should participate in all design meetings necessary, especially the weekly meetings.

The Health and Safety Environment was also mentioned at the kick-off meeting. The DM clarified that Company K emphasises the risk assessment, and advised that designers should carry out a risk assessment in accordance with the regulations and use Company K's risk assessment model, which is part of the planning CPD system.

With a clear understanding of Company K’s policies, CPD, BIM Plan and risk assessment, the designers started the strategical planning with post-its. The DM had previously prepared the project weeks, the milestones and post-it notes. At the end of the meeting, the design team had produced the Design Phase Plan, which was inserted in the MS Excel file by the Design Manager.

6.2.7.4.2 Design Meetings

The tactical and operational levels of planning were developed and controlled in the weekly Wednesday meetings at the on-site office. The Design Manager was responsible for drawing up a set of activities to prepare the meetings, and to distribute the information and set the future actions.

As part of the preparation for the design meetings, the designers had to send to the DM the updated BIM models in order to carry out a previous clash detection study. Then, during the meetings, the DM presented the detected clashes among the disciplines and other issues to solve. The issues could be new tasks for the weekly plan.

At the beginning of the detailed design phase, the meetings had a weekly recurrence, although the tasks were always planned two weeks ahead. At the end of the detailed design phase, the recurrence of the meetings changed from every two weeks to whenever was necessary. The CPD was very flexible and adaptable to the changes in the design development.

6.2.7.4.3 Special Meetings

Although design meetings occurred every week, on a Wednesday morning, if the designers needed more time or further information to solve a specific issue, then he/she could call for a special meeting. This meeting occurred after the design meeting or by Skype when appropriate. The special meetings were usually between architects and the consultant engineer from construction, or between the construction team and architects.

Examples of the themes of special meetings are: solid wood structure, acoustic, fire protection, geotechnical and foundation, outdoor, ventilation and air conditioning, energy, building structure, technical subjects and coordination, and interdisciplinary control. A summary of the three types of design meetings deployed by Company K in the CPD is presented in Table 37.

Table 37: Structure of design meetings in CPD.

	Kick-off Meeting	Design Meetings	Special Meetings
When it occurs? Which frequency?	Once at the beginning of the Design Phase	Every Wednesday morning.	When it is needed.
Who participates?	All the leading designers, consultants, owner, project manager, design manager, construction manager	Designers, possibly main subcontractors and suppliers, the PM, DM and CM.	Designers who need specific information, such as architects with consultants or construction team.
What is the purpose?	Get to know each other, develop the first version of the Design Phase Plan	Plan 4-week work, control 2-week work, measure design performance, review plan priorities, make decisions, BIM clash results in discussion.	Solve unresolved issues, doubts about specific themes.
What is the basis?	Project and Construction Master Plans	Design Phase Plan	Design Phase Plan.
What are the outputs?	Design Phase Plan	Design Lookahead and Weekly Plans, constraints removed, BIM coordination, and deliverables for construction or another stakeholder	Solutions or clarifications, detailed design plan of a specific theme.

6.2.7.5 Information Technology in Design

Design development was conducted in BIM. The architecture model was devised in ArchiCAD; the structural and MEP in Autodesk Revit. The study of clash detections was carried out in Solibri Model Checker during every design meeting.

All the design planning and control activities were developed in simple Ms Excel spreadsheets. Both BIM models and other documents relevant for the project were shared among the project participants by SharePoint (a cloud document service).

6.2.7.6 BIM Project Plan

BIM is used in Company K's project in order to improve communication through the clear visualisation of the models, assure design quality, collision control and quantities take-off. Company K develops a BIM Plan for each new project. It is a project-customised extension of the BIM guide of the company that provides general guidelines specific to a particular project.

The Project Manager, Design Manager and Construction Manager must prepare the BIM Plan and discuss how the BIM modelling will be used in the project. The purpose of the project's BIM Plan is to communicate the project requirements to set the interaction among designers and the use of BIM.

The BIM Plan for MP2 and MP3 was a strategical document that designers followed in order to work in a transdisciplinary way. The BIM Plan helped to all participants understand the objectives and uses of BIM in the project; their roles and responsibilities; establish the BIM workflow; identify the necessary resources for the BIM implementation; and define the deliverables for each project participant.

It contains the purpose and objective; the processes and participants (clarifying the roles and responsibilities, the collaboration and the co-location work); the routines of BIM modelling and the models structure, such as the zero and geographic position, the floor setting, naming the BIM model, the deliverables, how to storage and handle the files, quality assurance, tasks and responsibilities; and concludes with the tools and technology.

BIM is used in the project, and the models from architecture, structure, wood structure and technical disciplines are shared by IFC files. The verification for physical interferences among disciplines is done in a common Solibri model owned by the Design Manager. Every week or 14 days (depending on the design stage), previously to the design meeting, the design team updates the files in the SharePoint folder, then the design manager runs the clash detection. The results of this are presented in the Design meeting.

6.2.8 Construction Management – Collaborative Planning in Construction

At the construction stage, the project organisational chart was composed of company's K participants, except by the owner (Company N). The authority and power are clearly defined: the project manager is responsible for decisions related to the strategy of the project, such as purchases and design; the

Construction Manager controls the auxiliary activities such as safety, health, environment; and the operations manager controls the construction foremen on-site (see Figure 148).

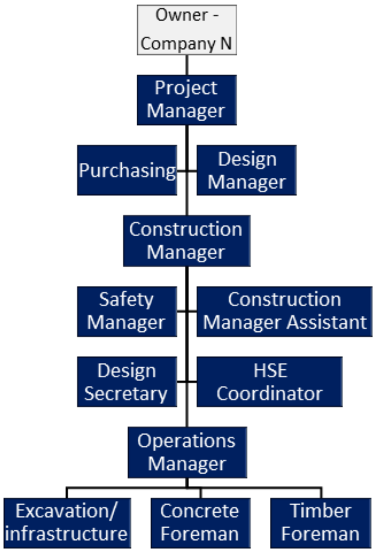


Figure 148: Organisational structure for the construction project. Source: Company K.

The construction activities were planned and controlled by the Collaborative Planning applied in construction (Figure 149). The CPC has five levels of planning and relates different people to participate in the project planning. It is a very adaptive system for the different functional needs; for instance, the lookahead planning presents different horizons of planning according to the function of the manager responsible. The system also contains a set of weekly meetings that are structured to enable the communication flow and Agile decisions between project teams.

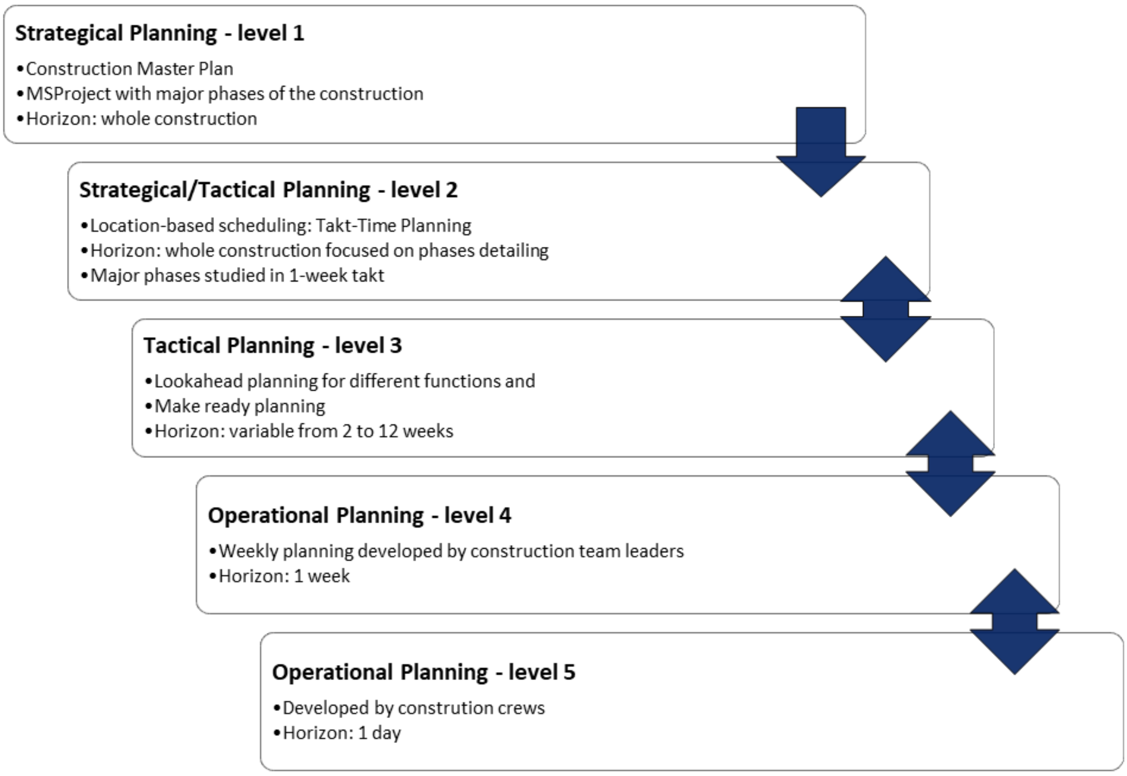


Figure 149: The five levels of planning and control in the Collaborative Planning in Construction.

6.2.8.1 *Strategical Planning – Level 1*

The Strategical Planning for the construction stage was represented by the Construction Master Plan developed in MS Project at the beginning of the project (Figure 150). It shows the main project phases at a low level of detail. It was developed by the project manager and the Construction Manager based on the Project Plan. The construction team also develops a risk analysis spreadsheet at the beginning of the construction stage.

The Construction Master Plan is the basis for the Design Planning at the kick-off meeting; it provides the construction milestones to reverse plan design activities. A master supply plan is also derived from the construction plan.

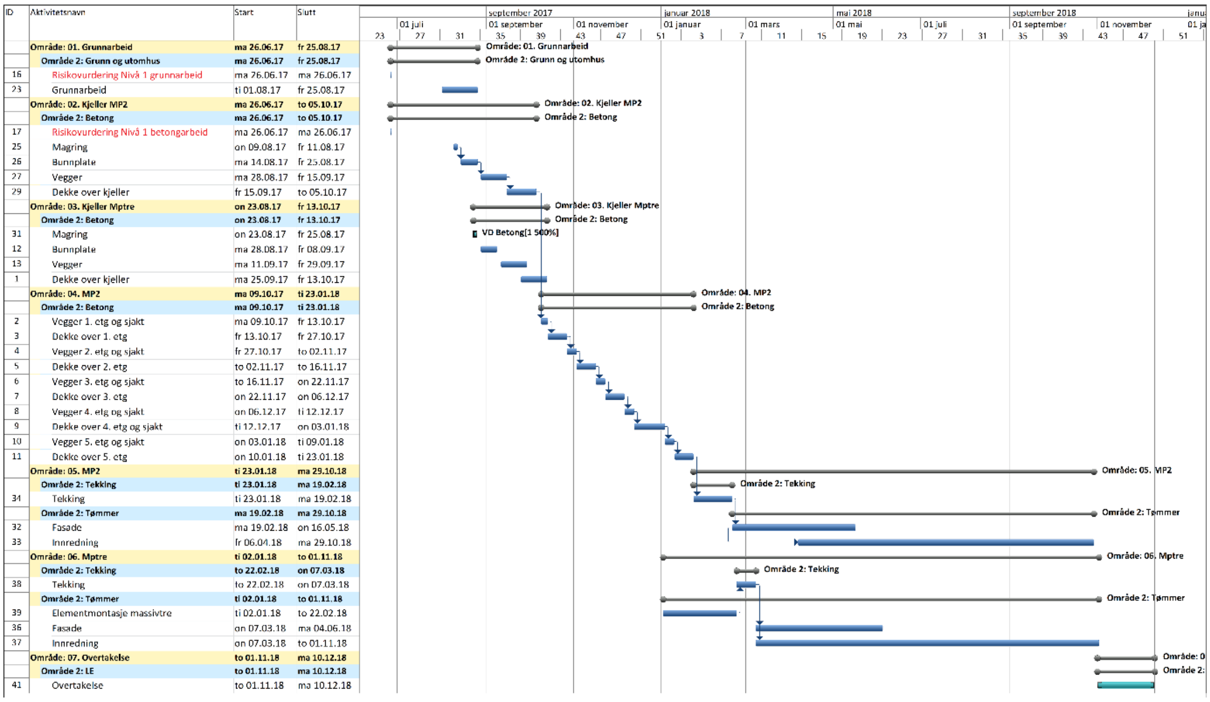


Figure 150: MP2 construction master plan in Gantt chart representation. Source: Courtesy of Company K.

6.2.8.2 *Strategical/Tactical Planning – Level 2*

At the second level of planning, the construction team developed the CSD, from which the Project Manager, Design Manager and Construction Manager decided on the type of vertical transportation, the physical site flows, the location of temporary facilities, i.e. strategical decisions about the site operation. The team used plans and the BIM model to study the crane areas of interference, such as demonstrated in Figure 151 and Figure 152.

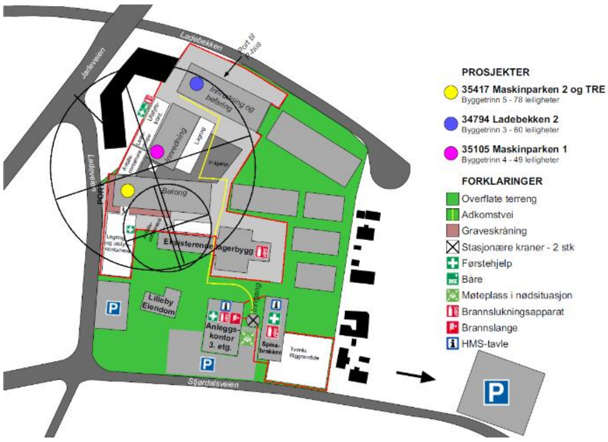


Figure 151: Study of vertical transport equipment in the B1/B2 stage. Source: Courtesy of Company K.

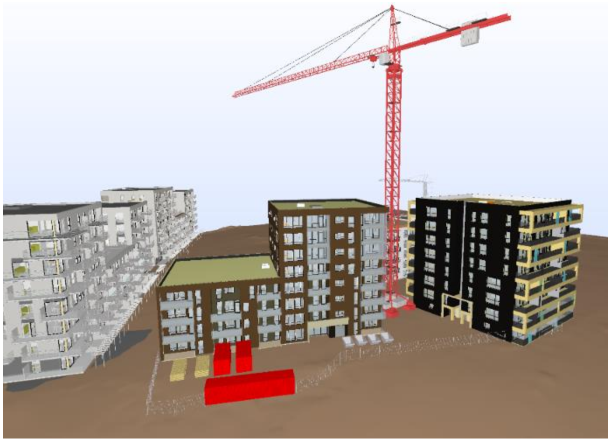


Figure 152: Study of vertical transport equipment in the B1/B2 stage – BIM Model. Source: Courtesy of Company K.

The construction company outsourced the bathrooms cabins, and this was reflected on the design and the production planning. The concrete structure was carefully studied and, to minimise its costs, the apartment terrace slabs were pre-casted on-site using a standardised formwork because they had the same size. However, at other stages of the project, the terrace slabs with different dimensions were outsourced because it was slow to cast and expensive to have different sizes of formwork on-site.

Using the TTP (Figure 153) as an LBS tool, the team studied the construction workflow, the crew size, buffers and the takt-time for production. In the TTP, a 1-week takt was adopted for almost every activity. Company K was building MP2 and MP3 with some months of delay, which facilitated the resource sharing between both projects.

The TTP represents the Phase Plan. It is interesting to note that it is divided by phases of construction: foundation, structure, façade and interior work. This means that each phase is represented in separated rows in the planning spreadsheet, which may hamper the visualisation of the WIP at the same location.

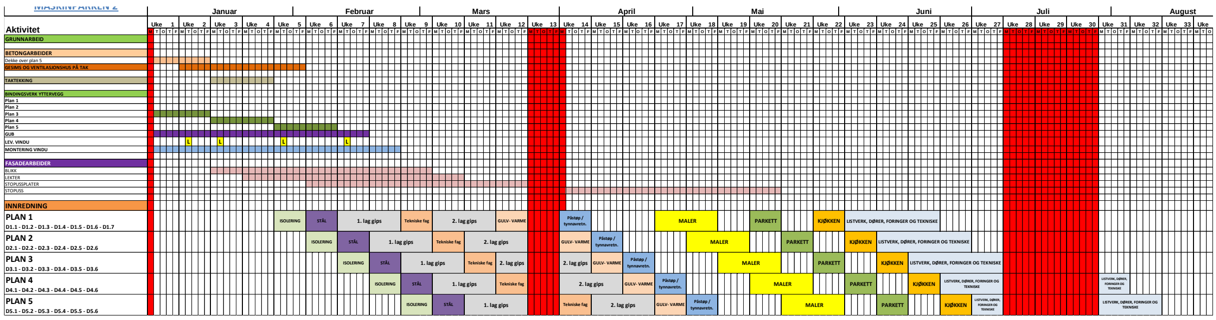


Figure 153: Takt-time plan of MP2. Source: Courtesy of Company K.

The TTP was used by other project participants to plan the construction activities in more detail, as shown in the next subsection.

6.2.8.3 Tactical Planning – Level 3

Company K developed three different lookahead planning meetings, involving different functions of construction to remove constraints from different horizons:

- 8-12 Week Lookahead Planning: developed by the Site Manager, Design Manager and Project Manager;
- 4-8 Week Lookahead Planning: developed by the Operations Manager, and;
- 2-4 Week Lookahead Planning: developed by the Operations Manager and Foreman.

One interesting difference between the CPD and the traditional LPS is the engagement of different construction stakeholders in the lookahead planning. Instead of having only one lookahead plan for production involving all the stakeholders in planning the same horizon, at Company K the stakeholders develop different plans looking ahead at different horizons. As a consequence, different hierarchies of professionals contribute to the planning at a scale where they can visualise the constraints in separate meetings. For instance, the Operations Manager focuses on the supply system, using a specific spreadsheet and based on the level of detail expressed in the TTP of MP2.

Although there were different horizons of planning, the participants of the meeting used a single plan spreadsheet, as shown in Figure 154.

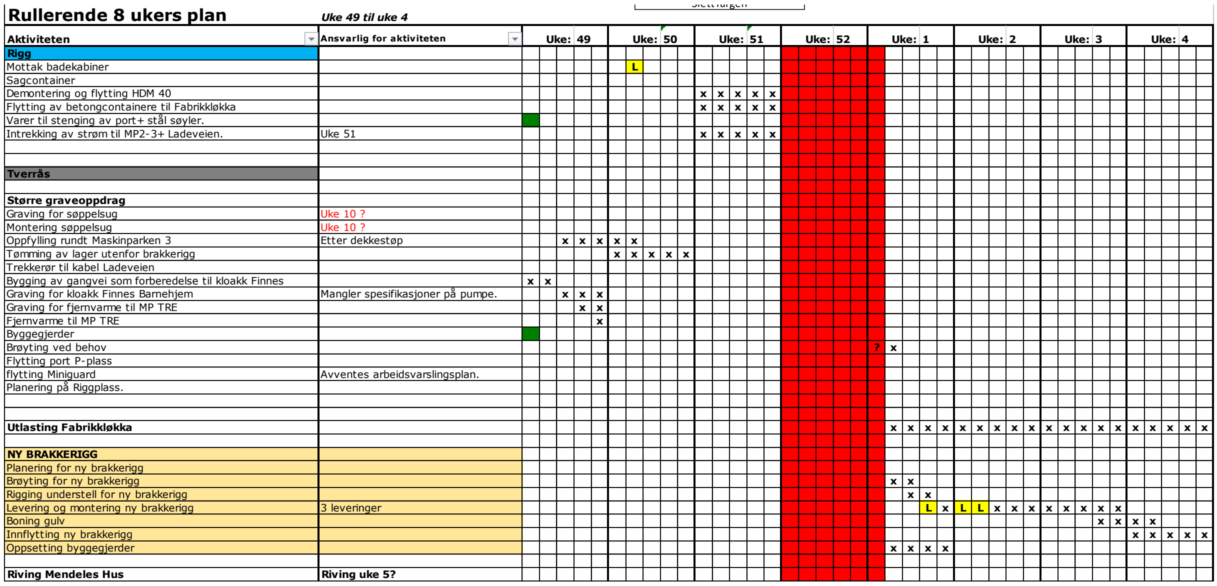


Figure 154: Lookahead spreadsheet. Source: Courtesy of Company K.

6.2.8.4 Operational Planning – Level 4

At level 4, the team leaders devise the weekly plan, revising which activities were concluded in the current week, and predicting the next work week according to his/her crew's production capacity. Then, in the weekly meetings, the crews understand and negotiate their activities. In the weekly plan, the team leaders pull from the lookahead plan only the activities that have no constraints remaining, which increases the plan reliability. A specific spreadsheet is used by the crews to plan and control their activities. They measure the PPCb and the causes for non-compliance with the plan.

6.2.8.5 Operational Planning – Level 5

The level 5 of planning has a 1-day horizon and occurs every working day. The crew's members gather in the first hour of work to draw in the floor plan that should be executed on the day, considering the previous tasks executed. It becomes clear for the team where exactly they should be and what work should be done.

6.2.8.6 Construction Meetings

In summary, the construction meetings adopted in the CPC, their relationship with the planning levels and scope are described in Table 38.

Table 38: Structure of construction meetings.

Plan level	Responsible	When	Plan detail	Scope
Level 1 Master Plan	Project Manager and Construction Manager	Before starting the project	Summarise the main activities and set milestones	Devise the construction plan
Level 2 Phase Plan (TTP)	Project Manager, Construction Manager and Design Manager	Phase plan meeting – before starting construction	Detail phase plan	Create a unified plan for the phase using Takt-Time Plan

Level 3 Lookahead Plan (8-12 weeks)	Site Manager, Design Manager and Project Manager	Internal meeting	More detailed activities; Identify and remove constraints	Consider the location of future deliveries in the construction plan
Level 3 Lookahead Plan (4-8 weeks)	Construction Manager and Operations Manager	Operational meeting	More detailed activities; Identify and remove constraints;	Consider the location of future deliveries in the construction plan
Level 3 Lookahead Plan (2-4 weeks)	Operations Manager and Foreman	Planning meeting with the foreman	Verify that all activities are at the same level of detail and in the correct order; Identify and remove constraints	Review deliveries over the coming weeks and update plan
Level 4 Weekly plan (Week)	Leaders and Crews	Team leaders meeting	Review the week's activities; Plan the week	Review weekly delivery of location
Level 5 Last check out (Day)	Crews' members	Morning meeting	Check work from the previous day and briefly review the day's tasks	A brief review of delivery and placement

The structure of the weekly meetings also facilitated the Agile communication between the project stakeholders. In Figure 155, the light grey arrows demonstrate the flow of information from the operational meetings on Mondays until the progression status meetings on Fridays. The blue arrows represented the communication flow from construction, designers to the owner and client of the project. The flow of information has a short update cycle time of only one week. For this reason, the communication of changes required, decisions and other information is considered agile and transparent.

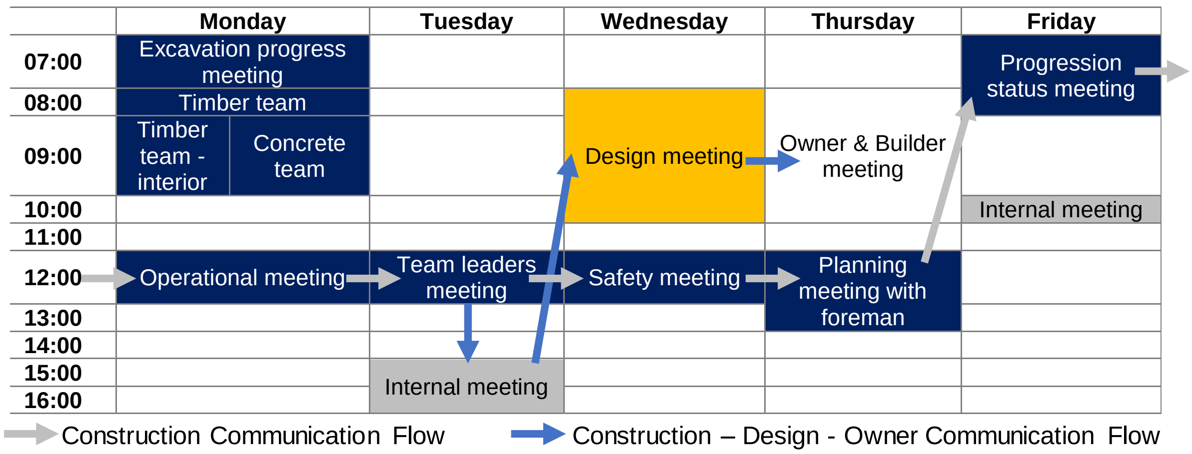


Figure 155: Project meetings structure and the weekly communication flows.

6.2.8.7 *Information Technology in Construction*

The information technology used for construction planning and control were the MS Project for devising the master plan of the project, plus the MS Excel spreadsheets for the Takt-Time plan, purchasing plan, lookahead plan and weekly plan. The project team also used the 3D BIM model to study the site layout, physical flows, temporary facilities, and to locate the principal vertical transportation equipment. To share files and documents, the teams used SharePoint, which is accessible on-site.

6.2.9 Integration Between Design and Construction Management

The integration between design and construction management in the MP2 project was seen since the conceptualisation of the design solution of the whole development area. Company N portrayed the early participation of Company K in the product development, providing opinions about the adequate construction sequence for production. The companies' collaboration was enabled by the fact that one of the investors in the project is a "sister" enterprise of Company K.

The participation of the Design Manager in the CSD was also crucial to study the optimal construction site, flows, and temporary facilities. The integration between CPD and CPC occurred mainly between the Design Plan and the Lookahead Plans for construction. Both represent the tactical planning level, which has the role of making feasible the executions of the production tasks at the right time and adjust the activities dates and sequence when necessary according to the feedback from the weekly plans.

The integration of information was supported by the sequence of the weekly meetings that facilitated the quick distribution of decisions or issues between Owner, Designers and Builder. Figure 156 depicts the flows of integration in the D-C interface. Briefly, the final design version of the developed design stage is shared with the Construction Managers to devise the construction master plan. The output then is sent to the design team as the input of construction milestones. The team sets its deadlines, stages and gates, which are followed by the lower levels of planning. The same occurs with the Phase Plan delineated by the construction team and used by the lookahead plans.

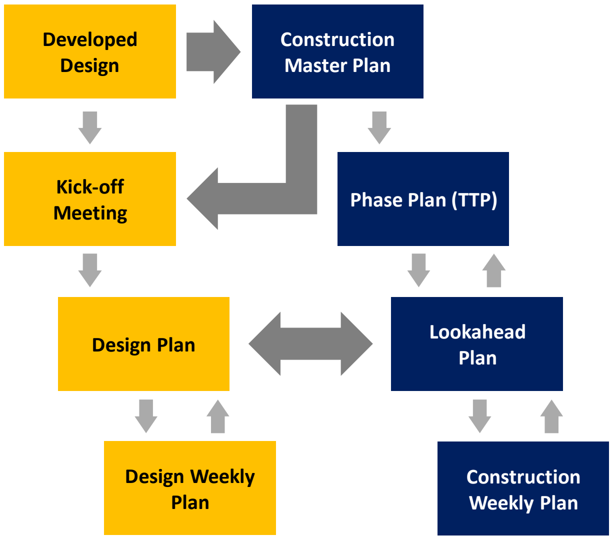


Figure 156: Integration between design and construction planning and control systems.

Figure 157 below is part of the Design Plan spreadsheet. It is possible to see that design deliverables were produced according to the construction plan: in light green cells, the design was delivered in a large batch to be the basis for other disciplines; the dark green cells represent design for construction; in dark blue cells are the start of construction. It is worth noting that the design deliverables are divided by floors. First, the solution is viewed for the whole project discipline when interactions with other designers are necessary. Second, the solution is detailed for construction use, and that is the reason for it to be delivered in smaller batches (the same used in the construction plan).

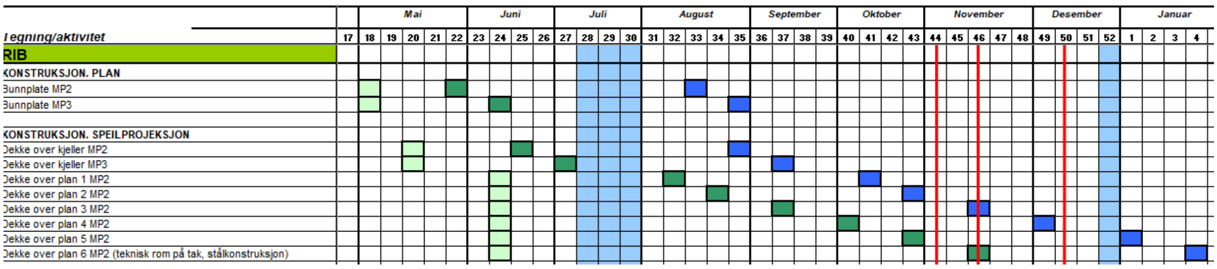


Figure 157: Example of using location-based from construction to pull design.

6.2.10 Project Management Improvement

At the end of each construction project, the managers are invited to reflect on the management practices and register the positive and negative points in the project. An A3 is used as a tool to summarise and simplify the main ideas for improvements. As presented in Figure 158, Company K has a standardised structure for A3. Afterwards, the participants devise the A3, which is escalated to a higher management level to study possible improvement ideas to be implemented in all the company's projects.

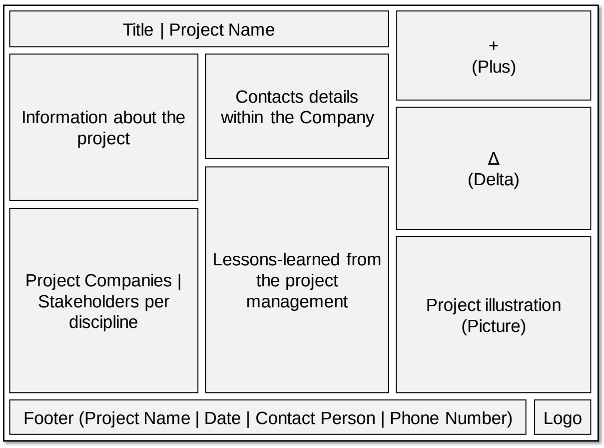


Figure 158: A schematic content of A3 deployed at Company K.

6.2.11 Analysis and Discussion of CS6

At the beginning of the detailed design stage, the organisational structure of the design and construction stages are presented to all participants. It defines the planning responsibilities of Design Manager, Designers, Project Manager, Site Manager, Operation Manager, Foreman, crews' leaders and workers. Although it is a simple and common practice of management, it is frequently neglected by the companies and project managers. The transparency of the organisational structure clarifies the authorities and power of decisions.

The CPD has proved to be an agile production planning and control system in view of its quick adaptation to changes in the owner's requirements, construction sequence, etc. Moreover, the way the designers are invited to participate in the planning and control activities promotes their ownership of tasks, mainly due to the fact that they are all collaborating and sharing responsibilities from the beginning of the design stage. This work environment promoted the "team atmosphere".

The Design kick-off meeting enabled the designers to clearly understand the dependencies among design deliverables, and the milestones and gates. It was devised based on the Construction Master Plan, which provided milestones from construction and, consequently, milestones for design deliverables. When the pull plan for design was applied, the design team assured a smooth production in just-in-time, i.e. deliver the right drawings/information at the right moment, to the right person. Then, it can be assumed that the output of the design kick-off meeting is the Design Plan for the phase.

The Design Plan should be planned in more detail, to further control the design tasks and the remove constraints. The Design Plan is a “live” planning document, updated every week. It tracks the design production and updates the construction demands.

The following level of planning and control is the Design Weekly Plan, which mixes a tactical view four weeks ahead to remove constraints, and an operational view at the horizon two weeks ahead, which is easier to control. When the design solution is completed, the deliverables are produced according to the construction needs, e.g. per floors. At these meetings, the designers also planned the decisions needed and made.

In summary, the CPD stimulated transparency of people’s responsibilities, tasks, dependencies, decisions, planning and project goals. Moreover, it was intrinsically connected with the BIM model’s development and construction.

The CPC has also promoted the ownership of plans by its stakeholders, which was boosted by the high transparency of planning. The Construction Master Plan is the first level of plan that pulls the design planning.

The Construction Location-Based Plan improved the transparency of construction activities and enabled the negotiation between subcontractors and Company K regarding the crews’ composition, activities duration, sequence and takt-time.

The Lookahead Plans increased the level of planning detail and removed constraints, enabling the execution of construction tasks at the right time. Different construction stakeholders were planning different horizons in separate meetings, but using the same plan spreadsheet. It made the meetings more effective and focused. The sequence of their meetings also enabled a smooth communication flow with short control cycle time.

The Weekly Plan was more similar to the ones adopted by the LPS. Two differences are: a) the activities not completed are also evaluated according to the impact caused on the next tasks, and b) the crews attend daily morning meetings to review and define the work on the day using floor plans, which clarifies the production batch and sequence of work for the day.

In summary, the benefits of the CPD and the CPC for the integration of design and construction activities rely on the collaborative and integrated PDS promoted at the beginning of the detailed design phase, as well as the collaborative and integrated production planning and control of CPD and CPC through the pull plan and lookahead planning communication. Three success factors in the D-C integration are due to the way design was managed: 1) Small batches of production (2 weeks); 2) Short cycle time of control (1 week), which is the same cycle time of construction management meetings; and 3) Construction feedback as part of the design planning and control system.

One additional factor for the success of the integration between CPD and CPC relies on the fact that some participant enterprises were the designers, manufacturers and installers. It facilitated the knowledge management between downstream and upstream processes, plus improved the communication flow. Regarding the CPC, Company K had a high number of in-house workforces which were familiar with the collaborative planning practices.

The short control cycle time enabled not only the communication in the D-C interface, but also between Client-Construction Company K and Owner-Designers. In the MP2 and MP3 projects, there was early participation of the construction Company K in the project programming and construction strategy jointly with the Owner. It enabled both companies to align their goals with the project goals since the first stages of the product development.

CS6 also contributed to answering some of the research questions displayed in Table 39.

Table 39: The main contributions of case study 6 for the research aim and objectives.

Aim/ Objective of the Thesis	Study Contribution
Devise a **model** to **design, plan and control** the stages of **design and construction** in the context of projects with **overlap** between these stages, using **location-based tools** and other **lean tools to pull and align the project production**	A third version of the model was devised based on the AR5 and CS6. The model was improved around the project and interface D-C management, as such planning all the stages, milestones, gates, collaboration required from the stakeholders according to the procurement route. Design has shown a difference of batch size of deliverables from preceding and subsequently the decoupling point. Also, design should be planned and controlled weekly but with a 2-week horizon. The construction lookahead plans should be performed by different experts viewing ahead of different horizons in separated meetings.
How to use location-based tools to **structure the work** for design, suppliers and construction	The construction location-based plan pulled the design for construction deliverables. They were released per floor, as with the construction batch. It corroborated with CS4 regarding the existence of transdisciplinary and interdisciplinary detailed design development.
How to **assemble design packages** to meet suppliers' and construction requirements	The design packages were designated by deliverables. Each discipline was broken down into floor plans and other areas. The deliverables followed the pull flow of information for procurement, construction phases (foundation, structure, technical), customisation, clash detection and construction drawings.
Determine the **decoupling point of design** development	The decoupling point observed in the Design Plan occurred at the delivery of design for X previous to the development of the construction drawings (the detailing step).
Analyse existing **types of pull production systems**	In the project, there was a central pulled flow from construction to design. The construction master plan and phase plan (takt-time plan) pulled the procurement process and, mainly, the design process. The information from

	the construction plan was updated weekly through the lookahead planning, achieving the weekly design plan.
How to measure and manage the **work in progress and buffers**	The way that the Design Plan sheet was conceived, all the deliverables for a particular discipline were at the same timeline. It facilitates the sum of DIP: days of stocked design until its use by the next development stage and ending in construction.
Identify the **best tools to control the production system**	The project must have a Master Plan containing all the NPD stages. In particular, to the D-C interface, the Process Map using post-it is a transparent tool to understand dependencies, deliverables and sub-systems. Design and Construction should use collaborative planning, such as the LPS. One adaptation for Design is: deploy the lookahead plan in combination with the weekly plan meeting. Adaptation for Construction is arranged at different weekly meetings to plan different horizons of lookahead.

6.2.12 Suggestion for Improvements

At the end of CS6, the researcher presented to the participants some suggestions for the project management improvement. Regarding the CPD, it was suggested, based on the interviewees' comments, that the detailed design development could be executed concurrently by all disciplines at the same level of detail to avoid unexpected design changes later in the process. Plus, some metrics could be added to control the production with more transparency, such as:

- Metric for designers' performances in weekly meetings to enable learning and corrective actions;
- Metric for decisions made on time (monthly);
- Metric for decisions opened (monthly).

Regarding the CPC, the interviewees reported that the spreadsheets used in the management could be more automatic. The researcher's suggestion is to develop a software for the CPC and CPD, considering that the collaborative planning is already a current practice adopted in all Company K projects.

The second level of the CPC had some suggestions surrounded the TTP tool. They were:

- Increase the level of detail of the façade plan and study interferences between the façade, as well as the interior works of the building;
- Use the TTP to count the WIP in the same location, for instance in the interface between structure and interior works;
- Use the TTP to produce the histogram of workforce, which would make it easier to share the crews between the construction projects, as shown in Figure 159, made by the researcher to MP2 and MP3.

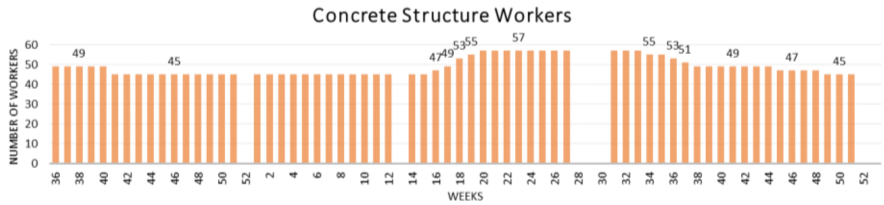


Figure 159: Concrete structure workforce histogram per week.

With regards to the lookahead planning, the use of metrics was proposed to control the constraints removed. Metrics for the weekly plan also clarify the need for improvement of the management system, which could be correlated with the safety and quality.

The improvements to the management system should be carried out throughout its operation and not only at the end of the construction project. The root causes of the task's non-compliance could create corrective actions for the continuous improvement.

As the MP2 project is only one part of a broader development area where there were people already living in some houses, it was recommended to use the BIM models of the site to communicate to the residents during the construction stage sequences, as well as during the car and pedestrian flows around the site. The BIM models could also be used to study the views from the residents' houses over the construction site in order to improve the fencing design.

6.3 THIRD VERSION OF THE MODEL

The CS6 gave some additional insights into the second version of the model. Added to the model were aspects concerning the product development process and the pull production system. Bellow, the improvements were sorted by model area:

Regarding the Project Management and Interface D-C Integration:

- At the beginning of the project organisation, define the main project goals, target budget, phases of development (design-construction), process areas, gates, milestones, dependent relationship between activities and participants' responsibilities;
- Outline a clear project organisational authority and power structure for planning and decision-making;
- Understand the limitations of the stakeholders' collaboration in the project planning according to the procurement route adopted;
- Understand the pros and cons of the vertical integration of designer-manufacturer-installer firms and in-house versus outsourced construction teams in the D-C interface;
- Clear structure of weekly meetings that contributes to the short cycle time of control, which promotes the smooth flow of information and work between different professionals and functions;
- Explicit connections between plans that pull design production.

Regarding the Design Management:

- One adaptation of the LPS for design is to use, for the operational tasks, a horizon longer than one week, usually two weeks.

Moreover, regarding the Construction Management:

- The LPS should adopt different horizons of lookahead planning for different stakeholders to remove different levels of constraints in separated meetings.

Graphically, the third version of the model has changed only at the reverse design plan, where the design delivery batches are large in size during the transdisciplinary development. Then, when the design solution is complete, the decoupling point highlights its production according to the supply or construction batches (smaller batches usually following the location-based planning).

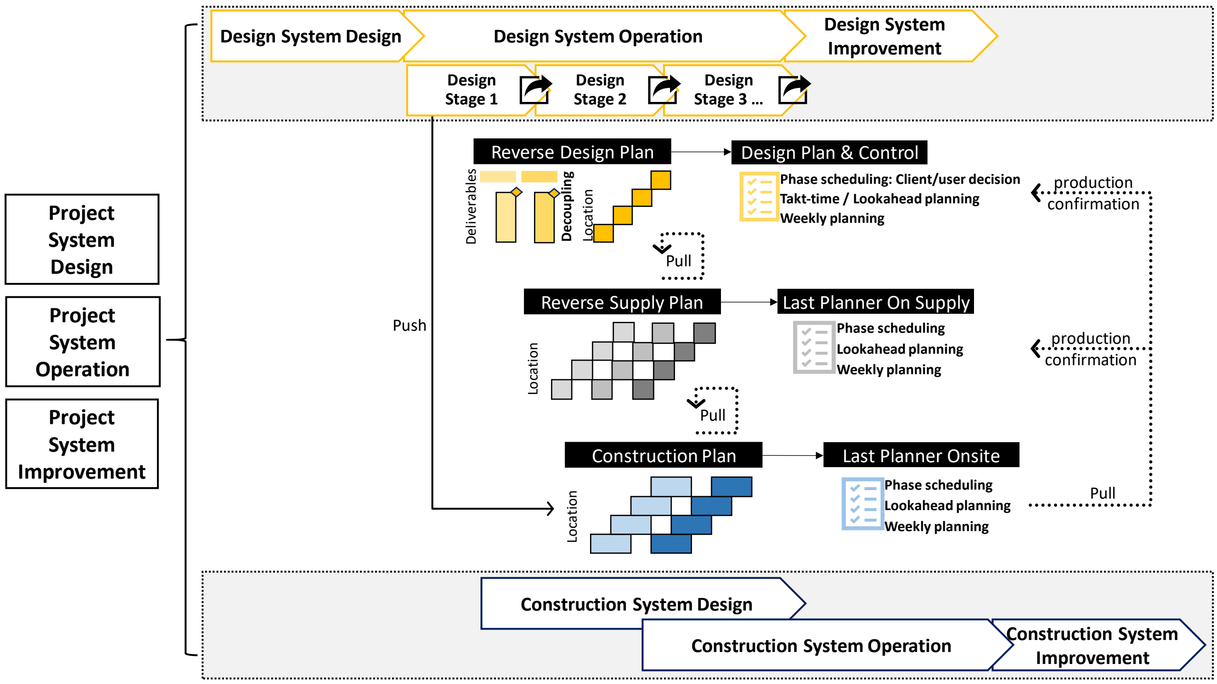


Figure 160: Third version of the model to integrate design and construction stages resulting from the action research 5 and case study 6.

6.3.1 External Model Evaluation

In the evaluation meeting, almost all the case study participants were in attendance: Project Manager, Design Manager, Architects and the Head of Design Management Development of Company K. The participants commented on the model after its presentation.

Regarding the managerial activities, they portrayed the importance of the triad of Design, Operation and Improvement. In the construction projects, people tend to “jump” direct to operation without stopping to consider how they want to operate the production system, and how to improve it.

The participants also claimed that the teams usually forget to communicate, and construction merely pushes the issues for the designers to solve. The model may then support the proactive communication for improvements. The lookahead planning should be an opportune moment to gather the D-C interface participants together and improve the project. They claimed that improvements should also be made during the tactical plans, not only based on the root causes of the weekly plans, but as a post-mortem act.

The participants also expressed their concerns about the lack of precise information to devise the master plans of design, supply and construction. They highlighted the necessity of having loops to check the procurement, supplier, and design plans after devising their plans based on construction.

The use of buffers is essential in order to protect the project and assure plan adherence, although the participants believe that they all overestimate their work. This implies that, in production, there are capacity buffers that are hidden throughout the duration of the task. In practice, it is challenging to estimate the production capacity. The histogram for designers' production capacity could work only if planned by people who know the project well. Even though the design workload is different from the one planned, it is always necessary to make adjustments. However, the histogram for designers is an excellent information to have, even knowing that the best situation is to have a stable number of architects throughout the design development.

It was also mentioned that the parallel development of all disciplines at the same level of detail is not always possible, if somewhat desirable. However, instead of seeing it as a process, it should be part of the Design Development Plan which includes the BIM Plan and the level of detail of models. A further breakdown of the detailed design stage per construction phases could be a solution.

The architects and the Design Manager also mentioned having BIM kiosks and tablets on-site to enable workers to visualise the BIM models.

The most satisfactory statement in the evaluation meeting was made by the Head of Design Management Development: "*First of all, I think your model is very much like how we want to execute our projects. This is kind of our goal for collaborative planning in both construction and design. If we could execute our projects the way we really want to do, it should be much like this.*" This quote demonstrated the accomplishment of the research aim.

This final case study provided significant insights for the design management, but it showed to have achieved a certain saturation of new data. For this reason, no more studies were necessary at this stage of the research.

7 FINAL MODEL FOR INTEGRATING DESIGN AND CONSTRUCTION STAGES IN PROJECTS WITH OVERLAP BETWEEN STAGES

This chapter presents the final version of the model for integrating the design and construction stages in projects with overlap between these stages. The model is explained in two sections: Section 7.1 – The Product Development Process, and Section 7.2 – The Pull Production System.

Section 7.3 presents the discussion surrounding the model and its internal evaluation according to the constructs presented in the research method chapter. Section 7.4 discusses the theoretical contributions of this model and research.

The final version of the model is an artefact resulting from the contributions of six studies of this thesis. The studies contributed in different ways and contexts. Figure 96 below is the final version of the model. It is divided into two parts: 1) the managerial activities of **the product development process** viewed by the perspective of the project system, design sub-system and construction sub-system, and 2) **the pull production system** that guarantees the integration of information in the design-construction interface.

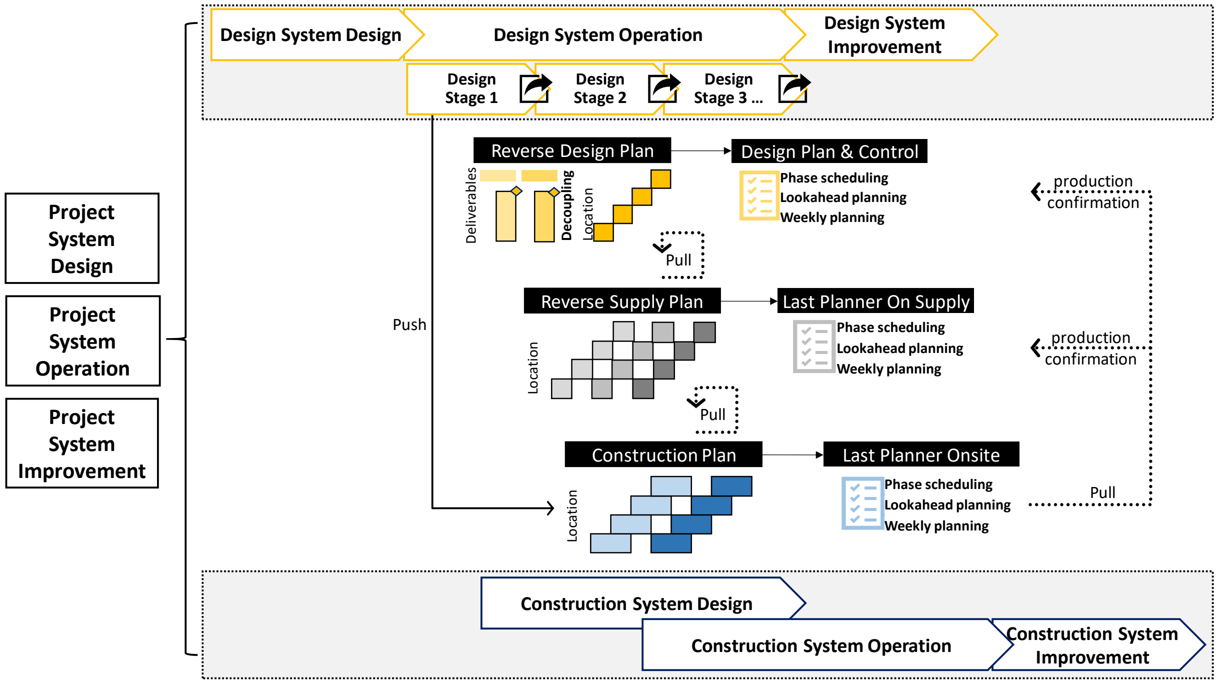


Figure 161: Final version of the model to integrate design and construction systems using location-based planning tools.

7.1 THE PRODUCT DEVELOPMENT PROCESS

The model embraces only the phases of design development and construction, ignoring other phases of the product lifecycle. It then combines, at the project system level, the overlap of the management of design and construction sub-systems (Figure 162). The managerial activities occur in the production design, operation and improvement (Koskela & Ballard, 2003). In each phase of management decisions, tools and actions must occur to integrate design and construction planning and control.

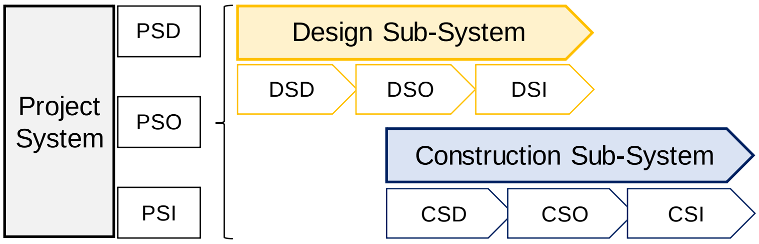


Figure 162: Product development stages in the model composition.

7.1.1 Project System Design

Projects with overlap between design and construction stages require a high level of information and people integration. The Project System Design (PSD) is the first managerial activity where decisions around integration D-C should be made. The owner and project manager should define the structure and workflow of the whole project, and in what way different functions and stakeholders need to communicate, collaborate and make joint decisions. The more structurally complex the construction building, the higher must be the integration of stakeholders. Therefore, in this scenario, the early participation of the leading designers and builders is beneficial for the success of the D-C integration in the project.

Some procurement routes are more suitable to promote the early engagement of the stakeholders. The owner and project manager should be aware of the pros and cons of each route and choose the one that might facilitate the D-C integration, such as: design-and-build, construction management, and management contracting.

At that point, the project team should outline a clear project organisational authority and power structure for planning and decision-making. The small project team on board (designer, builder and owner) should define the project system regarding its phases, gates, activities-zones, dependencies and deliverables. A lean tool that supports the transparency and development of these definitions is the Generic Design and Construction Process Protocol (Kagioglou et al., 2000). Its intention is to clarify the whole project view through a process map. Case Studies 4 and 6 used a similar tool for the detailed design and construction stages. Figure 163 depicts a schematic Project Process Map.

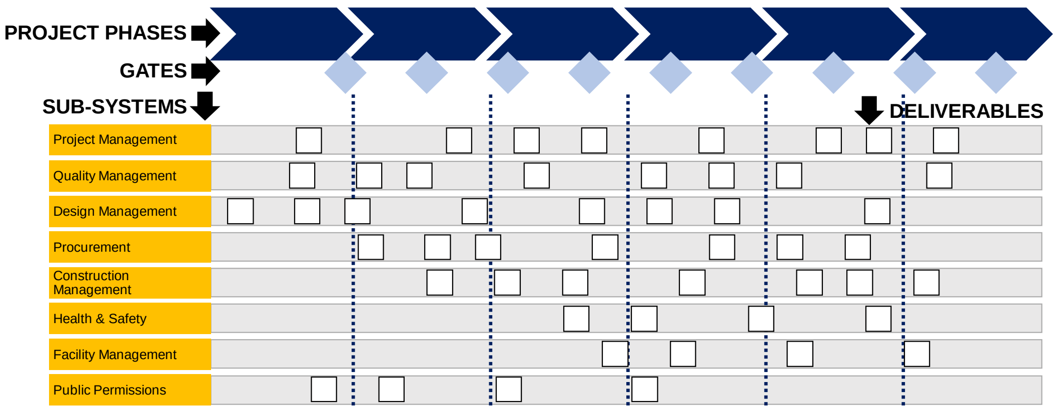


Figure 163: Schematic Project Process Map for PSD.

The development of the Project Process Map requires collaborative meetings between the leading stakeholders of the project. The tool aids the team to define strategical decisions about the structure of the project and its workflow. The tool allows:

- The stages of the project development. It is suggested to follow the professional institutions' protocols, such as (RIBA, 2013). However, at the design stage, more stages could be adopted if the project's participants judge it is necessary;
- The main sub-systems, or "activity-zones" of the project, such as Design, Procurement, Construction, Quality, Health & Safety, and so on;
- The main gates and milestones for each sub-system inside the phases of the NPD;
- A logical sequence of milestones and deliverables through the sub-systems and phases;
- The lead time of each main stage based on the:
- project delivery date;
- complexity of the project (longer design development and construction);
- type of procurement route and context (public projects have longer lead time for procurement);
- A strategical plan with the major milestones for each sub-system.

7.1.2 Project System Operation

With these definitions, the dependencies among different project systems are clarified, and the sequence of work settled. The Project System Operation (PSO) starts when any sub-system begins its operation, and finishes when the last sub-system closes out its activities.

To keep the project adherent to the strategical plan previously defined, the PSO should: a) plan and control the progression of all sub-systems' activities; and b) use metrics to control the strategical plan by deliverables from other levels of plans and functions.

To assure the control, the PSO relies on the feedback from downstream to upstream activities, mainly between different sub-systems, such as the design and construction. Herein, it is important to keep a smooth collaborative planning integrated between the stakeholders.

7.1.3 Project System Improvement

To enhance the performance of the project management along its execution, in the Project System Improvement (PSI), the team should:

- Gather information of suggested improvements from the Design and Construction, but also from other project sub-systems;

- Have frequent *kaizen* meetings with project stakeholders to collect recommendations and develop action plans to implement the improvements across project functions;
- Document the *kaizen* in A3 sheets;
- Distribution of knowledge acquired across the project's participants.

Through these actions, the project participants can be assured that the ideas of improvement can be applied during the project operation. Otherwise, the ideas will emerge only at the end of the project as lessons learnt for future projects if the knowledge is retained and distributed across the companies.

7.1.4 Design System Design

The Design System Design (DSD) is the first managerial activity to define how the design development should operate regarding the design goals, workflow, communication, approval process, tools and people. As recommended by Ballard and Koskela (2009) and brought as insight from the studies, a set of decisions about the design phase must be made. For instance:

- Contractual relations and incentives;
- Targets (target value design/cost);
- Client involvement in the design process;
- Decision-making structure;
- Methods and tools: choose whether to adopt set-based design, choosing by advantages, collaborative planning, LPS and/or agile practices;
- Design Stages:
- Number of stages;
- Use future-state Value Stream Mapping (VSM) (Rother & Shook, 1999) or other process mapping tool to define the workflow of the design development process and indicate deliverables and gates that each design stage will have.
- BIM Plan for a quick design development defines:
- The software to produce models, to study clashes;
- BIM models file extension for exchanging information;
- Process to record clashes;
- Use of common server;
- The verification and validation process of the BIM models. Include the client/user;
- Information content in each stage;
- Level of detail (LOD) of BIM models throughout the design stages (Svalestuen et al., 2018);

- Adoption of progressive design fixity: BIM model freezing.
- IT tools for communication and data exchange process:
- Outputs of each design stages for each stakeholder;
- Files storage and access;
- Communication tools.
- Collaborative Planning:
- Physical layout of designers when co-located;
- Based on the strategical project plan, prepare the master plan for design;
- Define how the master plan will be controlled: through the last planner system, or agile design management, or takt-time planning, or other;
- Understand the pros and cons of the vertical integration of designer-manufacturer-installer firms;
- Clear structure of meetings that contributes to the short cycle time of control, which promotes the smooth flow of information and work between different professionals and functions;
- Explicit connections between plans that pull design production.

With reference to the methods used in design management, the Stage-Gate (Cooper, 2016) is suggested to support the development of the design versions to avoid reworks and to control better the drawings/models versions between stakeholders. Still, the use of the Last Planner System (Ballard, 2000a) to plan and control the designers' activities is recommended, primarily because it will be related to the last planner used on-site. However, other methods such as Agile can be adapted for the design management (Demir & Theis, 2016), notably to include the client constantly in the design process.

7.1.5 Design System Operation

Next, the Design System Operation (DSO) should be divided into the stages defined in the DSD. The design plan for the detailed design stage will be a product of the reverse plan derived from the construction master plan described in the "pull production system" section, plus the data from the Project Process Map for the whole project. In the DSO, the project team should:

- Deploy a hierarchical level for design planning and control composed by:
- Design Master Plan (milestones/stages/gates/relation with other project areas);
- Meetings to Control the master plan using information from other levels of plans;
- Pass through the gates with the client/user agreement, design validation and review of deliverables;

- Metric: adherence to the plan = time and information deviation of deliverables.
- Tactical and Operational Design Plans:
- Takt-time Plan (2 weeks of horizon planning and 2 weeks of control cycle), plus remove constraints; or,
- Lookahead and weekly plan combined (2 to 4 weeks of horizon planning and 1 week of control cycle), plus remove constraints;
- Metric: PPCb and root causes for non-completion of tasks;
- Connection with tactical plans of supply and construction systems.
- Decision Plan:
- Decision-made log list, and decisions to make list; or,
- A3 sheets to record the decisions made and make them accessible and transparent;
- Metric: percentage of issues solved vs opened on time and by the person;
- Kanban cards: request decision/information accurately from other designers.
- Set the decoupling point between transdisciplinary and interdisciplinary design development;
- Design specification or design for construction developed for building areas following the location breakdown structure of downstream processes, e.g. construction line of balance (LOB).

7.1.6 Design System Improvement

The Design System Improvement (DSI) should occur during the NPD process, not only at its end. The collaborative planning should be an open space for project participants to suggest ideas and necessities of improvements. Then, it is advised to establish:

- Regular *kaizen* meetings to collect ideas for improvement and discuss their implementations;
- Use the lookahead meetings to improve the design solutions based on builders' feedback, and vice versa;
- Deploy a common project database to record *kaizen* suggestions for design and construction processes;
- Use of A3 sheet to make transparent and easy to understand how the improvement should be and why;
- Metric: control the number of improvements implemented versus opened.

7.1.7 Construction System Design

The early participation of construction stakeholders is highly recommended for starting the Construction System Design (CSD) in concurrence with the DSO. The CSD should use drawings/models from a design stage containing more information than the conceptual design, for example geometry, volumes and structural system defined. However, the project team should settle which design stage will be the input to the CSD.

The CSD should be developed using location-based tools such as LOB or flowline, but not the takt-time planning because of the high level of uncertainty at this project stage, but also because of the lack of subcontractors' participation in the planning. The main idea of these tools is to break down the work into small batches that are based on location and then to plan the activities, set their sequence and the necessary resources to deliver the project. Location-based tools aim to achieve a unique production pace for activities, which eliminates work in progress (WIP) and reduces the project lead time. These tools have proved to improve project performance, supporting waste reduction and decreasing lead time, costs and risks.

Location-based tools are appropriate for the construction industry, mainly because we can visualise many production characteristics, such as delivery and production paces, crews' workflow, cycle time, lead time, buffers, WIP, and so on. These tools are flexible regarding the plan LOD, which, during the construction system operation (CSO), will be gradually detailed with construction participants.

During the CSD, the construction team should use 4D BIM models to study the site flows. Herein is expected construction feedback to designers about constructability, improvements in the product to reduce costs, time for construction, and so on. In the CSD, the constructors and subcontractors (when available) will pull some design decisions in order to study construction strategy, main transport equipment, site layout, flows, and activities duration. They will be able to present to designers the advantages and disadvantages of each design solution from the point of view of construction lead time, costs, risks, procurement and quality. The CSD will evolve according to the design development, and its output is the construction master plan.

In overlapped projects, the CSO occurs in concurrence with the DSO, which brings many opportunities for design and construction improvements.

Summarising, at the CSD, the project team should:

- Use a location-based planning tool (flowline or LOB);
- Send the construction master plan to prepare the reverse supply and design system;
- Make decisions about production batch size, systems testing batch size, work packages, construction sequence, resources capacities and duration, logistic flow, critical processes, and buffers to shield the production against variability;
- Use of BIM for 4D simulation and 5D quantities take-off;

- Make collaborative and jointly decisions;
- Designers should understand the impact of design solutions for production;
- Production of reverse plans for suppliers and designers.

7.1.8 Construction System Operation

In the Construction System Operation, the decisions made about the work structure in the CSD should be carried out and controlled by the project team. In the CSO:

- The LOB or Flowline should be refined collaboratively with the subcontractors on board; or
- A TTP may be applied for the Phase Plan, as it is a technique that requires collaboration, accurate information, and an engaged subcontractor;
- Ownership of the plan by the subcontractors is essential;
- Last Planner System:
- Phase Scheduling with TTP;
- Lookahead Planning and remove constraints with Make Ready Plan;
- Designers and Suppliers should be included as responsible for removing constraints;
- Different horizons of lookahead planning for different professionals in separated meetings;
- Connections between the tactical planning used in construction with those used by suppliers and designers;
- Metric: ICR (Index of Constraints Removed);
- Commitment Planning to operationalise the plan and control its deviations;
- Metric: PPCb (Percentage of Plan Concluded) and PPCT (Percentage of Plan Concluded and Tested);
- Use of root causes analysis to improve the system.
- Clear structured weekly meetings connecting the LPS activities with the design meetings and client/owner meetings for short cycle of control;
- *Kanban* to request information/drawings/decision.

7.1.9 Construction System Improvement

In the Construction System Improvement (CSI), the project participants should gather and analyse data to implement *kaizen* in the next projects. However, the improvements do not necessarily need to be pointed at the end of the project, but during the system operation by means of tools and techniques for problem-solving, such as the 5WHYs for tasks not completed, A3 to report a problem, and so on.

Then, in the CSI, it is prescribed:

- *Kaizen* to improve the system while it is in operation;
- Common project database to record *kaizen* suggestions for the design process;
- Use of A3 sheet to make transparent and easy to understand how the *kaizen* should be and why;
- Regular meetings to discuss the *kaizen* implementations (maybe every three months);
- Metric: control the number of improvements implemented versus opened;
- Send suggestion of improvement for designers and suppliers.

The operation of design and construction systems is better described in the next section, the pull production system.

7.2 THE PULL PRODUCTION SYSTEM

The lean value stream focuses on client requirements. However, in a project with overlap between the design and construction stages, the last stage is the final internal client who will dictate how to build the facility, at which pace and lead time. Identifying the construction demand is important in order to structure the work of designers and suppliers. For this reason, the CSD should start early in the project development, as soon as the drawings/models are becoming more mature, and then gradually developed following the design/information updates. The CSD is responsible for studying and describing the construction demand that is represented by the LOB or flowline. In the same way that the location-based planning tool is useful for the production planning and control for construction, so it will be useful for design and suppliers.

Following that, the design pushes the building information for the CSD. Its output is the construction LOB or flowline that will pull reverse plans for suppliers that will pull a reverse plan for designers. The idea of using the construction batch (location) from all suppliers and designers is to allow the alignment of plans. The suppliers will deliver the material/components to construction following the construction batch and sequence. The same is valid for designers, who must produce the detailed design following the suppliers' production batch and sequence. This idea enables a new way of assembling work packages, and support the continuous flow by pulling only the necessary information, when necessary, which are concepts of the just-in-time (JIT) production system.

Thus, the design packages will be composed by a combination of drawings/models of a certain location necessary to be released to the next supplier. The supplier will use this pack of drawings to develop the engineering design (if applicable), and plan the fabrication of components necessary to be delivered to a particular construction location. In order to develop the reverse plan, designers must structure their work and know their production capacity to estimate the duration. On the other hand, suppliers must provide information about the engineering design duration, fabrication, delivery time, and so on to produce their reverse plan.

In summary, the construction LOB receives pushed information from design to prepare the construction LOB or flowline. This one will settle the milestones for suppliers to develop their reverse plans using the same location breakdown structure. Based on design deadlines from the suppliers' plan, the designers should produce their own reverse plan. However, as construction projects have uncertainty and variability, the whole production planning and control system should be connected. It is suggested that the LPS should be used on-site, on design and by suppliers.

It is very important to classify the supplier according to their lead time. The time necessary for an ETO company to produce and deliver a component for assemblage is usually longer than an MTO company, which is longer than an MTS company that has components available for delivery in their stock. These lead times or delivery times should be included at each level of the LPS in order to remove suppliers' constraints and update the supply chain about the construction status. This information is vital in order to keep every stakeholder in the same production sequence to deal with the right construction batch.

In the CSO, the LPS starts with the phase scheduling based on the LOB or flowline milestones. Major suppliers and subcontractors should be included in this planning process to refine the LOB and update the reverse plans (design and supply). Next, in the lookahead planning, the project participants should focus on removing the constraints, updating the reverse plans and, when necessary, replan the construction. These two LPS levels of planning are critical in order to confirm with designers and suppliers the right priority of production based on construction status. This idea of confirmation points was suggested by Viana (2015) in her work regarding integrating the planning and control system in ETO companies. However, the integration of the LPS adopted by designers and builders was suggested by Bolviken et al. (2010).

The adoption of a location-based plan for designers, suppliers and builders is expected to produce an optimal project plan based on the JIT principle (Ohno & Mito, 1988). The reduction of project lead time is expected and an increase in the design and supply reliability to deliver the right information/material at the right time for builders.

7.3 DISCUSSIONS ON THE MODEL

The model presented in the previous section requires an adequate procurement route to promote integration of stakeholders from the design and construction stages. The Integrated Project Delivery is the preferable scenario for integration and collaboration of participants. However, the model can be applied in most procurement routes, the exception being the traditional one.

The project system has also gained the managerial activities of design, operation and improvement proposed by (Koskela & Ballard, 2003).The PSD in the model is similar to the Pre-Development Activities of the NPD process (Kagioglou et al., 2000), but with focus on designing the integration of D-C.

The project operation comprises the design and construction stages. The design evolves from phase to phase, passing through a set of criteria and review of the BIM models and documentation. This idea comes from the Stage-Gate with agile elements (Cooper, 2014, 2016; Cooper & Sommer, 2016) to coordinate the work of cross-functional teams, working preferably in collocation.

The PSI should be carried out throughout the project execution and at the end as lessons learnt. The improvements are based on the Toyota production system tools (Morgan & Liker, 2006), such as A3, root causes analysis, 5W2H, *kaizen* meetings, and so on.

The model depends on the concurrent engineering approach for the product development. Namely, when the design is progressing, the CSD must start structuring the work in parallel. This intersection enables the builders to analyse the constructability of design solutions and provide feedback to designers. Improvements can be done before the design completion. To enhance the agility of the NPD process, the weekly meetings for design, construction and owner planning comprise a procedure by which stakeholders can communicate. Weekly, they might request information, receive updates, change production sequence, batch, and so on.

In order to enable the concurrent engineering, the model needs to coordinate the design production to distribute the drawings and documents to their downstream dependant activities. That is why there exists the combination of Stage-Gate method with the Activity Stage model for organisation level. Design needs to go through the gates in order to be released to other departments with distinct activities in the NPD. The progressive design fixity concept is also behind the model and its part of the stage-gate method.

At the first design phases (conceptual and developed), the design production flow is pushed. At the detailed phase, there occurs the decoupling point, which is the interface between push and pull flows (Kiiras & Kruus, 2005). It also points to the interface between transdisciplinary and interdisciplinary design production. The interface push and pull was explained by (Hopp & Spearman, 2011). Learning about the PP interface enables the use of CONWIP in the project system (Arbulu, 2006). Then, it is understood by the project team when a particular design deliverable needs to continually progress in push flow, instead of being pulled by a downstream activity.

The control of the effectiveness of the project system should be done by controlling the number of WIP in the interface D-C. Specifically, through the use of the location-based scheduling tools, it is easier to count the number of days of WIP in the interface design-supply-construction because their production batches are aligned, or have the same size, or location.

Along the NPD process, the nature of management changes. Following (Austin et al., 2002) model of complexity, the initial stages of NPD prevail the negotiation activities between a few but key project participants. In a certain moment of the design development, the project management changes its focus to the coordination of teams and work, especially due to the high number of participants acting in the project.

Based on that, the collaborative planning or LPS should be adaptable to the changes of management focus: from negotiation to coordination. The studies showed that, given the high level of uncertainty and few number of participants at the initial phases of the project development, the collaborative meetings were more frequent in order to create space for negotiation. The opposite occurred at the final stages of the detailed design stage, where the coordination meetings were becoming less frequent, but the number of participants was high. This proved that the agility of the management structure, including frequency of the meetings, should follow the level of uncertainty, i.e. the higher the uncertainty in the NPD process, the higher is the frequency of meetings to promote agility. And, when there is more certainty in the project, the meetings become less necessary, thus changing the focus to coordination of work between designers, suppliers and builders.

The LPS also needs to adapt and be flexible regarding the horizons of planning for different stakeholders. The short term of design planning had the minimum horizon of planning of two weeks. The construction used daily plans to weekly plans. The lookahead planning in construction had three different horizons. Instead, the medium term of design planning used the whole design stage as the horizon. The decisions about the planning horizon and frequency of meetings should be decided by the project team, and in an experimental way, according to the needs and complexity of the project.

Summarising, the model to overlap the design and construction stages relies on anticipating decisions, negotiations, uncertainties removals, and coordination, and tries to increase the structural complexity (number of model components/details and people involved) to fix design at the decoupling point. Herein, the pull flow can be deployed.

7.4 THEORETICAL CONTRIBUTIONS

This research has five major contributions for knowledge to address the integration of overlapped stages of design and construction. The first one was brought by the model. It structures the new product development process relating it with the managerial activities of a production system (design, operate and improve) (Koskela & Ballard, 2003) to be applied in the project, design and construction level. A set of actions and decisions was prescribed at each project stage based on the literature review and studies. Therefore, the lean tools were contextualised into the NPD stages and management activities, and used for integration purposes.

A second contribution regards the use of location-based scheduling tools to pull production, reduce the production batch size, the WIP and align the production sequence in the D-C interface. The LBS tools are the LOB, flowline and the takt-time planning. Each one of them has different potentials of use depending on the level of uncertainty and collaboration. The LOB should be used in the CSD to structure the work, the location breakdown structure, define workflow, construction sequence and production batches. In the CSO, the LOB should be used as a Master Plan and be the basis for the lookahead planning. The LOB does not require a high level of collaboration from subcontractors due to the fact that it contains buffers to absorb the uncertainty and variability.

Although the flowline was not applied in the studies of this thesis, it is assumed the same benefits as the LOB due to their similarities. However, the TTP showed some limitations when dealing with uncertainty in the CSD. In case study 4, TTP was conceived without the participation of the key contractors, which caused a lot of disruption during the tasks execution. In case study 6, the TTP was devised at the CSO, in the Phase Planning. The tool works better at this level of planning due to the close collaboration of the main construction stakeholders.

The development of this research also contributed to articulate the production planning and control to integrate decisions and information between participants at the interface D-C. The plans are connected vertically and horizontally. In each phase of design and construction, the hierarchy of plans (strategical, tactical and operational) provide information from the upstream plan to the downstream and feedback in the opposite direction. The horizontal integration between the phases D-C occurs at the strategical levels, properly from the construction master plan reversely towards the design master plan. The updates for confirmation of production occurs at the tactical levels, which receive updates from the operational plans in their respective stages. Figure 164 demonstrates the vertical and horizontal connections between hierarchical plans in the D-C interface. This contribution suggests an integrated use of the LPS (Ballard, 2000a) to plan and control the overlapped stages of design and construction. It also expands the collaborative planning model of Bolviken et al. (2010) to include the suppliers' planning activities.

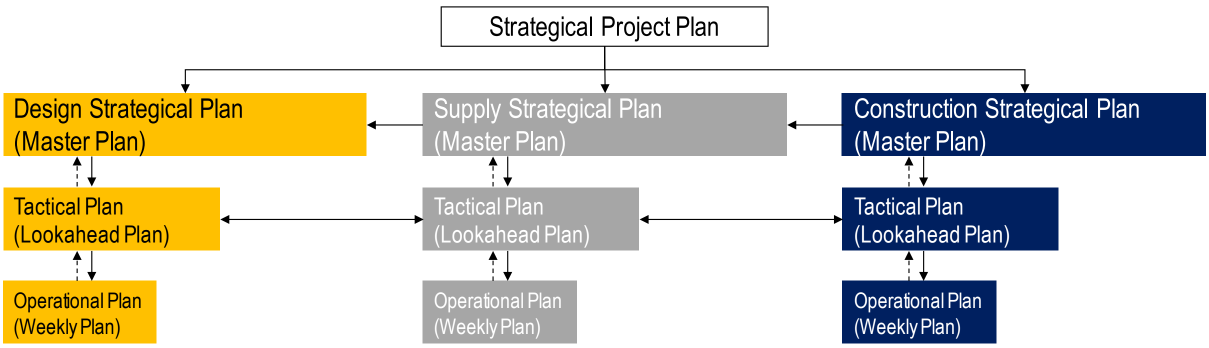


Figure 164: Vertical and horizontal connections between construction, supply and design plans.

Through the combination of these contributions, the model brings a new perspective to the overlap design and construction stages: breaking down the activities based on location breakdown structures of construction master plan, and then applying pull flow towards design. In order to control the project system, the collaborative planning must be connected vertically and horizontally. This way, the project system supports the integration of information, the application of JIT, and collaboration between stakeholders.

8 CONCLUSION

This research addressed the problem of managing construction projects with overlap between the design and construction stages adopting lean thinking as a more complete paradigm for production. The TFV theory (Koskela, 2000) is the conceptual basis of this research to understand the complexity of transformation activities, the necessary and hidden flows behind the tasks and their impacts on the value generation.

The literature review has brought together a wide range of concepts and tools to be deployed in construction projects in order to promote shared understanding, collaboration, stabilise production, implement BIM, increase transparency, reduce wastes, increase value, compress projects lead time, improve quality, and so on. Lean thinking is the background of this thesis as it addresses all these issues in the AEC industry.

Moreover, the literature review presented research related to the overlap-dependent activities as a means of shortening the duration of projects. These studies addressed the overlap of design and construction activities in a variety of forms: considering rework at the downstream activity (Bogus et al., 2011; Hossain & Chua, 2014; Lee, Hsu, Chuang, & Yang, 2008), using simulation (Bogus et al., 2011), and assessing the pace of evolution and sensitivity of dependent activities (Blacud et al., 2009; Krishnan et al., 1997).

These studies limited their analysis of the problem at a theoretical level of discussion, and applied only a conventional view of production model, i.e. production as a conversion of inputs into outputs after a conversion process. The use of the traditional approach for project management limited also the understanding of flows and the whole complexity around the dependent tasks. Moreover, the researches that tackled the overlapped activities were mainly exclusive for the planning process, and contributed poorly for the operation of these plans.

This began when the researcher was working as a lean consultant implementing production system design, last planner systems and location-based planning tools in AEC companies and projects. One recurrent problem realised was the lack of integration between design and construction. As the researcher was adopting the line of balance in her projects across many clients, she decided to experiment to pull all the production chain based on how the construction was planned, namely by location. A series of attempts was conducted in practice and these attempts became the retrospective practitioner studies 1, 2 and 3 of this thesis.

Then, the researcher sought the literature works that applied pull planning between design and construction. Some works focused on the interface of manufacture-construction (Sivaraman & Varghese, 2016; Viana, 2015), or design-construction interface (Bolviken et al., 2010; Holm, 2014; Kiiras & Kruus, 2005; Tiwari & Sarathy, 2012). However, the focus of these works is not the overlap, but the integration of the production planning and control in the interface design-production.

To promote the overlap it was necessary to understand the whole product development process, in which, at the strategic level, the procurement route that facilitates or not the overlapping between design and construction is frequently determined. Furthermore, it was also necessary to comprehend the design management and adapt it for the pull production. Two references of the literature review were observed in practice in case studies 4 and 6 of the thesis, and both deployed location-based planning tools to pull design production.

Considering the practical problem and the necessity to design a solution for it, the research approach for the thesis was the Design Science Research (DSR). The chosen method addresses better the purpose of designing a solution for a real problem while, at the same time, it contributes to theoretical knowledge. Six studies were carried out to create a final version of a model through a cycle of learning, evaluating and improving. The variety of studies and their contexts made the model richer in process and tools. The first study with overlap between design and construction was the project of an aquarium facility. The second study described the integration of the construction plan with the customisation of residential units within the construction company E. The last study presented a lean office implementation in the construction company E, in which the design process was responsible for connecting all the company's areas. Case study 4 brought the focus on design management through the concept of takt-time and BIM freezing models, while case study 6 clarified adaptations in the last planner system for design. The opportunity to implement part of the model in a construction project jointly with its employees occurred in action research study 5, which enabled the partial field test of the artefact and its evaluation.

The model reunites the best lean practices to manage AEC projects described in the literature review, which were somewhat disconnected or not related to the context of overlapping design and construction stages. Plus, the learning emerged from the reflections of the studies.

In this sense, the model fills the theoretical gap regarding how to integrate the overlapped stages of design and construction through their production management using location-based planning tools and lean thinking of pull production. Moreover, the other objectives of the thesis were achieved, as described below:

(i) Determine how to use location-based scheduling tools to structure the work for design, supply and construction

The studies demonstrated the use of location-based scheduling tools to structure the integrated planning and control system for the interface D-C. The LBS tool used in the construction planning (Master or Phase Plan) supports the pull flow in the D-C interface, the reduction of the production batch size, the reduction of WIP, and facilitates the detailing of plans. Devising an LBS tool involves a series of decisions related to the Construction System Design. The LBS tools also increase the plan's transparency, enabling negotiation between participants in the CSD. It aligns the production sequence between manufacturers and builders, and between manufacturers and designers. It also enables the pull flow from construction towards the interdisciplinary design production stage.

The use of LBS in the D-C interface allowed the implementation of the just-in-time concept (Ohno & Mito, 1988) in overlap context. It also added the design management as part of the construction management as pointed out by Kiiras and Kruus (2005).

(ii) Find out how to assemble design packages to meet suppliers' and builders' requirements

The thesis also answered how to assemble design packages to meet suppliers' and builders' requirements. The studies provided different solutions to it. The design package changes according to the identified necessity of the downstream dependent activity. For instance, design should be delivered to different stakeholders, such as public permissions, procurement (foundations, structure, façade, and other construction phases), construction tasks, customisation options, and so on. The intention of applying the pull flow and collaborative meetings is for participants to proactively specify the content and the level of detail of information inside the design packages needed. The design deliverables might be pulled by the kanban cards, as described by Tiwari and Sarathy (2012), but also in the lookahead meetings when removing constraints.

(iii) Determine the decoupling point of design development in order to apply pull production

The moment when the pull flow can be applied was called a decoupling point. In the design development, it marks the interface between the transdisciplinary and the interdisciplinary production. The decoupling point also represents the decrease of uncertainty and negotiation around the design solution. To achieve the decoupling point, the design requires the elimination of clashes among the design disciplines and construction feedback. It symbolises the interface push-pull production flow, and, for this reason, the design should be highly developed for further detailing. The production batch size after the decoupling point should follow the one required by the downstream activity.

(iv) Identify and analyse pros and cons of existing types of pull production systems that suit better the context of overlapped projects

The pull flow system proposed in this research involves the connection between different levels of planning and control in the D-C interface. In the studies, the production system that prevailed was the mix of push and pull flows using CONWIP. To design the production systems in the interface D-C, the data from the construction master plan devised in the location-based tool is pulled to design the supply and design systems. The reverse plans contain a constant number of WIP that should be controlled based on the lower levels of planning, such as the lookahead planning. The medium-term plans in the interface D-C are connected to update upstream production according to downstream requirements.

(v) Explore how to measure and manage the work in progress and buffers in an integrated project system

An aligned production system using location-based planning tools facilitates the measurement of WIP in the plans and between the plans. WIP is understood as the amount of days a particular production batch is waiting to be processed. Although none of the studies measured the WIP in practice, some of them used spreadsheets in which its measurement could have been done easily, as in case study 6. Similar to the WIP, the buffers are presented in the project system. It should be estimated according to the level of uncertainty at the moment of planning. Higher uncertainty regarding the constraints of a particular activity deserve a large amount of buffer. Production capacity buffers are also desirable at more strategical levels of planning.

(vi) Identify the best tools to control the production system in the interface design-construction

To support the smooth functioning of the integrated D-C system, a set of tools and process were identified in the studies. The collaboration of designers, suppliers and builders can be promoted through their early involvement in the project to make jointly informed decisions. The project process map was identified as a first tool to promote transparency and shared understanding among participants. Moreover, other tools and process are suggested, such as: a project organisational chart to clarify the authorities and power of decision; the BIM Plan; the location-based planning tools; the collaborative planning with the Last Planner System; the weekly structured meetings; the A3; the *kaizen* meetings; the supply system; freezing BIM models, and others.

8.1 PRACTICAL CONTRIBUTION

The final model of this thesis might support future project teams to improve the workflow and constructability of projects with overlap between design and construction. Although the focus of this thesis is on overlapping, the findings did not support any definition of degree or percentage of overlapping between the phases. On the contrary, the findings proved that the information produced and required must be planned and controlled collaboratively between those involved in the interface design-construction in order to avoid rework.

The whole AEC industry will benefit from the use of the model in projects with overlap between design and construction stages. The model bring a set of lean tools and processes that support the integration of decision-making regarding the production management in D-C interface.

8.2 THEORETICAL CONTRIBUTION

The main contribution to knowledge of this work is the presentation of a new perspective to overlap design and construction activities. Instead of exploring in planning the degree of overlap between design and construction activities, this thesis analysed the use of a set of lean practices organised to not only plan, but also operate, a production system where the design and construction is overlapped. The model articulates the new product development process with the managerial activities to design, operate and improve the activities in the interface D-C. Plus, it assures the use of location-based tools to reduce the production batch size in all stages of the NPD, and pull the production.

8.3 RESEARCH LIMITATIONS

The thesis had some limitations that were mitigated or require future research to be addressed. Because the thesis brings a lean perspective to overlap design and construction, it does not focus on the degree of overlapping between dependent activities. Its context is the intersection between developed and detailed design stages with construction. It implies organising the project production system that enables the “conversation” between downstream and upstream dependent activities. The focus of the thesis is to use the production planning and control system in combination with a series of lean practices to produce the right information, at the right time, to be delivered to the right stakeholder. For this reason, the final model does not represent the context of flash-tracking projects (80% of overlap D-C).

A second limitation relates to the data collection process in the studies. Namely, the retrospective studies imposed a challenge to recover data. The data of the studies were produced a few years before the writing of the thesis and for different purposes. To deal with this limitation, the research interviewed one of the managers from company C to remind them of the context of the studies, and provide more documents.

Case studies 4 and 6 had the barrier of the language and short time to collect data. To overcome this, the researcher produced reports of her understanding and sent these back to the participants in the case studies for revision. They revised the translation of terms from Norwegian to English, corrected errors in dates, but also added extra information that was not collected in the one-week period.

A limitation in action research study 5 was the extension of the model implementation. Due to the lack of designers' participation in the study, only a small part of the model was field tested. Plus, the project was put on hold by the client, which has affected the model evaluation.

Although all the studies had some sort of limitations, they were overcome thanks to the research method adopted. The DSR was opportunistic regarding the availability of studies. The combination of retrospective practitioner studies, with case studies and action research study in different time scales, countries, contexts, and procurement routes, maximised the model development during the course of the three years of the PhD. Instead of emerging in only one action research study, the final version of the model was built based on the practices of six studies in different stages of the NPD. The limitation has turned into an opportunity to fully implement the model and test it.

The practices prescribed in the model, such as the stage-gate, CBA, DSM, agile, and so on, require more research to be detailed and understood for the context of overlapping design and construction activities.

8.4 FUTURE RESEARCH

This thesis was the first attempt to integrate the planning and control activities in projects with overlap between design and construction stages. Although it contributes to knowledge, the literature review and the studies here presented opened more research questions which could not be tackled in this work. Therefore, the opportunities raised for future research are as follows:

- Implement all the stages of the model in one project for further refinements. As one limitation of the research, the short duration of the PhD did not enable the researcher to find a new project at the early stages of development to implement the whole model. Field-testing the model in different contexts of the project is also an opportunity to refine it for distinct purposes.
- Explore in detail how to assemble design packages. Through the studies, different forms to assemble design packages were identified. It needs to be investigated what influences this

process: if it is the structural characteristic of the buildings, complexity of supply chain, procurement route, and so on.

- The Design Structure Matrix (DSM) is a well-established tool deployed in design. However, its combined use with construction activities is still a gap in the literature review. Is it possible to use DSM to define an optimal design and construction sequence for overlap their activities?
- Explore the Stage-Gate and Agile methods for the context of overlapping stages. Even though the model of this thesis highlights the use of both methods, it does not go into any depth to explain their use in order to organise and coordinate the work in the interface D-C.
- Extend the use of Choosing by Advantage (CBA) considering construction organisation alternatives with design alternatives. The CBA is usually applied in the design stages to support decision-making of design solution alternatives for the project. However, the tabulation method does not include information from downstream activities, such as the design impact on construction.
- Explore similarities and differences between Agile Design Management and Last Planner System (LPS) for design to apply them in different project contexts. To achieve a successful design management, the implementation of the LPS requires a series of adaptations. Some of these adaptations is a requirement to become more agile regarding attending downstream needs. On the other hand, the agile design management provides some features that could be adapted into the LPS. Both methods deserve a more detailed study to understand the elements of agility in the management and the right context to implement them.
- Study the level of development of BIM models and the workflow to improve integration of the planning and control systems of design and construction activities. This investigation is connected to the design packages in terms of understanding what information is needed, at which level of detail and when. For this reason, the LOD of BIM models should also be integrated into the design planning and control based on downstream demands.

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APPENDICES

Appendix 1

Construction Master Plans in Aquarium Project, RPS1.

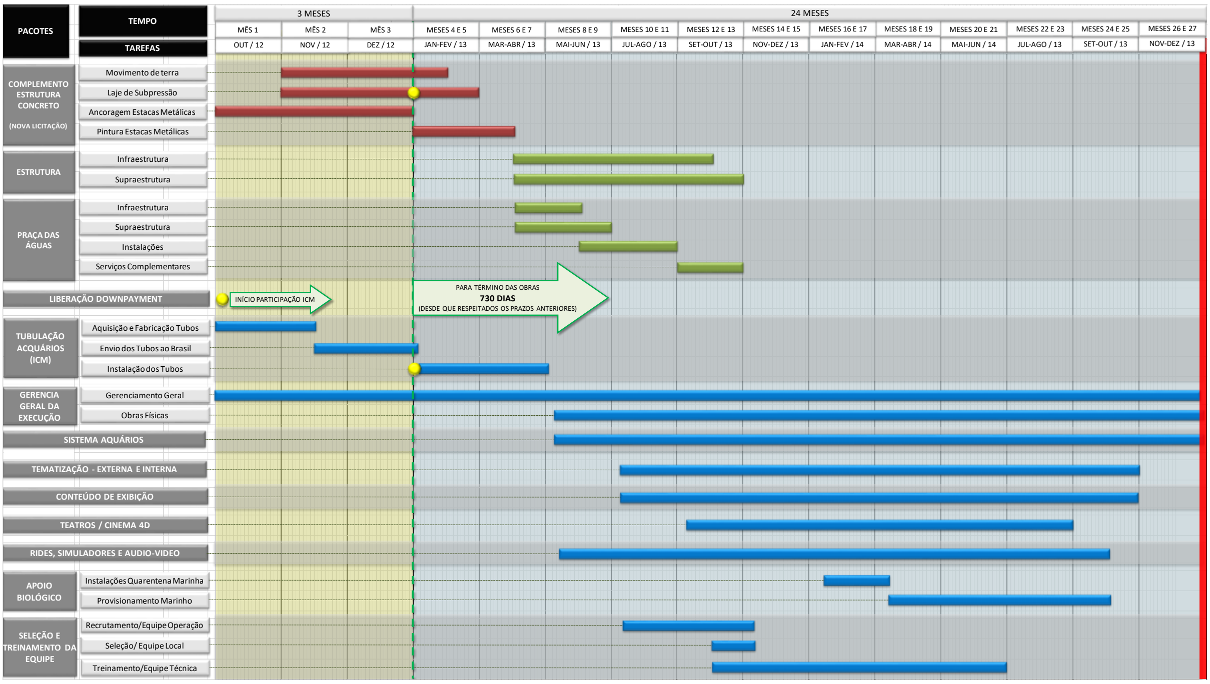


Figure 165: Construction master plan developed by Company C.

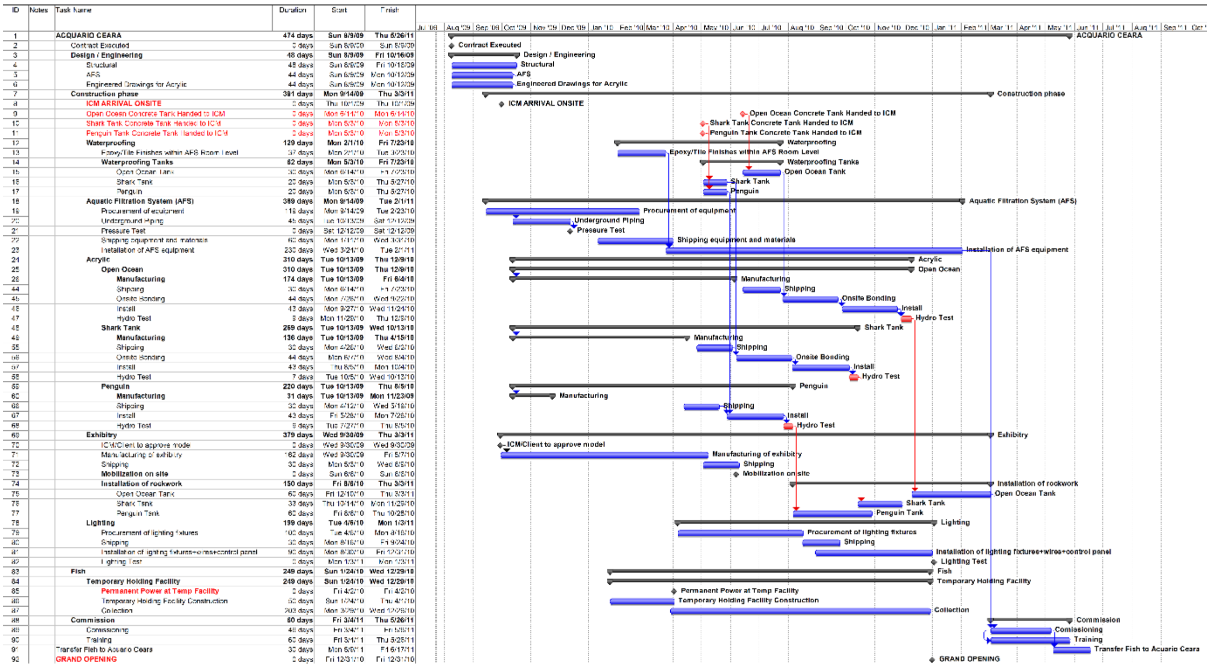


Figure 166: Construction Master Plan prepared by Company B.

Specific Work Packages Sequence in Aquarium Project, RPS1.

Figure 167: Work packages sequences in specific batches. Source: Company C.

General Work Packages Sequence in Aquarium Project, RPS1.

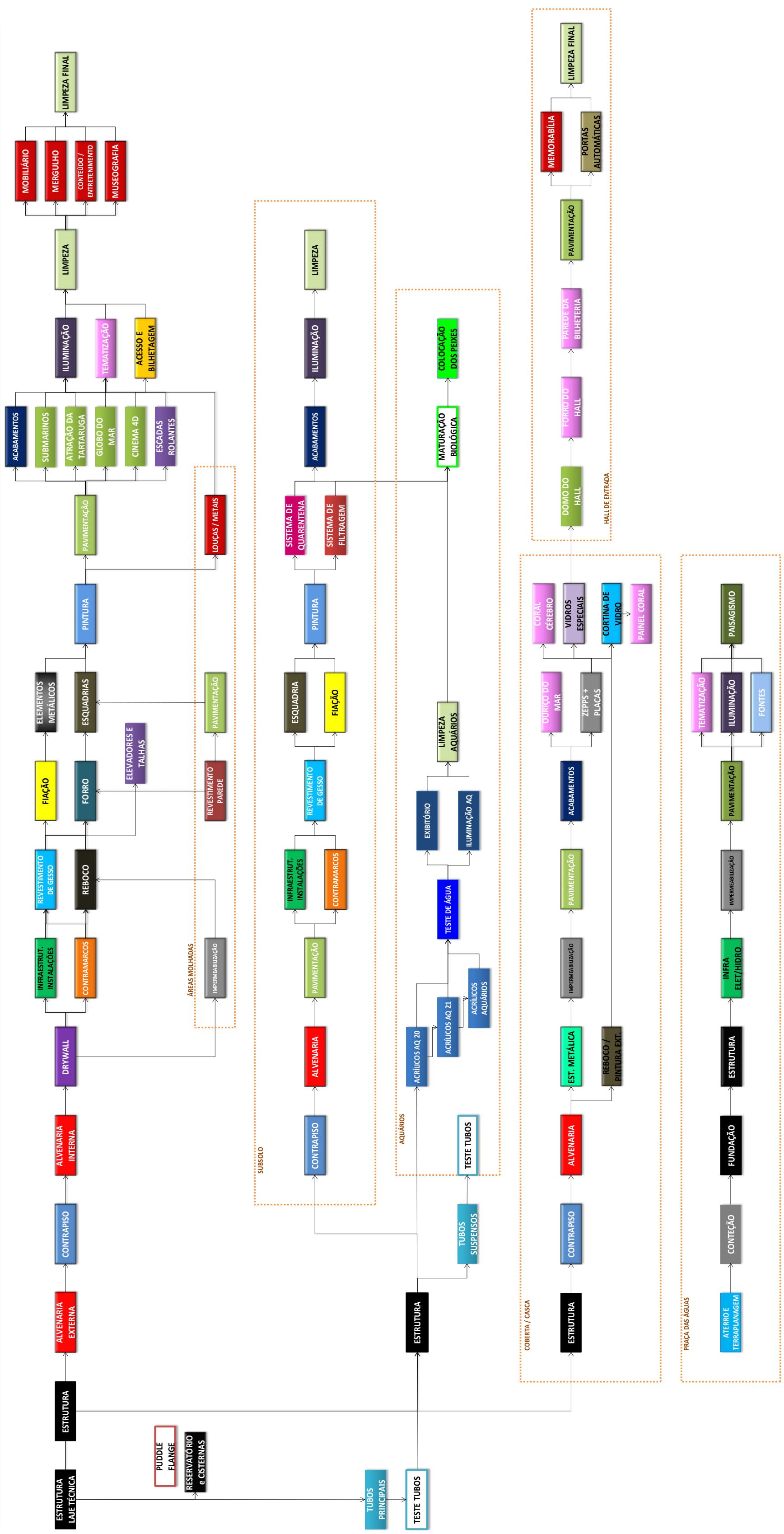


Figure 168: General work packages sequence net. Source: Company C.

Tactical plan for architectural designers in Aquarium Project, RPS1.

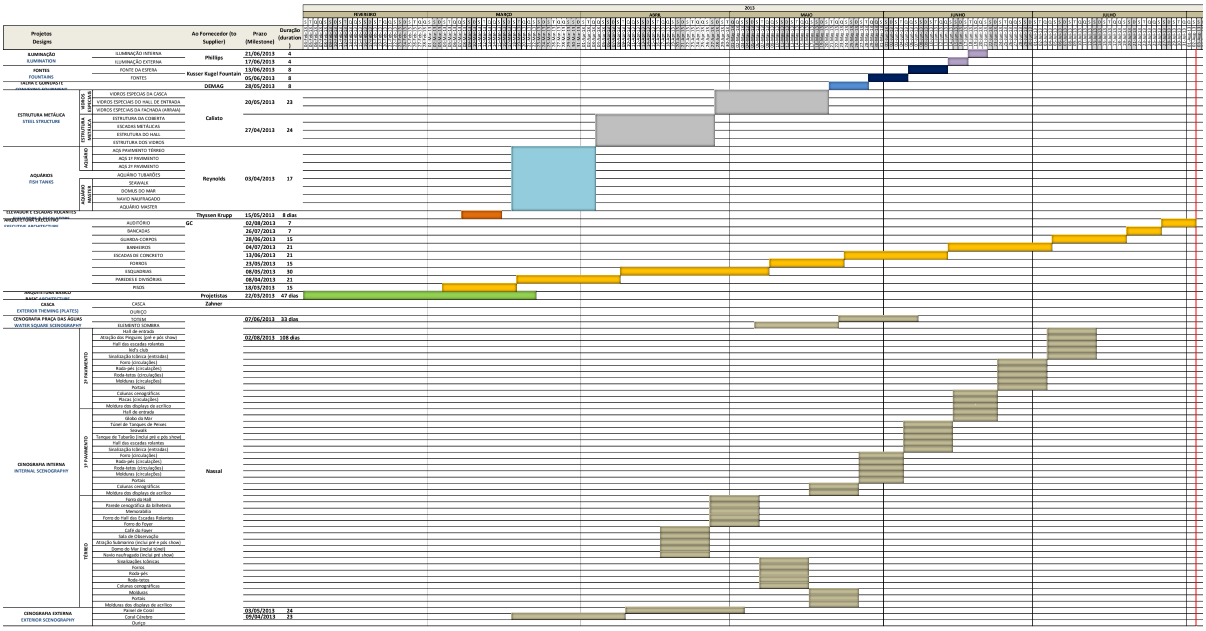


Figure 169: Tactical plan for architectural designers. Source: Company C.

Appendix 2

Future-State Value Stream Map for the residential units customisation in RPS2.

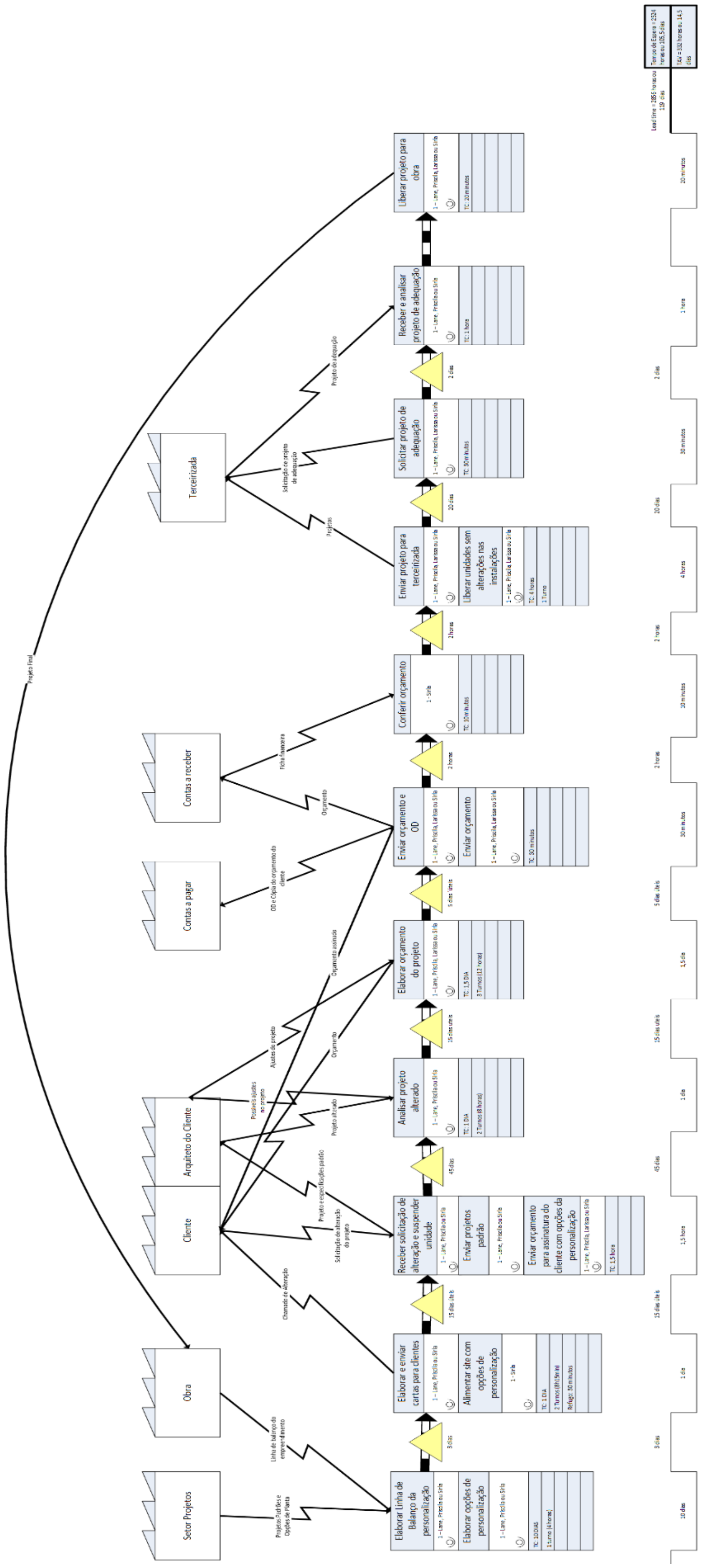


Figure 170: VSM of the new processes for the residential units customisation department. Source: Company C.

Dashboard of residential customisation units of a project in RPS2.

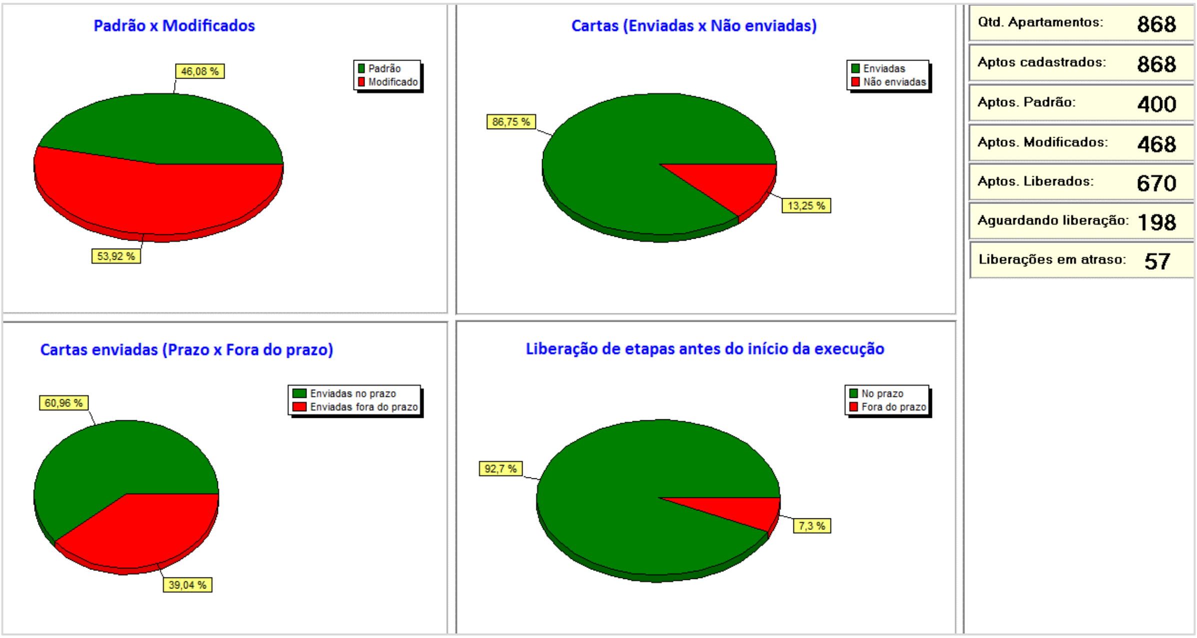


Figure 171: Dashboard of residential customisation units of a project. Source: Construction Company E.

Appendix 3

Flowchart of the design management process in RPS3.

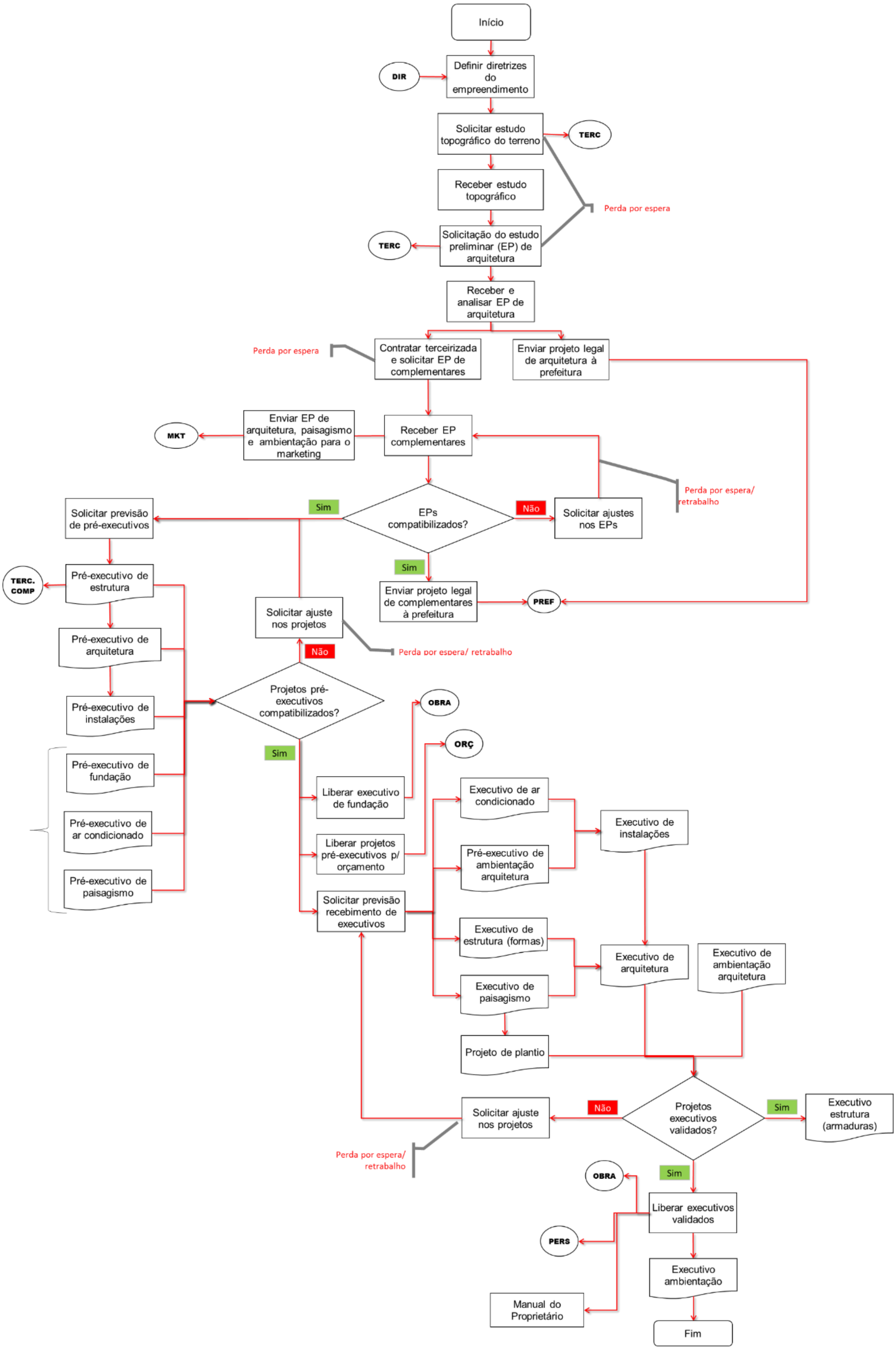


Figure 172: Flowchart of the design management process. Source: Company C.

Data flow diagram (DFD) of the design management process in RPS3.

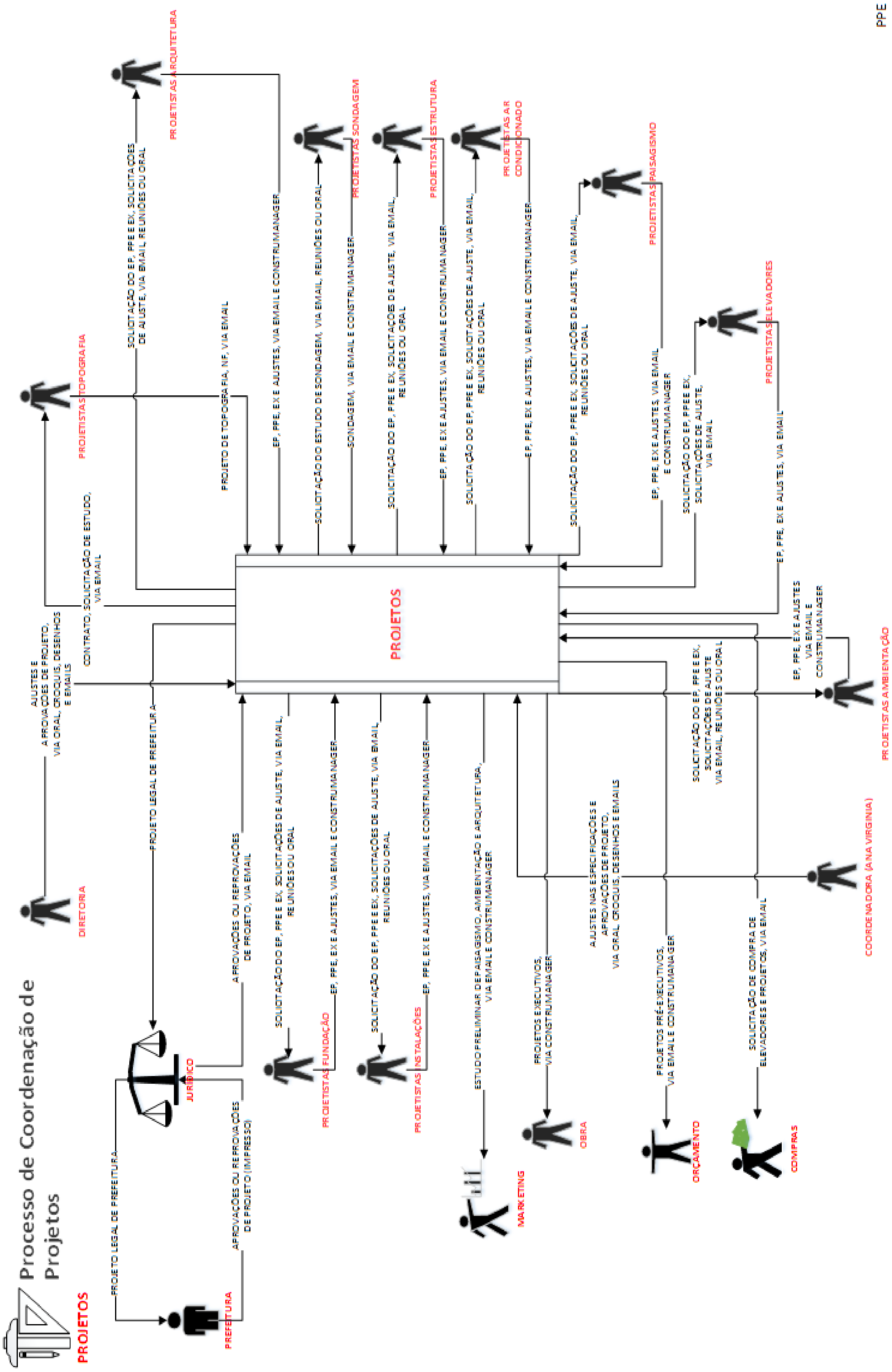
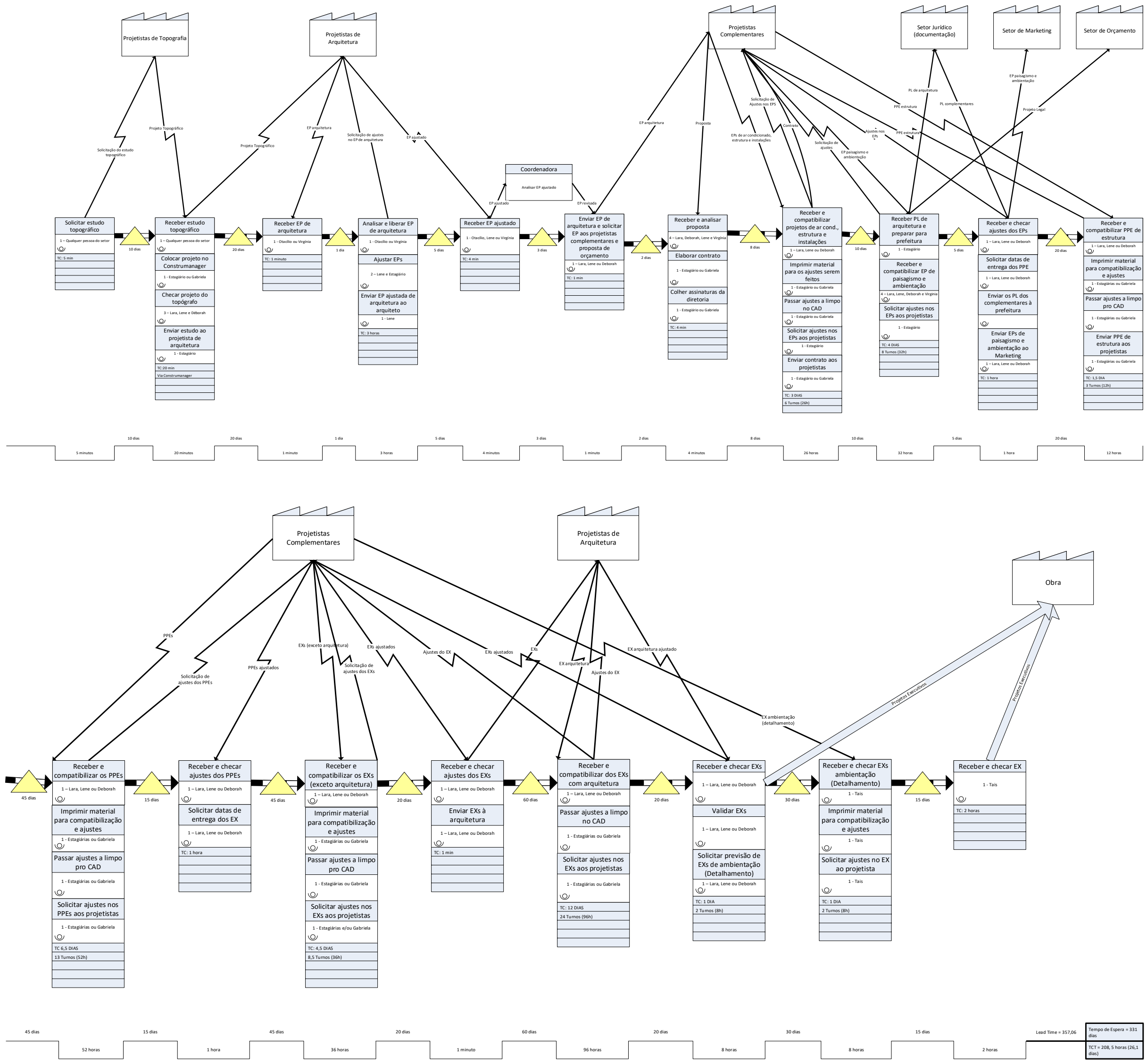


Figure 173: Data flow diagram (DFD) of the design management process. Source: Company C.

Current-sate VSM of design management in RPS3.



VSM Current-State	***Lead Time***	***Waiting***	***Value Adding Time***	***% Value Adding***
	357 days	331 days	26 days	7.3%

Figure 174: Current-sate VSM of design management. Source: Company C.

Appendix 4

Model evaluation questionnaire:

1. Do you think the practice of overlapping between design and construction stages is beneficial for projects' performance?

Of course - this is not something you need to prove. Rather, what do you expect people to do when they overlap? What processes do they manage? What is the nature of the work that happens in that overlap? In the Boston area, the primary contractual delivery methods are Design-Bid-Build (supposed to be no overlap), Design-Build (architect and contractor operate as a single entity), and CM-at-Risk (in which the contractor gets involved more in providing feedback during design development, and they will negotiate with the client a Guaranteed Maximum Price once the design has reached a "100% Construction Documents" stage). In a traditional project delivery environment using any of the three contractual delivery methods that I have just mentioned, it is common practice to use "Value Engineering" because the design is revealed to be too expensive to build. I argue that "Value Engineering" often results in scope removal, and this ultimately leads to Owners having decision regrets which lead to very expensive changes in project direction after fabrication and installation has begun.

2. What do you think about adopting the Stages of product development proposed by the architects' institutions, such as AIA and RIBA?

SD, DD, and CD (Schematic Design, Design Development, and Construction Documents) as currently practiced results in large batch passing of design information… design specialists are silo'ed in their work, and we have difficulty in allowing fabrication and job site construction to begin due to lack of design direction. This is why we are trying to use different lean tools and techniques to allow for smaller batches/handoffs of design information to pass on so key long lead time items can begin fabrication and job site installation.

4. What is your opinion about Stage-Gate to manage design? Is it a good practice to control negative design interactions?

An architect friend of mine is on the co-location IPD team at the Boston Medical Center project - a difficult renovation project. She noted that they use the term "lock", which to me is identical in concept to stage-gates. They would declare to the project team, "OK - now we are going to lock the structural grid" - this is a key moment in design development because if the structural grid still moves, we cannot allow any fabrication to proceed. Use of the term "lock" or "stage-gates" is fine, but what is more important is, as a facilitator, have we been able to get the project team to agree that after a "lock" or a "stage-gate" - are we truly committed to not having a decision regret and try to change our minds later? As a result, if you propose to use this mechanism, I recommend that one of the Project Conditions of Satisfaction should be "Adherence and respect of the design locks / stage-gates - once key design decisions are made, the project team will move on to ensure successful project outcomes with those decisions kept in place."

5. Agile can also be used in design management. What is your opinion on this method?

There is a time and place for agility - conceptually, agility implies that we “roll with the punches” - with each problem that emerges, we have an agile production management system that can handles these changes/wicked problems, but we stay on course for the Project’s Conditions of Satisfaction. I would believe that agile can be misused if an Owner claims that they have decided to change their mind later re. design direction, and they are violating the Project’s Conditions of Satisfaction, but they claim that the Architect/Engineer and General Contractor needs to be agile/flexible and accommodate that change even if it violates the original agreement.

6. What is your opinion about the Last Planner System (LPS) in the design stage?

Using LPS in design is much more challenging that construction because we are talking about how we manage intangible objects (e.g. a material selection, a ceiling height, a window size, etc.). We should use LPS to identify long lead items and this will help us determine when key design decisions need to be made. Then, we can use a combination of:

- Project Conditions of Satisfaction (to determine key project goals)
- Target Value Design (to determine in great detail the budget and where we are spending the project's budget)
- Set-Based Design (to consider ranges and combinations of design alternatives)
- Choosing by Advantages (to narrow the design set and ultimately get design direction)

within the LPS framework, to manage the design process well. This challenges Architect/Engineer + Construction teams to synthesise key information that the Owner needs to give design direction. Also, I have learnt from a local architect that they find using swim lanes while pull planning is helping to keep track of the handoffs. The swim lanes provide a helpful structure to track the design specialists and regulatory agencies that need to be involved in providing design direction.

7. I suggested a production system design of projects with overlap where the construction system design starts with the design still in early stage of detail. What is your opinion about it?

My company does this all the time, but it is a hard process to manage if we are not aligned with the Owner and Architect. This is why I use the tools I listed above (CoS, TVD, SBD, and CBA) to help my project teams improve their efforts on project team alignment.

8. The use of line of balance and flowline is suggested in place to the Takt-time planning because the former are more flexible to low levels of plan detail. Do you have any opinion about TTP used in the construction system design?

Yes, project teams have used TTP in the past, but it requires discipline on the part of the general contractor + trade partners to be committed to it and stick with it to be successful.

9. The supply and design plans are reverse plans based on construction line of balance/flowline/TTP. Do you suggest any action to include contractors and designers in the planning?

Of course.

10. In location-based tools, how do you count the WIP?

Depends on what you mean by WIP. Material WIP can be observed on-site, but it's a challenge for contractors to understand how to make it explicit, or how much WIP exists and the transformation process from raw materials into final installed work.

Appendix 5

Workshops Evaluation Sheets used in ARS5.

ART
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Lean Construction Implementation Course

Module 1: Lean Thinking, Wastes, Production System Design and Line of Balance

Lecturer:
Organiser: Clarissa Biotto and

Date: 14/09/2017
Attendees: 13
Evaluation fullfillec 13

Module Average	%
4.49	90%

		Bad 1	Deficient 2	Regular 3	Good 4	Great 5	TOTAL	%
1.	**Participant**						**4.38**	**88%**
1.1	Punctuality		1		6	6	4.31	86%
1.2	Participation in the course			1	7	5	4.31	86%
1.3	New topics presentation				6	7	4.54	91%
2.	**Facilities**						**4.62**	**92%**
2.1	The classroom was appropriate for the course				4	9	4.69	94%
2.2	Information technology equipment, chair and tables				6	7	4.54	91%
3.	**Course**						**4.46**	**89%**
3.1	Relevance of the content of classes with the course objectives				4	9	4.69	94%
3.2	Contribution of the course for your work			1	8	4	4.23	85%
4.	**Lecturer**						**4.51**	**90%**
4.1	Knowledge about the topic				4	9	4.69	94%
4.2	Quality of material				8	5	4.38	88%
4.3	Communication hability			1	5	7	4.46	89%
4.4	Class plan and method				7	6	4.46	89%
4.5	Punctuality				6	7	4.54	91%

General Observations

Intersting slides and lecturer;
Very good engaging;
Excelent and well presented course.

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Lean Construction Implementation Course

Module 2: Production Planning and Control, Production System Improvements

Lecturer:
Organiser: Clarissa Biotto and

Date: 12/10/2017
Attendees: 12
Evaluation fullfillec 10

Module Average	%
4.48	90%

		Bad 1	Deficient 2	Regular 3	Good 4	Great 5	TOTAL	%
1.	**Participant**						**4.43**	**89%**
1.1	Punctuality			1	2	7	4.60	92%
1.2	Participation in the course				2	7	4.30	86%
1.3	New topics presentation				6	4	4.40	88%
2.	**Facilities**						**4.30**	**86%**
2.1	The classroom was appropriate for the course			4	1	5	4.10	82%
2.2	Information technology equipment, chair and tables			2	1	7	4.50	90%
3.	**Course**						**4.45**	**89%**
3.1	Relevance of the content of classes with the course objectives				4	6	4.60	92%
3.2	Contribution of the course for your work			1	5	4	4.30	86%
4.	**Lecturer**						**4.74**	**95%**
4.1	Knowledge about the topic				1	9	4.90	98%
4.2	Quality of material				3	7	4.70	94%
4.3	Communication hability				4	6	4.60	92%
4.4	Class plan and method				4	6	4.60	92%
4.5	Punctuality				1	9	4.90	98%

General Observations
Great Module, well Deliveried. Sergio explained the Module content clearly with the use of relevant examples to aid understanding. Good group activities. Room to warm. / Room to hot and chairs unconfortable. / Classroom too warm.

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Lean Construction Implementation Course

Module 3: Visual Management, 5S and SMED

Lecturer:
Organiser: Clarissa Biotto and

Date: 16/11/2017
Attendees: 10
Evaluation fullfillec 8

Module Average	%
4.42	88%

		Bad 1	Deficient 2	Regular 3	Good 4	Great 5	TOTAL	%
1.	**Participant**						**4.13**	**83%**
1.1	Punctuality				5	3	4.38	88%
1.2	Participation in the course			2	4	2	4.00	80%
1.3	New topics presentation			3	2	3	4.00	80%
2.	**Facilities**						**4.63**	**93%**
2.1	The classroom was appropriate for the course			1	2	5	4.50	90%
2.2	Information technology equipment, chair and tables				2	6	4.75	95%
3.	**Course**						**4.31**	**86%**
3.1	Relevance of the content of classes with the course objectives				4	4	4.50	90%
3.2	Contribution of the course for your work			1	5	2	4.13	83%
4.	**Lecturer**						**4.60**	**92%**
4.1	Knowledge about the topic					8	5.00	100%
4.2	Quality of material				4	4	4.50	90%
4.3	Communication hability			1	4	3	4.25	85%
4.4	Class plan and method				4	4	4.50	90%
4.5	Punctuality				2	6	4.75	95%

General Observations
Very good. Intersting course - Thanks.

Appendix 6

Questions used for the model evaluation through focus group interview:

1. Do you think the practice of overlapping between design and construction stages is beneficial for projects' performance?
2. What do you think about adopting the Stages of product development proposed by the architects' institutions, such as AIA and RIBA?
3. How could you suggest the creation of design stages for projects?
4. What is your opinion about Stage-Gate to manage design? Is it a good practice to control negative design interactions?
5. Agile can also be used in design management. What is your opinion on this method?
6. What do you think about Takt-time planning for design?
7. What is your opinion about the Last Planner System (LPS) in the design stage?
8. I suggested a production system design of projects with overlap where the construction system design starts with the design still in early stage of detail. What is your opinion about it?
9. The use of line of balance and flowline is suggested in place of the Takt-time planning because of the former are more flexible in low levels of plan detail. Do you have any opinion about TTP used in the construction system design?
10. The supply and design plans are reverse plans based on construction line of balance/flowline/TTP. Do you suggest any action to include contractors and designers in the planning?
11. Do you think it is possible to develop a design based on building areas?
12. What are the implications of freezing main structures of design?
13. How do you think the client/user could participate and help the project develop?
14. The line of balance/flowline/TTP from construction, supply and design are pushing the work to be done to the Last Planner System. However, one of the inputs in the LPS for supply and design is the construction information. This latter can change the sequence of production and activities duration of suppliers' and designers' production in order to attend construction demand. What is your opinion about this connection between LPS for construction and design?

Appendix 7

Model Implementation Guide

To start using the model, at the beginning of the project, the Owner or the Project Consultant should have in mind that decisions need to be made considering the whole project system. This means that one decision will interfere and influence other decisions in the design and construction systems. There are in the model four major management activities regarding the product development process.1. The project management overview; 2. The design management; 3. The construction management; and 4. The pull production system.

If the Project Consultant has lean knowledge it will be necessary to prepare a set of trainings for the future stakeholders. Otherwise, the Owner can hire a Lean Consultant company to carry on with the trainings. Different topics are necessary for different stakeholders. However, the project management and the pull planning are required for all the stakeholders involved in the design and construction phases.

Topics suggested for the implementation of the model and the following exercise to be conducted by the participants are presented in table below.

Management areas	Topics for training	Collaborative Exercise	Participants
1. **Project Management**	New Product Development Process; Models of NPD, Lean Product Development Process; NPD in Construction; Overlap between design and construction	Plan the whole project: define phases, gates, people, documents, deadlines.	Owner, Project Consultant, Design Manager, Design Leaders, Construction Manager, Contractors Leaders, Project Manager
2. **Design Management**	Lean Design Management Concepts; Lean Design Tools, such as LPS, Agile Design, DSM, TVD; BIM	Plan the design phase: define the stages of design, the gates, people, ICT, LOD, production sequence, dependencies (it is recommended to use), capture client's requirements.	Owner, Project Consultant, Design Manager, Design Leaders, Project Manager
3. **Construction Management**	Lean Construction Management Concepts; Lean Construction Tools such as LBS (LOB), LPS; BIM for Production	Plan the construction phase using a LBS tool, such as LOB.	Owner, Project Consultant, Construction Manager, Contractors Leaders, Project Manager
4. **Pull Production System**	Toyota House Concepts: JIT, Jidoka, Kaizen, Batch Size, Takt-time, etc.. Reverse Planning using LBS.	Apply the Pull Production Concept in all the plans developed by construction and design, including the supply interface. Review the batch size to align it among the detailed design plan, supply plan and construction plan.	Owner, Project Consultant, Design Manager, Design Leaders, Construction Manager, Contractors Leaders, Project Manager

After training, the project team should start the production planning and control activities. Collaborative meetings should occur every week to plan design and construction tasks. The distribution of the information from these planning should occurs weekly as well in order to keep the stakeholders aware of changes. The lookahead planning should be adapted to project changes. Improvements should emerge and implemented continuously throughout the NPD.