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Integrated Production Planning and Control Model for Engineer-To-Order Prefabricated Building Systems

Daniela Dietz Viana

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DANIELA DIETZ VIANA

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Thesis submitted in partial satisfaction of the requirements for the degree of Doctor in Engineering awarded by the Postgraduate Program in Civil Engineering, Construction Area, of the Federal University of Rio Grande do Sul.

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Prof. Carlos Torres Formoso
Ph.D., University of Salford, United Kingdom
Supervisor

Prof. Armando Miguel Awruch
PPGEC/UFRGS Coordinator

EXAMINERS

Prof. Eduardo Luis Isatto (UFRGS)
Dr., Federal University of Rio Grande do Sul, Brazil

Prof. Iris D. Tommelein (UC Berkeley)
Ph.D., Stanford University, USA

Prof. Ricardo Augusto Cassel (UFRGS)
Ph.D., Lancaster University, United Kingdom

Ao Miguel,
por me ensinar a ver o mar

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“[..] Y fue tanta la inmensidad del mar, y tanto su fulgor, que el niño quedó mudo de hermosura. Y cuando al fin consiguió hablar, temblando, tartamudeando, pidió al padre: "¡Ayúdame a mirar!"

Eduardo Galeano

ABSTRACT

VIANA, Daniela Dietz. **Integrated production planning and control model for prefabrication and site installation.** 2015. Tese de Doutorado - Programa de Pós-Graduação em Engenharia Civil, UFRGS, Porto Alegre.

The industrialization of construction work is one of the ways it is possible to achieve better quality and productivity in this competitive environment. However, in order to improve efficiency using industrialized technologies is not enough. There is a need to improve planning and control systems. Although the Last Planner System has been developed for the construction environment, since it was devised the successful results promoted its implementation in different production environments. Regarding lean production implementations, the system has been pointed out as a starting point for a company to achieve the basic stability. This study is focused in one type of industrialized production system: the engineer-to-order. By industrialized, it is the prefabrication that has been addressed. In these kinds of production systems, there is a need to integrate the prefabrication plant with the construction site needs.

This research project aims to develop an integrated planning and control production planning and control model for ETO prefabricated systems, integrating design, manufacturing and site assembly. The research is part of a partnership with a steel fabricator company (Company A) that was interested in improving its production planning system. The research method is grounded in the design science research, in which there is an effort from the researcher to develop an artefact as an output of the research process, in this case, a planning and control model. The implementation adopted some strategies from the action-research, so some solutions needed to be collectively constructed between the researcher and the practitioners, in order to have an effective use in the organization. Following this strategy, it is possible to have same learning cycles during the implementation of the solutions, which are continually assessed and adapted in order to improve the processes analysed.

The results are divided into four phases of implementation. In the first step the main effort was in consolidating an integrated planning and control process for the short-term in the production units. In the second step the focus was the overall system, mainly providing mechanisms to collect the status of all construction sites for the plant. The barriers to improve this feedback process brought to light the need for using visual management tools. This development concerned the third step of implementation, further improving the changes made in the previous phases. The fourth step was based on the analysis of the logistics processes, as the interface between the plant and site assembly.

After the main empirical study on Company A, two studies were carried out abroad in order to understand a different context of ETO production systems. The first concerns a mechanical contractor situated in a high complex project. In this study, it was possible to develop some planning tools to facilitate the analysis between the fabrication and site installation of the products. The second concerns a steel fabricator focused on the structural system. This was a descriptive study that analysed the differentiation of the products provided by this company and the impact of it in the planning and control system.

Based on the results obtained in the implementation process, the integrated planning and control model for ETO building systems was devised. Most of the processes proposed in the model were assessed in Company A. Although there is still a need to improve the production planning and control system of that company, the implementation enhanced the communication between the operational and tactics level and also promoted a systematic way to collect information for each level of the production planning and control system.

The theoretical contributions of the research were the development of a framework to understand the complexity of this kind of production system; the identification of the main requirements for developing a planning and control system for this environment; and the adaptation of the concept of WIP using the status of the product.

Keywords: Production Planning and Control systems, Engineer-to-order, Last Planner System.

RESUMO

VIANA, Daniela Dietz. **Integrated production planning and control model for prefabrication and site installation.** 2015. Tese de Doutorado - Programa de Pós-Graduação em Engenharia Civil, UFRGS, Porto Alegre.

A industrialização da construção civil é uma das possíveis estratégias adotadas para melhorar a qualidade e produtividade da produção neste ambiente altamente competitivo. Entretanto para uma melhoria na eficiência da produção, a simples implantação de uma tecnologia industrializada não é o suficiente. Existe a necessidade de melhorar os sistemas de gestão como um todo. O sucesso da implementação de sistemas de planejamento como o *Last Planner,* desenvolvidos especialmente para a construção civil, instiga o desenvolvimento de estudos em diferentes processos produtivos. Em relação à implementação de princípios da produção enxuta, o sistema é apontado como um ponto de partida para uma empresa atingir uma estabilidade básica. Este estudo foca-se em um tipo específico de sistema de produção industrializadas chamado *engineer-to-order* (ETO), quando a requisição de produto pelo cliente é realizada na fase de projeto. Neste tipo de sistema construtivo há uma necessidade de integrar a fabricação das peças conforme as necessidades do canteiro de obras. Esta pesquisa visa a desenvolver um modelo integrado de planejamento e controle da produção de sistemas ETO pré-fabricados para construção civil, integrando o projeto, manufatura e montagem em obra. A pesquisa faz parte de uma parceria da Universidade Federal do Rio Grande do Sul com uma empresa de fabricação e montagem de estrutura (Empresa A) metálica interessada em melhorar seus processos de planejamento e controle da produção. O método de pesquisa é baseado na pesquisa construtiva, ou *design science,* em que há um esforço do pesquisador em produzir um artefato como resultado da pesquisa, que neste caso, é um modelo de planejamento e controle da produção. O processo de implementação de mudanças da empresa adotou a estratégia da pesquisa-ação, de forma que as soluções eram coletivamente acordadas com as pessoas responsáveis pela sua utilização, para garantir que a mesma se efetivasse nos procedimentos da empresa. Neste tipo de estratégia procura-se estabelecer ciclos de aprendizagem ao longo da pesquisa, em que as soluções são continuamente avaliadas e adaptadas para melhoria dos processos em análise.

Os resultados da empresa A foram divididos em quatro fases de implementação. Na primeira fase houve um esforço em consolidar uma integração nos planos de curto prazo. Na segunda fase o foco foi no sistema como um todo, promovendo mecanismos para coletar informações sobre o andamento das obras para retroalimentar a fábrica. As barreiras enfrentadas para garantir esta retroalimentação demonstraram a necessidade da utilização de outros métodos. Por isso, a terceira fase se concentrou no desenvolvimento de ferramentas de gestão visual para melhorar os processos analisados nas fases anteriores. A quarta fase do estudo foi baseada no estudo dos processos logísticos da empresa, visto que representam a interface entre fábrica e obra. Terminado o estudo na empresa A dois estudos foram conduzidos no exterior para compreender contextos distintos de sistemas de produção ETO. O primeiro (empresa B) responsável pelo sistema de climatização da edificação. A empresa realiza o projeto, fabricação e instalação dos sistemas de dutos em metal laminado, assim como o maquinário necessário para as trocas de ar. O estudo foi baseado no fornecimento do sistema para uma obra específica. Neste estudo foram desenvolvidas ferramentas de planejamento para facilitar a sincronização entre fabricação e instalação do material em obra. O segundo estudo (empresa C) foi realizado em uma empresa de estrutura metálica que desenvolveu uma conexão inovadora, facilitando seus processos produtivos. Este estudo teve caráter descritivo, analisando como a sua tecnologia facilitou o sistema de planejamento e controle da produção.

A partir dos resultados obtidos nos estudos foi possível desenvolver o modelo final de planejamento e controle da produção para sistemas ETO de pré-fabricados. A maioria dos processos propostos neste modelo foi testada na empresa A. Embora a empresa estudada ainda necessite implantar algumas melhorias no seu sistema de planejamento e controle para se adequar ao modelo proposto, as mudanças realizadas trouxeram benefícios na comunicação e sistematização das informações entre os diferentes níveis de planejamento e controle. As contribuições teóricas do trabalho foram um modelo conceitual para compreender a complexidade neste tipo de sistema de produção; a identificação dos principais requisitos para desenvolver sistemas de planejamento e controle da produção para este ambiente; e a adaptação do conceito de WIP utilizando o status dos produtos.

Palavras-chave: sistemas de planejamento e controle; *Engineer-to-order*, *Last Planner System*.

ACRONYMS

ATO – Assemble-to-Order

BOM – Bill of Materials

CII – Construction Industry Institute

CODP – Customer Order Decoupling Point

CONWIP – Constant Work-In -Progress

CPM – Critical Path Method

ERP –Enterprise Resource Planning

ETO – Engineer-to-Order

FIFO – First In First Out

FILO – First In Last Out

FTO – Fabricate-to-Order

HVAC – Heating, Ventilation and Air Conditioning

IGLC – International Group for Lean Construction (IGLC)

IMVP – International Motor Vehicle Program

LOB – Line of Balance

LPS – Last Planner System

LRM – Last Responsible Moment

MRP – Material Requirement Planning

MRP II – Manufacturing Resource Planning

NORIE – Building Innovation Research Unit

P2SL – Project Production Systems Laboratory

PERT – Program Evaluation and Review Technique

PFC – Project Flow Control

POLCA – Paired-cell Overlapping Loops of Cards with Authorization

PPC – Percentage of Plans Complete

PU – Production Unit

PUC – Production Unit Control

RBCs – repeat Business Customizers

TOC – Theory of constraints

TPS – Toyota Production System

UFRGS – Federal University of Rio Grande do Sul

VMCs – Versatile Manufacturing Companies

WIP – Work-In -Progress

WLC – Workload Control

LIST OF FIGURES

TABLE OF CONTENTS

1 INTRODUCTION

As a Design Science research project, this investigation started from a real problem, and the process of understanding this problem and developing a solution guided the literature review and the search for a research problem. For this reason, this chapter starts with the description of the real problem, which also stands for the motivation of this work. Then, the context followed by the research problem are presented. This discussion leads to the definition of the research scope, described in the research questions and research aim. Lastly, the structure of this document is presented.

1.1 REAL PROBLEM

The starting point for the development of this thesis was a real problem identified in a company, which established a partnership with the Building Research Innovation Unit (NORIE) of the Federal University of Rio Grande do Sul (UFRGS) for developing research, since January 2011. The company is a Steel fabricator able to provide a complete steel solution for a building. The design, fabrication, and assembly of the components on the site are under their scope.

The extent to which the clients were able to affect the production process and the level of customization of the projects were considered critical factors to understand the complexity of this production system. For this reason, this work explores the characteristics of engineer-to-order (ETO) production systems in which the decisions and interference of the customer starts in the design phase.

The first investigation from the partnership of this company with the university was carried out by Fabro (2012). It aimed to develop guidelines for the implementation of a production planning and control system based on the Last Planner System for the site assembly process. That investigation was focused on planning problems faced by site management when delivering the product to the client. In the existing planning and control system, the control of construction site activities poorly connected to the planning and control system of the company as a whole. By using the Last Planner System, it was possible to promote a basic stability in the assembly processes. That study also pointed out the root causes for the problems in the construction site, which were mostly related to the lack of reliability in upstream processes. In fact, there were isolated incentives for each production phase (design, manufacturing, logistics, and site assembly) creating a disconnected production process, in which each department was attempting to maximize capacity utilization. Consequently, the site assembly process had a very long lead time, mostly due to delays and errors in the delivery of components on site.

The company realized the need for more research concerning the production planning and control system as a whole, in order to provide mechanisms to integrate the needs of the construction sites with the manufacturing process. This research was carried out in collaboration with a research team, as part of a larger research project which gave the opportunity for the development of other studies. This was the case of Wesz (2013), focused on the LPS in the design phase; Bortolini (2015), logistics planning in the construction site; and Sanches (2015), standardized work in the site, using resilience engineering. Other researchers played an important role in the development of this investigation: Iamara Bulhões and Ana Etges.

1.2 CONTEXT

The underlying assumptions of project management of construction projects have evolved over the time, improving their ability to cope with uncertain situations (LAUFER; DENKER; SHENHAR, 1996). Those authors establish four distinct generations of styles, from the 1950s until 1990s, each one incorporating the principles of the preceding one: scheduling (control), teamwork (integration), reducing uncertainty (flexibility), and simultaneous management (dynamism). Those authors discussed the story of managers who were able to deal with the challenge of working in a high uncertain environment, pressed by short delivery time, and high quality.

The first period accounts for the beginning of the modern notion of project management in the late 1950s and early 1960s, when CPM and PERT techniques emerged (LAUFER; DENKER; SHENHAR, 1996). This management style is called by Johnston and Brennan (1996) as a *management-as-planning* approach, in which a key underlying assumption is that plans can be used as a control structure for action. This approach assumes that there is a strong causal connection between the actions of management and outcomes of the organization (KOSKELA; HOWELL, 2002). As highlighted by the criticism of those authors, this is still a common approach in construction project management.

For Johnston and Brennan (1996), this traditional management approach is based on a planning model that understands the developer of plans as an agent from outside the world that is been managed. This world is considered objective and stable, and a high degree of continuity, predictability and causality is ascribed. Therefore, this approach tends to be effective for simple projects that have a relatively low level of uncertainty (LAUFER; DENKER; SHENHAR, 1996).

Around the 1970s, several organizations realized the need to deal with complex projects consisting of a larger number of parts, and highly interdependent components managed by different disciplines (LAUFER; DENKER; SHENHAR, 1996). Those authors pointed out that, in this context, it is necessary to ensure teamwork and integration between disciplines, and project managers play mostly the role of a facilitator, defining the role of other participants accordingly.

The third management style, which emerged in the 1980s, emphasized the reduction of uncertainty to a manageable size, in order to make stable decisions that will last over time (LAUFER; DENKER; SHENHAR, 1996). According to those authors, there was a trend of building buffers for protecting the project against future uncertainties, with the aim of creating stability.

The fourth management style belongs to the realm of simultaneity. Those authors argue that during the 1990s, time-to-market became the driving factor in many industrial companies. In this context, managers strive to integrate widely separate areas in space and time so that goals and means do not need to be resolved sequentially and separately but simultaneously and interactively.

In the last decades, production started to be seen as a flow (KOSKELA, 2000; SHINGO, 1989), leading to the emergence of the transformation-flow-value theory to support the understanding of a production system, highlighting the importance of not focusing on only one dimension of the production process (KOSKELA, 2000). Koskela and Howell (2002) stressed the need for new theories to support management practices, focusing on learning from the production level for planning and controlling, and enabling participation.

Williams (1999) define project complexity considering two main dimensions, structural complexity and uncertainty. It can be argued that those elements have been gradually included in the evolutionary view of Laufer, Denker and Shenhar (1996). Firstly, structural complexity started to be considered by managers, when teamwork were emphasized in order to deal with the amount of interdependence between parts of the project. Then, the problem of uncertainty and the need to use buffers to protect production appears in the following style. Finally, there is a need to adopt different hierarchical levels and integrate distinct disciplines in order to deal with both complexity and uncertainty.

Simultaneous management has some similarities to the approach called as management-as-organizing by Johnston and Brennan (1996). In that approach, the manager (also named agent) is a functional part of the world with which he or she has immediate contact and interaction. Those authors argue that management should be modular, parallel and distributed referring to the use of functionally complete sub-units, which could independently sense, model and act. Due to their small size, it would be possible to implement a tight coupling between sensing the world and acting in it. In this context, the tasks of planning and control are distributed rather than centralized.

Johnston and Brennan (1996) see the manager as a coordinator and enabler of autonomous activities. For Koskela and Howell (2002) this should be a basic assumption to develop a planning theory for construction. According to Laufer, Denkar and Shenhar (1996), managers are not responsible for taking the best decisions but to ensure that the best decisions are made by managing the decision-making process.

These changes of managerial styles in projects have also affected the movement of the construction industry towards industrialized production. The traditional idea of industrialized construction is often reduced to the use of prefabrication, while the term have evolved in the last few decades to a wider context, including technical and organizational aspects as well as the supply chain and information-related issues (LESSING, 2006). As construction projects have become more industrialized, there is a growing need to manage a complex network of suppliers, within a higher pressure to deliver the projects in a compressed time. Moreover, in some segments of the construction industry, competition has become more refined, since many projects are released when most of its definitions are still uncertain, in order to enable the customer to gain market primacy, increasing the uncertainty in the production process (TELEM; LAUFER; SHAPIRA, 2006).

According to Koskela and Vrijhoef (2001), the lack of a theoretical foundation of production management in construction is a major hindrance for further advances of this industry. One source for this theoretical foundation could be the understanding of the underlying assumption of the lean production philosophy, which have improved the production on manufacturing in different dimensions: efficiency, customer attendance, quality, safety.

The work of Koskela (1992, 2000) was the most prominent theoretical effort concerning the adaptation of the lean production concepts into construction. His main contribution was to discuss the lean production philosophy from a theoretical point of view, and the unique background of the construction industry.

Koskela, Bølviken and Rooke (2013) discuss the need to understand the leading wastes of the construction industry, which means that each production process has to be understood according to its idiosyncrasies and peculiarities in order to define what should be noted as waste, ultimately defining how this process could be enhanced. It is worth noting that the translation of lean production concepts from manufacturing to construction is not simple because of the unique characteristics of the construction industry, in addition to the geographic diversity among projects (TOMMELEIN, 1998).

Lessing (2006) also highlights the need for adapting the concepts from Supply Chain Management, originally from the manufacturing industry, to the construction context in order to meet customer demands. The importance of managing the supply chain of the construction industry is due to a movement towards industrialization in which production processes that used to be produced on-site start to be produced by a different entity. O’Brien *et al.* (2008) emphasize the peculiarities of this practice in the construction industry, where the SCM is more concerned with the coordination of discrete quantities of materials to specific construction projects. Vrijhoef and Koskela (2000) remark that it is a converging supply chain where all materials concentrate in one location; it is, in most cases, a temporary supply chain.

1.3 RESEARCH PROBLEM

In the context of growing industrialization in construction, an important competitive advantage is the focus on engineer-to-order (ETO) products. In an ETO production system, the customer order is placed at the design stage (GOSLING; NAIM, 2009), which means that the customer order is a unique project and the outcome is the final assembled product (BERTRAND; MUNTSLAG, 1993). In contrast to make-to-stock (MTS) products that are already produced whenever the customer arrives. A similar production situation is make-to-order (MTO), in which products are made from previously-engineered designs, but are made only after an order is received (KACHRU, 2009).

In the construction industry, every site uses some degree of prefabrication, starting from make-to-stock elements, such as bricks and bolts, to the prefabrication of complex building elements, such as power distribution equipment (ELFVING, 2003). This research study is focused on ETO prefabricated building systems, which refers to one specific building system, which is a solution provided by a single company, such as the structural or mechanical systems.

In these cases, products are not usually specified when the customer place an order and the main criteria for deciding to choose a company is the price and lead-time for production. Therefore, these items are estimated at the very beginning of the project and are stated in the contract with the customer, compelling the company to follow them in spite of the high level of uncertainty in the product specification and processes that the project will face (BERTRAND; MUNTSLAG, 1993). Little *et al.* (2000) discussed the results of a survey carried out with over 100 ETO manufacturing companies from France, Great Britain and Germany, that pointed out the need for developing management techniques able to deal with a high level of complexity and uncertainty.

Regarding production planning and control systems, the Enterprise Resource Planning (ERP), a development of the Material Requirement Planning (MRP), is one of the most popular planning and control models used in manufacturing. However, some authors (BERTRAND; MUNTSLAG, 1993; LITTLE *et al.*, 2000; STEVENSON; HENDRY; KINGSMAN, 2005) argue that this type of planning system is not suitable for the uncertain and dynamic environment of ETO.

Bertrand and Muntslag (1993) stress that the MRP assumes that processes and lead times of a given product are predictable, but this ability is hindered by the level of uncertainty within the product development process of an ETO product. Those authors also emphasize that interference from the customer during the whole product development may compromise the deliveries previously agreed in the project and can even affect other projects. Elfving, Tommelein, and Ballard (2004) assessed that, in ETO power distribution equipment, change orders from the customer can affect up to 30% of the contract prices, considering only direct costs. The same authors pointed out that the production process is strongly coupled with the decisions of the customer even after the design phase, and the need to use a planning and control system capable of dealing with these changes.

Stenvenson, Hendry, and Kingsman (2005) assessed the applicability of a number of planning and control models for make-to-order environments, using some criteria based on the literature review. Although they argue that the assessment could also be used for engineer-to-order situations, there seems to be a need to better understand the complexity and peculiarities of this kind of production system in order to develop suitable production planning and control systems for that context.

Besides the need for understanding what kind of production planning and control model is more suitable for ETO production systems, it is also necessary to innovate on the way performance is measured. According to Soman *et al.* (2007), when production depends on customer orders, the focus of production planning should be on order completion. So, the performance measurements should be focused on orders, e.g., average response time and average order delay (SOMAN; VAN DONK; GAALMAN, 2007). When products are made prior to the receipt of a customer order, such as in a make-to-stock production system, the performance measurements are based on utilization of the capacity, e.g., line items fill rate, throughput, and average inventory levels (SOMAN; VAN DONK; GAALMAN, 2007).

Little *et al.* (2000) emphasize the need for devising production planning and control models for ETO environments, which enable the integration among the different production phases: design, manufacturing, assembly. It is important to acknowledge the strong interdependencies among these production phases, managing the production process in an integrated way, in order to improve the final delivery process (ELFVING, 2003).

In the case of ETO prefabricated building systems, Sacks *et al.* (2003) emphasize the need to integrate the management of manufacturing plants and site assembly of prefabricated components by using real-time feedback information. This kind of feedback is essential for the adoption of a pull approach for controlling production (TOMMELEIN, 1998).

Regarding the construction environment, the Last Planner System™ of Production Control (LPS) is a planning and control model that is based on a set of lean production concepts and principles. This system was originally devised by Ballard (1994), and has been successfully implemented worldwide. The system encourages the decentralization of the planning process, avoid taking decisions too early, and promote learning from one planning cycle to the other. For those reasons, it is possible to state that LPS is strongly based on a management-as-organizing approach, which is suitable for the construction environment. For Aslesen and Bertelsen (2008), LPS should be understood as a more general approach for production management, and should be adapted for different types of production systems.

However, most implementations reported in the literature have been limited to site installation (BALLARD; HOWELL, 1994, 2003; BALLARD, 2000). There have been only a few cases reported in the literature of implementation in the design phase (e.g., HAMZEH; BALLARD; TOMMELEIN, 2009; KEROSUO *et al.*, 2012; WESZ; FORMOSO; TZORTZOPOULOS, 2013), and prefabrication (BALLARD; ARBULU, 2004; BALLARD; HARPER; ZABELLE, 2002), and hardly any in engineer-to-order prefabricated systems, considering all production stages, from design to erection. This brief literature review indicates that there is a lack of studies concerning the planning and control systems for engineer-to-order environment supporting the construction industry needs.

1.4 RESEARCH QUESTION

The research problem led to the following research question which has guided this research study:

> How to plan and control ETO production systems that deliver (design, manufacture and assemble) prefabricated building systems?

These are some secondary questions:

- How to enable pull production in ETO production systems in environments that have a high level of uncertainty?
- How can the Last Planner System be used as a basis for integrating the ETO planning and control system of the whole production process?
- How can performance measurement support the implementation of pull production in prefabricated building systems?

1.5 RESEARCH AIM

The aim of the research is to devise a production planning and control model for ETO prefabricated building systems, integrating design, manufacturing and site assembly. The secondary aims of the research are:

- Propose the operacionalization of some lean production concepts, such as pull production, and work-in-progress to the context of ETO prefabricated building systems;
- Propose a set of core requirements for developing planning and control systems for ETO prefabricated systems; and
- Devise a set of performance metrics for different levels of the planning and control system

1.6 STRUCTURE OF THIS DOCUMENT

This thesis is divided in ten chapters. After this introduction, Chapters 2, 3 and 4 present the theoretical background of the research. Chapter 2 discusses the complexity and peculiarities of the production environment focus of this research: the ETO prefabricated building systems. Chapter 3 discusses some important production management concepts and principles for the sake of this research. Chapter 4 is concerned with a merge of the previous chapters. It discusses how should be a planning and control system, considering the peculiarities of this environment.

Chapter 5 describes the research method, including the research strategy, and the steps carried out in the development of the research. Here the companies where the empiric case studies were carried out are described. There were three different empirical studies, two of them include an implementation phase and one of them is only a descriptive study. The first study can be considered the main one, where the author was able to participate in three different learning cycles of the implementation process. Chapter 6 presents the finding of this study. Chapter 7 concerns the findings of the empirical studies from abroad, where different contexts were analyzed, and where it was possible to find some important practices to be incorporated in the final model. Chapter 8 presents the main artifact of this research: the production planning and control model for ETO building systems. Last, Chapter 9 summarizes the main conclusions and discusses questions for further research.

2 ETO BUILDING SYSTEMS

This chapter explores the characteristics of the ETO production systems, and discusses the complexity that exists in those systems. It is divided into five sections. Section 2.1 presents some general concepts related the classification of production systems. Section 2.2 discusses some concepts related to construction Supply Chain Management, and how it is related to ETO production systems. Section 2.3 describes the main characteristics of the ETO environment. Section 2.4 is concerned with the forms of sense making in a complex systems, such as the ETO. Section 2.5 depicts the complexity in ETO production systems.

2.1 CLASSIFICATION OF PRODUCTION SYSTEMS

ETO production systems can be defined as the ones in which the customer order decoupling point (CODP) is located at the design stage, i.e., the customer order is delivered at the beginning of the design phase of a product (GOSLING; NAIM, 2009). Wortmann, Muntslag, and Timmermans[1] (1997 apud TOMMELEIN; BALLARD; KAMINSKY, 2008) differentiate the production that requires an order to start from the ones that produce to a stock, namely the make-to-order (MTO) and make-to-stock (MTS), respectively, as shown in Figure 2.1.

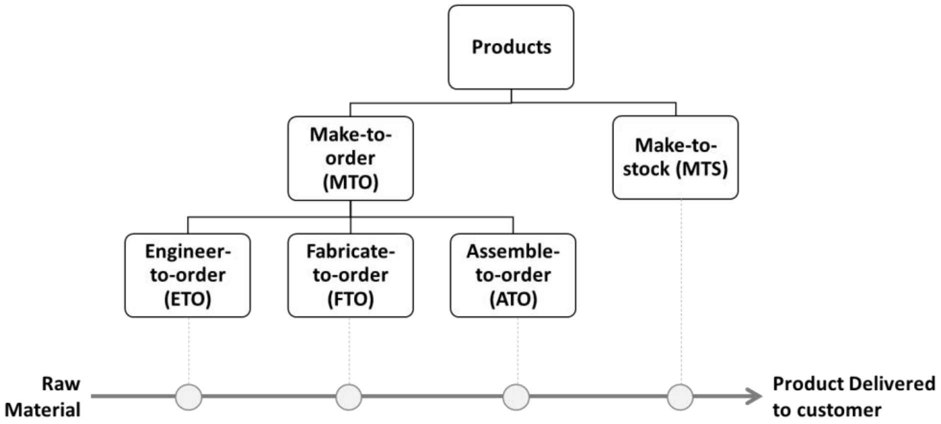

Figure 2.1: Classification of production systems, adapted from Tommelein, Ballard, and Kaminsky (2008)

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[1] Wortmann, J. C., Muntslag, D. R., and Timmermans, P. J. M. (eds). *Customer-driven Manufacturing.* London: Chapman & Hall, 1997.

Make-to-stock products are typically the ones that are repetitive and can be mass produced, (TOMMELEIN; BALLARD; KAMINSKY, 2008). Customers are able to find these products right away. According to Wortmann, Muntslag, and Timmermans (1997 apud TOMMELEIN; BALLARD; KAMINSKY, 2008), MTO products can be divided into three main subcategories: (a) Engineered-to-order (ETO), when the products are engineered according to the customer demand; (b) Fabricated-to-order (FTO), when the design is ready and the whole fabrication process is carried out after the order takes place; and (c) Assembled-to-order (ATO), when only the final assemble of the product follows a customer order.

Stenvenson, Hendry, and Kingsman (2005) also consider the ETO as a special type of the MTO production system. This definition of MTO is the same as produce-to-order from Kingsman (2000). The definition of those authors differ from other definitions presented in the literature (WIKNER; RUDBERG, 2001 *apud* RUDBERG; WIKNER, 2004), in which make-to-order is the same as FTO. Therefore, in most classifications of production systems, ETO is not considered as a subcategory of make-to-order production systems. However, this definition contributes to the understanding that the problems faced in a MTO production system are part of the problems for the ETO production system. Therefore, in this investigation, the definition of ETO as a specific type of make-to-order production system was adopted.

Van Hoek (2000) points out that the simple position of the CODP at the product development process is not enough for understanding the production system, there is a need to recognize at what degree this order can be applied. Rudberg and Wikner (2004) divide this categorization into an engineering dimension and a product dimension. Those dimensions can be understood as two axis of a chart, each of which can be either made to stock or to order. The production system type can be classified anywhere in between those extremes.

This classification opens up the understanding of different levels of design approaches. In the previous definition, the design could be either engineered-to-stock, namely a FTO or ATO situation, or engineer-to-order, while in this framework there is a new element, which the authors call as designs adapted-to-order, placed in between those extremes. Figure 2.2 depicts this two-dimensional framework of the CODP. In order to differentiate the adapt-to-order (ATO) from the engineering dimension, from the assemble-to-order (ATO), product dimension, Rudberg and Wikner (2004) use a subscript ED, or PD standing for the name of those dimensions, respectively.

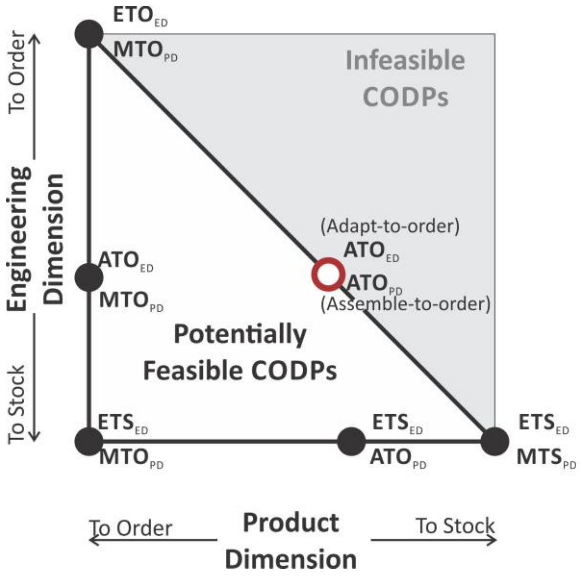

Figure 2.2: Dimensions of CODP space, (RUDBERG; WIKNER, 2004)

The definition of these levels of design readiness is important, since the degree of design modularity can facilitate product flow through fabrication and assembly processes. Bertrand and Muntslag (1993) highlight that in an ETO situation, the production control scope includes design and engineering activities, which they call as non-physical activities. In fact, this means that decisions about the production lead-times are taken under uncertainty, since it is made before the definition of product design. The CODP before the design leads to more decisions to be made under uncertainty.

2.2 SUPPLY CHAIN MANAGEMENT

Vertical integration approach is a possible business strategy for an ETO company, as highlighted by Hicks, McGovern, and Earl (2001). Vertical integration is “the degree to which a firm decides to produce in multiple value-adding stages from raw material to the ultimate consumer” (COX; BLACKSTONE, 2015). While some ETO companies adopt in-house vertical integration in order to get competitive advantage (HICKS; MCGOVERN; EARL, 2001), others are focused on design and assembly, design and contract, or only on project management (HICKS; MCGOVERN; EARL, 2001). .

Hicks, McGovern, and Earl (2001) point out benefits of integrating internal processes: (a) design produces full technical specifications based upon knowledge of available processes, which facilitates design for manufacturing and assembly; (b) the lead-time can be reduced, since it becomes potentially easier to overlap design and manufacturing, and (c) value-added margins might be increased, since the company’s scope is broader, e.g. from raw materials to the ultimate customer (HARRIGAN, 1985).

Stonebraker and Liao (2006) understand the view of vertical integration as a precursor to supply chain integration. “Supply chain management is the practice of a group of customers and suppliers working collaboratively in order to best satisfy end-customer needs while rewarding all the members of the chain” (TOMMELEIN; WALSH; HERSHAUER, 2003, p. 2).

The main goal of the SCM is to include the requirements of the customers within the flow of products from the suppliers, balancing high customer service, low inventory investment and low unit cost, which are often seen as conflicting goals (STEVENS, 1989). In order to deal with these trade-offs, Stevens (1989) emphasize the need of thinking in a single integrated supply chain. He remarks that, traditionally, these conflicting goals are managed through ineffective and expensive practices such as concentrating at the production level, compensating the imbalance with excess inventory and capacity.

Vrijhoef and Koskela (2000, p. 171) pointed out the peculiarities of supply chains in the construction industry:

- It is a converging supply chain directing all materials to the construction site where the object is assembled from incoming materials. The “construction factory” is set up around the single product, in contrast to manufacturing systems where multiple products pass through the factory, and are distributed to many customers.
- It is, apart from rare exceptions, a temporary supply chain producing one-off construction projects through repeated reconfiguration of project organizations. As a result, the construction supply chain is typified by instability, fragmentation, and especially by the separation between the design and the construction of the built object.
- It is a typical temporary supply chain, with every project creating a new product or prototype. There is little repetition, again with minor exceptions. The process can be very similar, however, for projects of a particular kind.

Vrijhoef and Koskela (2000) defined four different roles (Figure 2.3) of supply chain management in the construction industry: (a) managing the interface between construction and suppliers, (b) managing the supply chain, upstream from the construction site; (c) managing the supply chain, but considering that some operations have been transfer from the construction site to manufacturing plants; and (d) managing both the supply chain and the construction site.

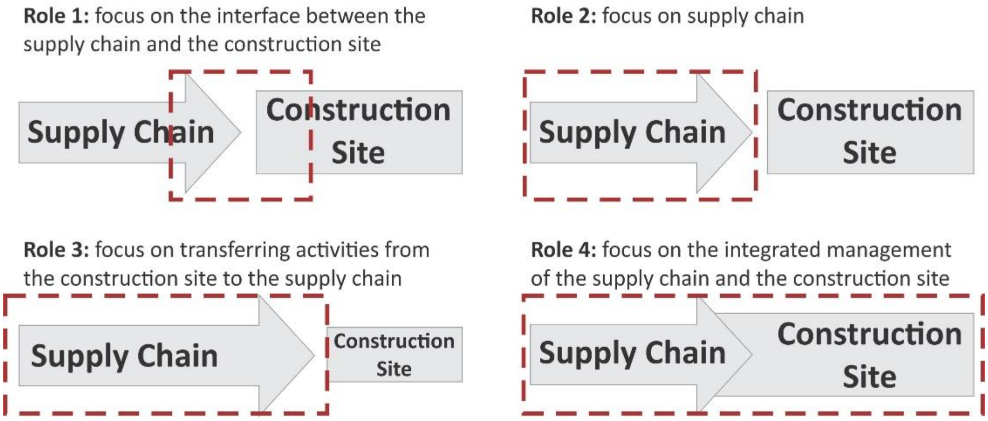

Figure 2.3: Roles of the Supply Chain (VRIJHOEF; KOSKELA, 2000)

The roles proposed by Vrijhoef and Koskela (2000) in fact refer to different stages of development of supply chain management. In the case of ETO prefabricated building systems, site assembly is often part of the scope of the fabricator. For that reason, managing in an integrated manner the supply chain related to the fabrication together with the site assembly is very important for the performance of the project.

2.3 ETO ENVIRONMENT

Elfving, Tommelein and Ballard (2004) investigated the challenge of reducing lead times in ETO production systems. When each of the production phases is carried out in isolation there is a significant increase in the overall delivery time. Long lead times contribute to more decisions to be made based on vague assumptions, leading to suboptimal solutions, quality defects and rework. According to Ballard and Arbulu (2004), this situation can be caused by contracts, since the owners buy products, rather than the shop capacity.

Kingsman (2000) distinguishes ETO organizations according to the level of customizations of the products, proposing two categories of ETO systems: (a) Repeat Business Customizers (RBCs) and (b) Versatile Manufacturing Companies (VMCs). The former produce customized products on a continuous basis, such as component suppliers to motor manufacturers. Once the order takes place, production becomes a repetitive business on a regular basis for a certain period of time. The latter, in contrast, supply a variety of products ranging from standard products to all orders requiring a customized product (KINGSMAN, 2000).

As a process in which the development of the design is part of the production process, Bertrand and Muntslag (1993) divide ETO production systems into four generic production phases: conceptual design, engineering design, component manufacturing, and assembly (Figure 2.4). Those authors also make an important distinction between the goods flow control (GFC) and production unit control (PUC). The former refers to the control of the product along production phases, while the latter focuses on the control of the different projects within one production unit (PU). A PU is defined as an organizational grouping of resources internally organized so that the operations can be performed independently from the other units. It is able of making reliable commitments with respect to the specific conditions (such as utilization levels, throughput times, etc.) under which the operations can be performed (BERTRAND; MUNTSLAG, 1993). The PU is responsible for one of the production phases. An organization may have several PUs in charge of the same production phase, in order to deal with a large number of projects.

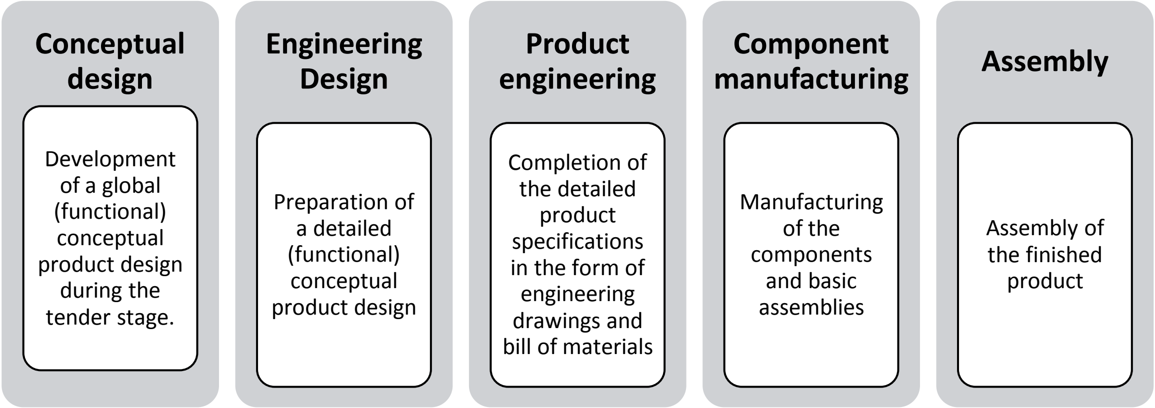

Figure 2.4: Generic production phases, after Bertrand and Muntslag (1993)

The goods flow control and the production unit control can be understood as different detail levels of control. In this regard, this differentiation is similar to the production function mechanism proposed by Shingo (1989), but rather in a more strategic view. The process axes, mentioned by that author, are concerned with the goods flow control, emphasizing the need to see the flow of the product through the work centres. The operation axes are concerned with the production unit control since it is a more operational level of control regardless the overview of one product among the other units.

Figure 2.5 illustrates the way goods flow control and production unit control are connected to each other. It also presents the main decision structure proposed by Bertrand and Muntslag (1993):

1. At the customer order acceptance and due date assignment: is a timely completion of the production of the customer order possible?
2. Just before starting the manufacturing process: which production unit will manufacture each component and what part of the work will need to be contracted out (outsourced)?
3. At each production unit: when will the work be released to the production unit?
4. At each production unit: in which sequence will the work be performed within the production unit?

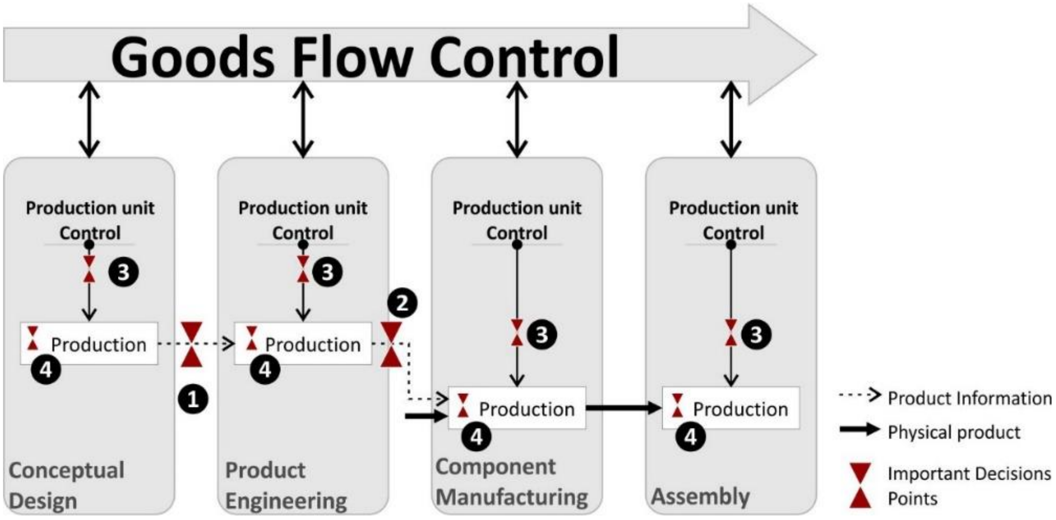

Figure 2.5: Good Flow Control and Production Unit Control (BERTRAND; MUNTSLAG, 1993)

The first decision is concerned with how much effort should be spent preparing the proposal, and this leads to the delivery time, and the price that will be proposed (BERTRAND; MUNTSLAG, 1993). They also emphasize the importance of the interface between Sales and Production, since the decisions made in translating the customer specifications into the technical specifications for a manufacturing product should be used by Sales to determine the price quotation.

Bertrand and Muntslag (1993) summarize the objective of goods flow control as coordinating the interface between products and sales. Sales are responsible for ensuring sufficient product demand and for accepting customer orders, while production is responsible for providing production capacity and ensuring that the customer order is completed on schedule. Therefore, those authors emphasize that the decisions made at the definition of product specification should be taken into account by the sales department, in order to learn and provide more suitable biddings.

2.4 SENSE MAKING IN COMPLEX SYSTEMS

There are different definitions of complexity, being a matter that almost every science deals with. Many definitions have in common the idea that complexity results in emergent behaviour that results from interactions between parts of the system, requiring no central control (MITCHELL, 2009). It means that even when it is possible to understand the behaviour of each component of the system, the collective behaviour is hard to predict. For this reason, when investigating a complex system, it is important to identify which are the components that affect this complexity.

Managing a complex system requires a different approach than in a simple system. The underlying assumption of the scientific management is based on the Newtonian science, encouraging some simplifications that are only useful in ordered circumstances (SNOWDEN; BOONE, 2007). Kurtz and Snowden (2003) emphasize the disastrous effects of assuming order in an unordered environment. David Snowden and other researchers developed the *Cynefin* framework, which aims to help people in sense-making when dealing with this kind of system (KURTZ; SNOWDEN, 2003; SNOWDEN; BOONE, 2007; SNOWDEN, 2002, 2010b). In that investigation, complexity is related to the extent to which future events are predictable, which affects the capability of understanding the cause and effect relationships. This conceptualization is not limited to project complexity, but is concerned with complexity in any human organization. Figure 2.6 represents the framework developed by Snowden (2010a).

Figure 2.6: *Cynefin* framework, proposed by Snowden (2010a)

The centre represents the disorder, when people do not recognize yet the domain they are into. The right side represents the ordered domains, while the left side the unordered. The ordered domains assume an ordered universe, making the cause-effect relationships predictable (SNOWDEN; BOONE, 2007). This environment makes it possible to determine the right answer for a problem, based on previous facts. The boundary between the simple and complicated domains represents the difference between the immediate answer provided by sense-making, and when there is a need to spend time and energy to find more about (KURTZ; SNOWDEN, 2003). In the simple domain, there is a category already analysed for that problem, so the decision model is to sense about the data, categorize that data and respond (KURTZ; SNOWDEN, 2003). In the complicated domain, the cause-and-effect relationships exist, but there is a need to analyse the situation before responding. The response should be based on an expert advice or interpretation of that analysis (KURTZ; SNOWDEN, 2003). As there is no ready categorization, assumptions must be open to examination and challenge; it is not possible to establish the best practice, but a good practice for a given situation.

In the unordered domains, those relationships are not clear, so there is a need to find emerging patterns (SNOWDEN; BOONE, 2007). Those domains deal with the wicked problems, in which the understanding of the problem is part of the development of the solution (MCLEOD; CHILDS, 2013). In these domains, the important distinction to be made refers to what can be patterned, and what needs a stabilization to enable the emergence of patterns (KURTZ; SNOWDEN, 2003). In the complex domains, there is a need to create probes to make the patterns visible. Then, it is possible to sense and respond (KURTZ; SNOWDEN, 2003). In the chaotic domain, patterns are not easily understood, and there is a need to act quickly for reducing turbulence. Then, it is possible to sense and respond in a more long-term approach.

Kurtz and Snowden (2003) highlight that through the first actions the environment might change to a simple or complex domain.

The Cynefin framework facilitates the understanding of a complex system. As it is aimed for the sense-making process, it depends on a person interpretation to be considered in one domain or the other. Another important contribution is that it is situated concept, as it depends on the situation under analysis. This means that a whole production system, which may have different phases, processes, facilities, and teams, cannot be placed in one domain. Each analysis should be focused on part of a problem, and should be allocated in the framework accordingly.

2.5 COMPLEXITY IN ETO PRODUCTION SYSTEMS

Williams (1999) suggests that there are two dimensions of complexity in project management: (a) structural complexity, which depends on the number of elements and the degree of interrelatedness between those elements; and (b) uncertainty, related to the goals and methods of the project that can be unknown. Figure 2.7 summarizes Williams' (1999) point of view.

The acknowledgement of the uncertainty as part of project complexity was an important step forward from the previous understandings in which complexity was seen only as the underlying structure of the project (see BACCARINI, 1996). By considering uncertainty as a dimension of project complexity, this framework assumes that complexity depends on the context where the project is situated.

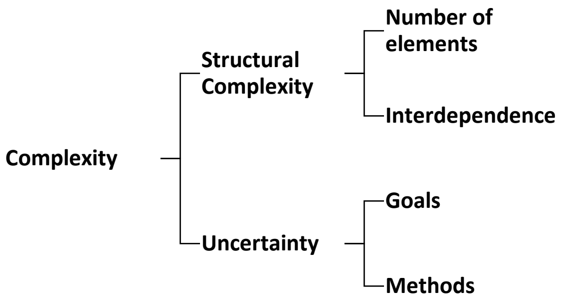

Figure 2.7: Project Complexity (WILLIAMS, 1999)

Crichton (1966) discusses the combined effect between interdependence and uncertainty. Interdependence is regarded as the extent to which one decision affects a set of other decisions. Since there are situations in which decisions are delayed until a given information is available, dependent operations can suffer from bad assumptions. It means that the interdependency increases the internal uncertainty of construction projects. There is also a source of uncertainty from outside, which has two sources: (a) the uncertainties engendered by the action of those not directly involved in the building process, such as government departments, planning authorities (CRICHTON, 1966), and (b) the uncertainties in resources, such as labour, equipment, and materials.

In an ETO production situation, Bertrand and Muntslag (1993) define three aspects that affect its control characteristics: dynamics (in demand), uncertainty and complexity. For them, a production situation is called dynamic when there is a need to anticipate relevant fluctuations in, for example, sales volume. It means it is unknown whether the available capacity is going to be idle or overloaded. This dynamic market situation asks for much internal flexibility to cope with these fluctuations (BERTRAND; MUNTSLAG, 1993). The same authors emphasize the need to fully understand how this kind of system works in order to devise a production control accordingly.

There is a very different conceptualization of uncertainty between the framework of Bertrand and Muntslag (1993) and the one of Williams (1999). The former is based on Galbraith (1973[1] apud BERTRAND; MUNTSLAG, 1993) as the difference between the amount of information required to perform a task and the amount of information already available in the organization. The latter uses the definition from Jones (1993), the “instability of the assumptions upon which the tasks are based would also increase complexity”. In the view of Bertrand and Muntslag (1993), it is assumed that there is a “known” amount of information required for a task. In the view of Williams (1999), decisions are instable and might be subject to change.

Due to this reductionist view, it seems that Bertrand and Muntslag (1993) do not understand the uncertainty as one dimension of complexity, discussing each of them independently. Although, uncertainty is considered as an intrinsic part of the system complexity in this investigation, the view provided by those authors is discussed, since their work is very much focused on ETO production systems. The relation between those factors is reinterpreted at the end of this section.

Bertrand and Muntslag (1993) emphasized three factors that contribute to uncertainty. The first is **product specifications**: the product has to be engineered at the start of the project, so

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[1] Galbraith. J.R . 1973. Designing Complex Organizations. Addison-Wesley. Reading.

there are some decisions such as capacity, lead time and price that have to be made under uncertainty. The second factor refers to the mix and volume uncertainty of the **future demand**, which is related to both sales demand and the moment of customer order intake, since customers often do a project quotation before deciding which company will carry out the project. The third factor refers to **process uncertainty**, which is closely related to the first factor, i.e., the types of processes that the product needs to pass through are also unknown at the beginning of the project.

Bertrand and Muntslag (1993) also point out three factors that contribute to the structural complexity of engineer-to-order production systems. The first factor refers to the structure of the **goods flow**, consisting of **physical** and **non-physical** stages of the production process. The latter contains some creative processes, which are difficult to standardize, and operations as in the physical production. The complexity of the physical stage is concerned with the differentiation of products.

The second factor is the **multi-project character** of a production system. A customer order may require a different set of parts that may be unknown at the beginning of the project. This uncertain situation may create bottlenecks within one project that can have serious effects on other projects. This factor can be considered a new dimension in the project view of Williams (1999). Therefore, when considering the whole production system, the number of projects carried out in concurrently will affect the structural complexity.

The third factor is called **element uniqueness**, which refers to the extent to which products are one-of-a-kind, requiring specific materials to be purchased for a specific project. This situation becomes more critical if some materials need to be purchased at an early stage because of long lead times. Figure 2.8 presents a summary of the factors proposed by Bertrand and Muntslag (1993) as influential in the level of complexity of the production system.

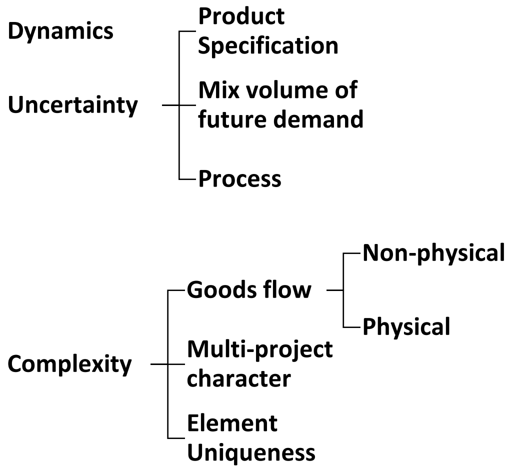


Figure 2.8: Scheme of the characteristics of engineer-to-order companies, from Bertrand and Muntslag (1993)

Figure 2.9 depicts the complexity aspects that affect an ETO production system, following both the points of view from Bertrand and Muntslag (1993) and Williams (1999). Each of dimensions is affected by factors from the multi-project environment and from within the project. Elements such as the goods flow described by the Bertrand and Muntslag (1993) were merged with the idea of interdependence between parts. Therefore, this factor was affected by the physical and non-physical flow.

What Bertrand and Muntslag (1993) considered as product specification and process, refers to what Williams described as uncertainty in goals and methods respectively. The dynamic aspect, from Bertrand and Muntslag (1993) was considered closely related to the uncertainty over fluctuations and sales demand and, for this reason, does not appear in the figure. The multi-project aspect is called as number of projects, to mirror the number of elements from Williams (1999)'s framework.

Also, as a matter of mirroring inter and intra project domains, the element uniqueness turned into project uniqueness. It is important to acknowledge that there is an increase of uncertainty in the peculiarity of the project as a whole, differently from the individuality of its parts. Baldwin and Clark (2000) highlight the importance of using the concept of modularity for dealing with complex systems. They define two main characteristics of the modularity, the interdependence within the module and the independence across modules. The increase of product modularity for construction elements means that the level of element uniqueness has been reduced. As described by Tommelein (1998), the more modular are the components, the less the system suffer with the matching problem, when the plant produce in a different sequence than the one required in the construction site.

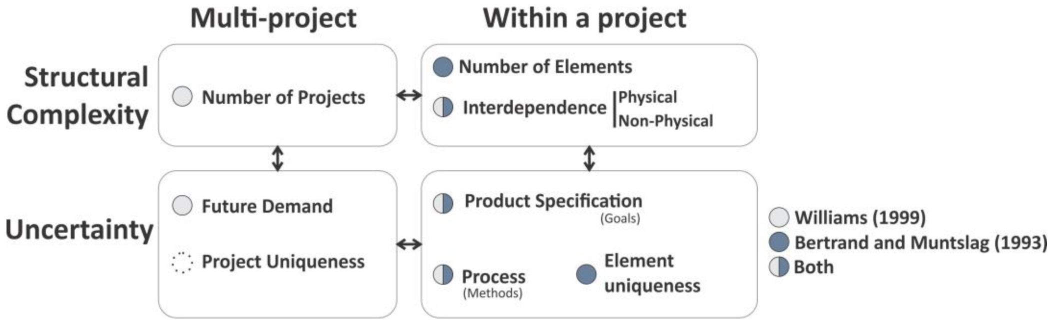


Figure 2.9: Elements affecting complexity in ETO production systems

Both the aspects within each domains, and the domains itself interact with one another. The representation of Figure 2.9 tries to avoid a hierarchical structure between those parts. It provides the basic elements to understand how an engineer-to-order production system is complex. This understanding is important for the development of planning and control systems for this environment. As discussed by Kurtz and Snowden (2003), the lack of understanding of the analysed environment domain can make managers to take the wrong actions, turning the system even more unpredictable.

Construction projects usually have a large number of parts, such as building materials and components, many interdependencies between parts, as well as a high degree of uncertainty both in demand and in processes (BALLARD, 2005) Moreover, in some building projects, a high level of customization is demanded by clients. Therefore, it is possible to infer that ETO production systems in that sector tend to have a degree of complexity even higher than in a purely manufactured engineered-to-order product.

3 PRODUCTION MANAGEMENT CONCEPTS AND PRINCIPLES

This chapter a presents brief history of Lean Production, emphasizing the context in which this philosophy has emerged. Understanding this historical perspective is important, since it provides insights about the origin of some of the underlying ideas of production management, and how these spread in other sectors. Then, most relevant concepts and principles for the development of this research are presented, such as TFV theory of production, waste, push and pull production, process transparency, and learning capabilities of the Toyota Production System.

3.1 HISTORIC BACKGROUND OF LEAN PRODUCTION

Henry Ford has played a key role in the adaptation to the automobile industry, of concepts from the already established high-volume production industries, which had been developed during the industrial revolution, such as steel, aluminium, oil, chemicals, food, and tobacco. According to Hopp and Spearman (2000), the most important innovation made by Ford was the moving assembly line. By contrast, Womack *et al.* (1990) pointed out that the moving assembly line would never be possible without the development of a complete and consistent interchangeability of parts, with the simplicity of attaching parts together. Therefore, the main contribution of Ford has to do with the way he developed interchangeability of parts and the moving assembly line. Although high-volume production was commonplace, it was Ford who enabled the development of a high-speed mass production for complex mechanical products (HOPP; SPEARMAN, 2000).

In contrast to the situation of USA in the late forties, the Japanese economy was devastated by World War II: labour productivity was one-ninth that of the United States, and automotive production was at minuscule levels (HOPP; SPEARMAN, 2000). Ohno (1988, p. 15) reported the words that he had heard from Toyoda Kiichiro, president of Toyota at that time: “catch up with America in three years. Otherwise, the automobile industry of Japan will not survive”.

Ohno (1988) stated that it would not be possible that a USA worker could do 10 times more physical effort, and, therefore, there should be some sort of waste in Japanese plants that was not being perceived. If that waste was eliminated, productivity could be improved to a great extent (OHNO, 1988). Although Toyota did not reach Americans in three years, it was this great effort that sparked the most fundamental changes in manufacturing management since the scientific management movement in the early 20th century (HOPP; SPEARMAN, 2000).

In 1945, when Toyota started its journey in pursuit of a production system appropriate to the Japanese background, the company was specialized in different types of trucks for the armed forces (GHINATO, 2000). In fact, Toyota's plant was conceived to produce small quantities of many types of products for the Japanese environment, which was unusual among car plants (OHNO, 1988). At that time, there was much concern about devising a new production system that was suitable for a period of relatively low economic growth (OHNO, 1988). Therefore, the genesis of the Toyota Production System was based on the idea that for a company to become more efficient it is necessary to reduce costs by eliminating waste (OHNO, 1988; SHINGO, 1989).

Although the expression Toyota Production System (TPS) is sometimes used to refer to this new production paradigm, other expressions have been proposed to describe attempts to generalize the set of underlying concepts and principles that could be used in a wide range of companies. Womack and Jones (1990) popularized a term Lean Production, coined by John Krafcik, a researcher on the International Motor Vehicle Program (IMVP). The term 'lean' was chosen because it is supposed to use less of everything compared to mass production: half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a new product in half the time (WOMACK; JONES; ROOS, 1990). In this research work, the terms TPS and Lean Production are used interchangeably.

Koskela (1992) argues that the development of this production philosophy was a process of trial and error, and that only afterwards the academic community attempted to understand those changes at a theoretical level. Since the early 1990s there has been much effort to use Lean Production ideas into the construction Industry. This effort was initially marked by the research report produced by Koskela (1992), in which he pointed out the need to establish a theoretical foundation for production management in this sector. This publication was the starting point for the creation of the International Group for Lean Construction (IGLC) in

1993. The goal of the group has been to "better meet customer demands and dramatically improve the architecture, engineering, and construction process as well as product" (IGLC, 2013).

3.2 PRODUCTION MANAGEMENT CONCEPTS AND PRINCIPLES

As the Toyota Production System was maturing, the need for teaching and engaging supply chain members in that system increased (LIKER, 2003). Therefore, Fujio Cho, an Ohno disciple, developed a simple representation of the system, a house, similar to the one shown in Figure 3.1, devised by Liker (2003), to point out the core concepts involved. Several versions of the TPS house have been proposed in other publications over the years (LEI, 2008; LIKER, 2003; MARKSBERRY, 2013; STEWART, 2012).

Figure 3.1: TPS house (LIKER, 2003)

Each component of the house emphasizes different building blocks of TPS. The two columns usually refer to Just in Time and *Jidoka* (or Autonomation), while the foundation typically include the concepts of stability, levelled production, standardized work and kaizen.

In most TPS houses, the goals are also similar: high quality, low cost and short lead time. The house proposed by Liker (2003) emphasizes the need to manage people and to achieve the goals through the elimination of waste. In fact, in Liker's version the role of people is pointed out in the middle of the house, acknowledging the socio-technical character of production systems. For that author, kaizen (continuous improvement) is the only means to achieve basic stability, and people need to be trained to identify and eliminate waste, by asking themselves what is the root cause of the problem. Spear and Bowen (1999) emphasized that the workers at Toyota are able to contribute to perform improvement since they were aware about what is good to the system as a whole.

According to Ohno (1988), the TPS has two pillars that provide support for the system: Just-in-time and autonomation (automation with a human touch). Just-in-time means that the right parts need to reach the assembly line at the time that they are needed, in the quantity that are needed (OHNO, 1988). Autonomation is related to the autonomy of any resource, either machines or workers, to detect failures and stop production with no need of further inspection (OHNO, 1988). Marksberry (2013) defines these as the “go” pillar and the “stop” pillar, respectively.

Finally, the foundation of the TPS house contains some concepts that must be implemented before the company is able to start the implementation of more complex changes (such as Just in Time). Smalley (2004) points out that when a company is not able to adopt those concepts at the foundation of the TPS house, it is not possible to achieve the higher level benefits of the system.

Ohno (1988) was also concerned about the separation of machines and workers. As he pointed out that a good production system should be effective even during a slow economic growth, it was counterproductive to install a machine that would demand the same number of workers that were on that line before. Providing machines with “human intelligence” functions made possible the clear separation of worker and machine (SHINGO, 1989). This notion, in turn, evolved into multi-machine handling operations and helped improve human productivity (SHINGO, 1989).

The concepts of the lean production are not directly applicable to the construction industry. Koskela (1992) proposed an adaptation of the lean production paradigm by eliciting a set of core principles and discussing the unique background of the construction industry. The lean production, originated in the manufacturing, is more concerned with the use of self-controlled tools than on developing tools for planning and control.

3.2.1 TFV theory of production

In an effort to understand the underlying theory for the production in the construction industry, Koskela (2000) developed the transformation-flow-value (TFV) theory that helps the understanding of any production system. It is, therefore, a theory of production. The TFV considers three different aspects of the production that have to be considered jointly to be able to provide an improvement for it.

One of the key conceptual changes that the Toyota Production System introduced in manufacturing concerns the way production process is understood (KOSKELA, 2000). In many operations management textbooks (e.g. SLACK; CHAMBERS; JOHNSTON, 2007), a production process is defined as a sequence of operations that uses material or information as inputs to be transformed into products or services (output of the process), as shown in Figure 3.2. Koskela (2000) highlights that this is the theoretical model was predominant in Mass Production.

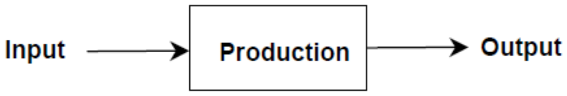


Figure 3.2: Transformation model (KOSKELA, 2000)

According to Koskela (2000), the main principles that underpin this conceptual model are:

- Decomposition of the transformation process into subprocesses, which are also transformation processes
- Overall cost minimization through minimizing the cost of each subprocess.
- Need of physical or organizational buffering, in order to protect the production process from the external environment.
- Value of the output of a process is associated with value (or costs) of inputs to that process

Koskela (2000) argues that it is assumed in this model that the overall efficiency is improved by increasing the efficiency of individual transformation processes. Therefore, process improvement is obtained through the increase of utilization rate of labour and equipment. He pointed out that the transformation model played an important role during the 20th century, influencing a wide range of fields, such as organizational design, accounting, project management, and various branches of engineering.

The problem with this point of view is that it is not enough to understand the intrinsic phenomena of production (KOSKELA, 2000). Koskela (2000) developed the Transformation-Flow-Value (TFV) theory, emphasizing the need of understanding, modelling, designing, controlling, and improving the view of production not only as a transformation process, but also as a flow and a value generation process.

The idea of production as a flow arose from the critique of the transformation model. Shingo (1989) suggested that there must be a clear differentiation between operations and processes in what he named "**production function mechanism**". According to that author, production is a network of processes and operations, as shown in Figure 3.3. A process analysis means that the focus is the flow of material in time and space, namely, its transformation from raw material to semi-processed component to finished product, while an operation analysis means that the focus is on the work performed to carry out this transformation (SHINGO, 1989).

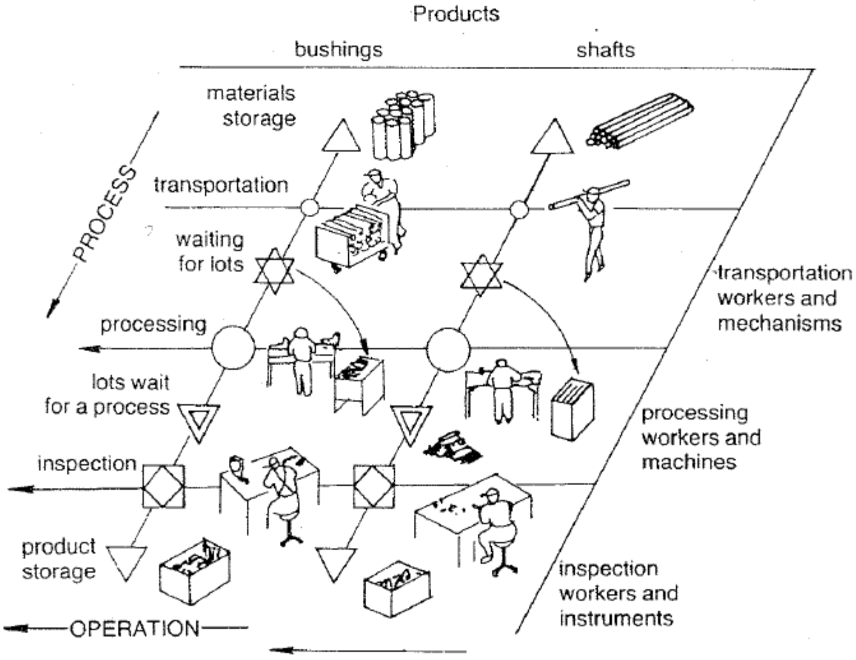


Figure 3.3: Production mechanism (SHINGO, 1989)

According to Shingo (1989) it is necessary first to improve the process, and only afterwards to improve operations, including efficiency of labour and equipment in individual activities. He also emphasized that it is misleading to look to at the process as a single line since it reinforces the mistaken assumption that improving individual operations will improve the overall efficiency of the process flow of which they are a part.

The conceptualization of flow proposed by Koskela (1992) has much to do with Shingo's production function mechanism. Koskela (1992) defined process as a flow that has both value-adding (transformation) and non-value-adding (flow) activities, as shown in Figure 3.4.

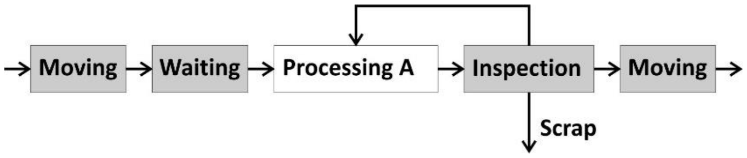


Figure 3.4: Production as a flow (shaded boxes represent non value adding activities), (KOSKELA, 1992)

These two conceptual models converge regarding the importance of not focusing the improvement effort on transformation activities. Since all activities consume time and money, but only transformation activities add value to the final product, there are many improvement opportunities by reducing or eliminating non value-adding activities.

Koskela (1992) also emphasizes that when a process analysis focuses only on the conversion activities, there is a misunderstanding that this would be the correct idealization from the customer point of view, since the remaining activities do not add value to the end product. However, the impact of this interpretation is that either the non-value-adding activities are left out of consideration or all activities are seen as conversion activities, and are therefore treated as value-adding. In the first case, what happens is that an effort to make a singular activity more efficient does not impact the production process as a whole (KOSKELA, 1992). In the latter case, it can lead to investments in non-value adding activities, instead of trying to eliminate them from the process (KOSKELA, 1992).

The understanding of the production system as a process of value generation is especially important in ETO environments, in which the relationship with customers needs to be constantly controlled. In this point of view, Koskela (2000) highlights the importance of understanding the production as a process of realization of the product as specified.

Shewart (1931 apud KOSKELA 2000) stresses that the first step for a company to satisfy customer needs is to translate their needs into physical characteristics of the product. The second step would be to establish means for obtaining these characteristics. Based on some prior research, Koskela (2000) depicted five different principles related to the customer – supplier relationship, as shown in Figure 3.5. The numbers presented in that figure refer to the following principles:

1. Ensure that all customer requirements, both explicit and latent, have been captured
2. Ensure that relevant customer requirements are available in all phases of production, and that they are not lost when progressively transformed into design solutions, production plans and products.
3. Ensure that customer requirements have a bearing on all deliverables for all roles of the customer
4. Ensure the capability of the production system to produce products as required
5. Ensure by measurements that value is generated for the customer.

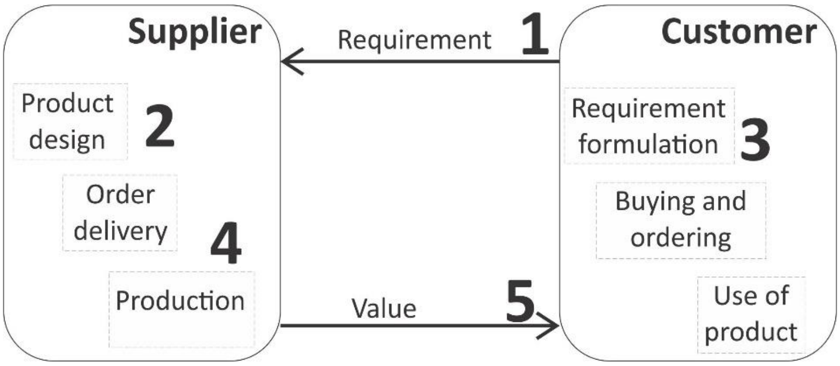


Figure 3.5: Principles related to the value generation concept (KOSKELA, 2000, p. 79)

3.2.2 Waste in production

Antunes Jr. (1998) emphasizes how the Japanese developed a new concept of waste in production, avoiding the traditional view of looking only at material waste that came from US mass production systems. The main idea of this new concept was to connect three different elements to the production: notion of value, costs and activities (ANTUNES JR., 1998a). Therefore, in TPS, waste can be generally understood as activities that generate direct or indirect costs but do not add value to the product from the point of view of the customer. Waste is concerned with any inefficiency that results in the use of equipment, materials, labour, or capital in larger quantities than those considered as necessary for the production (FORMOSO; ISATTO; HIROTA, 1999).

Ohno (1988) proposed seven categories of waste: (i) overproduction; (ii) waiting; (iii) transportation; (iv) processing itself; (v) inventory; (vi) movement; (vii) defective products. The main contribution of these categories for the way production was managed was the understanding that waste is more than material losses. There are also other categories of waste that have been proposed in the literature, such as (a) design of products that do not meet users' needs (WOMACK; JONES, 2004), (b) unnecessary capital investment (MONDEN, 1983), (c) theft and vandalism (BOSSINK; BROUWERS, 1996), (d) and a special kind called “making-do”, defined as a reduction of performance due to the fact that a task is started or continued even if not all standard inputs are available (KOSKELA, 2004), (e) not listening and not speaking (MACOMBER; HOWELL, 2004), (f) waste of worker's creativity (LIKER, 2003). It seems that the main role of existing classifications of waste is to call the attention of people to the most likely problems in a specific context.

Different types of waste have different impacts on a production system's performance (SHINGO, 1989). Ohno (1988) stresses the importance of being aware of overproduction in the car industry, since this waste is the root cause for most of the other types of waste. Overproduction makes it more difficult to identify problems, generating production islands with a large amount of inventory between the workstations (OHNO, 1988). Reducing overproduction is crucial because it means aligning supply with demand, requiring a deep understanding of demand and capacity (SHOOK, 2009). Liker (2003) also emphasize that overproduction discourage people to do preventive maintenance or to take care about the defective products since these problems do not affect the rest of the line.

The need for overproducing products is close related to the amount of work-in-progress (WIP) required in a production system. Hopp and Spearman (2000) define WIP as the inventory between the start and end points of a product routing, but not including, the ending stock points. In this regard, overproduction might cause WIP to grow and it is the WIP which turns the production process into a sequence of production islands hard to be managed. For Hopp and Spearman (2000) the amount of WIP can be used as a measure of effectiveness of a plant.

When production processes are separated from each other, there is a break in the flow of materials, often encouraging people to improve individual operations without much concern with the entire process. As discussed above, Shingo (1989) and Koskela (1992, 2000) strongly stress the importance of looking at the entire process instead of just at individual operations, as the latter may have a very small impact on the overall system.

3.2.3 Push and pull production

Pull production is considered one of the core concepts in the lean philosophy (HOPP; SPEARMAN, 2000; LIKER, 2003; ROTHER; SHOOK, 1999; SMALLEY, 2004; WOMACK; JONES, 2004), however, there is no full agreement in the literature on the definition of a pull production system. Pettersen and Segerstedt (2008) argue that the literature ends up advocating that the good things are “pull” and the bad things are “push”. The same authors state that push systems are said to be characterized by forecasting what will be needed, using large lots, high inventories, management by firefighting, and poor communication. By contrast, pull systems are characterized by considering actual demand, and using small lots, low inventories, waste reduction, management by sight, better communication.

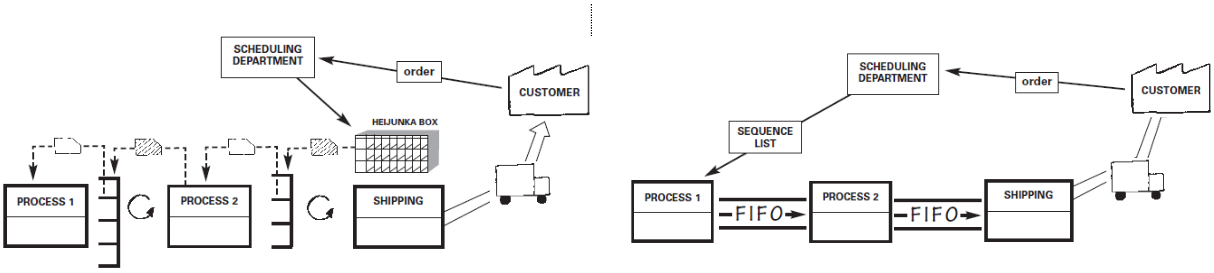
Frandson *et al.* (2013) highlights that pull systems are driven by demand, so that they ensure a steady flow because output rates and demand rates are matched; while push systems are driven by a plan or a forecast, so that output rates and demand rates are not necessarily matched. They argue that pull systems tend to have smoother flows in comparison to push systems.

The idea of pull is strongly related to a continuous flow, i.e., producing and moving one item at a time, or a small and consistent batch of items, through a series of processing steps as continuously as possible, with each step making just what is requested by the next step (LEI, 2008). For Monden (1983) continuous flow can be achieved either by the one piece flow, or by the use of a *kanban* (which means card in Japanese). A *kanban* contains information about the production needs from downstream processes (OHNO, 1988). As the *kanban* has become the main tool to manage the flow of materials in many plants, sometimes the whole production strategy is called *kanban* system (HOPP; SPEARMAN, 2000).

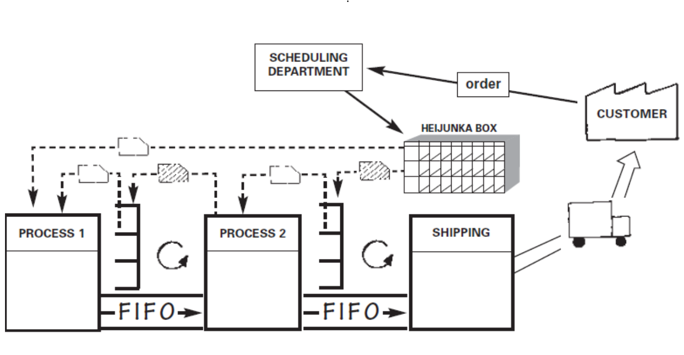
LEI (2008) defines a pull system as a method of production control in which downstream activities signal their needs to upstream activities, striving to eliminate overproduction; while a push system processes batches of items at a maximum rate, based on a forecast demand. Each process produces for a downstream process or just for storage. Womack and Jones (2004) stress that each process plays the role of internal client in the production system, by asking for the right quantity of products needed from the upstream process. Hopp and Spearman (2004) criticize this point of view by arguing that it confuses make-to-order with the idea of pulling.

Rother and Shook (1999) distinguish pull from push by the direction of information flows: in a push system information flows in accordance to material flow or each process is scheduled independently, while in the pull system information flows in the reverse direction in relation to material flows. The same authors emphasize that there is no pull system without using *kanban*. However Hopp and Spearman (2000) think that this kind of comparison is counterintuitive, since *kanban* is just a tool to enable pull production. In fact, Hopp and Spearman's definition of pull production contrasts with the understanding that is presented in publications of the Lean Enterprise Institute (LEI, 2008; ROTHER; SHOOK, 1999; SMALLEY, 2004; WOMACK; JONES, 2004), which is mainly based on the role of the final customer in the system.

The LEI (2008) considers that there are three types of pull production systems, as shown in Figure 3.6. The first type is based on the use of a supermarket between processes: withdrawal and production *kanban* cards regulate the need to replenish the supermarket through the production of the upstream process. It enables the final customer to have a product quickly, but requires a certain amount of inventory between processes. Although this is a controlled inventory, if there are too many different products to be produced this strategy might be infeasible.



Supermarket **Sequential**



Mixed Supermarket and Sequential

Figure 3.6: Types of pull production systems according to the Lean Institute (2008)

The sequential pull system represents one of the ways to manage inventory in a make-to-order production situation. Production only starts after the customer places an order. Products are, then, sequenced in a first-in-first-out strategy between processes. In this sort of system, there is a need to have short and predictable lead times. As products are not readily available, customers have to wait longer delivery times than in a system using a supermarket inventory.

Finally, the mixed pull system makes a differentiation between the most and the less required products, in such a way that the most required ones should be produced for supermarkets, achieving shorter delivery times, while the others could be produced according to customer orders.

For Hopp and Spearman (2000) what distinguishes a push from a pull system is the way work is released to the production system. In this conceptualization, the push and pull differentiation is not based on the use of real demand or forecasting. Those authors consider the client as an external member of the system, arguing that the so-called benefits of the pull production refers to the method of releasing work through internal processes, and controlling WIP. This idea led to the development of a production system called CONWIP.

This argument implies a different conceptualization of push and pull systems, which might lead to a different analysis of production systems, compared to some mainstream literature about lean. Indeed, Bonney *et al.* (1999) emphasize the contradictions of these definitions by arguing that sometimes the emphasis of the definitions can be on inventory replenishment, on lead times, scheduling methods, lean production, and the source of information.

Due to some criticism over their point of view, Hopp and Spearman decided to publish a further development of these ideas in the paper named “To pull or not to pull” (HOPP; SPEARMAN, 2004). In that paper, it is emphasized that a pull system is not the same as the *kanban* system or just-in-time. Regarding make-to-order production systems, those authors argue that this kind of system is not necessarily a pull system. They also make a distinction of pull systems at a strategic and tactic levels, stressing that, according to Ohno (1988), a just-in-time system should provide “what the clients need, when they need” at a strategic level, but not at a tactical level, since sometimes it is necessary to have some inventories in order to provide everything the customer needs. This is what Spear and Bowen (1999) call countermeasure.

According to Spear and Bowen (1999), Toyota has never considered its tools and practices as a fundamental part of TPS - the use of *kanban*, for example, was “a temporary response to specific problems”. Therefore, it was not seen as a solution, which would mean a permanent resolution, but rather as a countermeasure, to reveal the dynamics of the system and the acknowledgement to the benefits from the continuous improvement process.

Hopp and Spearman (2004) explored the benefits of using the *kanban* system, in order to understand the essence of pull production. According to those authors, these benefits are reducing WIP and cycle time, smoothing production flow, improving quality and reducing cost. For Krajewski *et al.* (1987[1] apud HOPP; SPEARMAN, 2004) those benefits are the consequences of an improved environment rather than any fundamental change in logistics.

However, Hopp and Spearman (2004) argue that if the flow control method provided by the *kanban* system was not important, companies would improve their environment and soon revert to MRP control system, which did not happen. Understanding this flow control as the main contribution for the pull systems, they developed in a series of papers (HOPP; SPEARMAN, 2004; SPEARMAN; ZAZANIS, 1992; SPEARMAN; WOODRUFF; HOPP, 1990), based on simulation models, discussing the benefits of keeping a constant WIP in the system. This analysis further developed the CONWIP model, as discussed in the next chapter. The main benefits are related to less congestion in the production line and to a facilitated control over the processes.

The CONWIP refers to the effects of modelling a push system, with a forecasted demand, in which the release of jobs was limited to a fixed size of queues, as a closed input-output network. In this scenario, Spearman, Woodruff, and Hopp (1990) argue that there is less cycle time variance using this close network because of a negative correlation between the number of jobs at each work station. In a pure push system, in which there is no control over the size of the queues, there is no correlation at all.

Regarding the facilitated control, Hopp and Spearman (2004) argue that WIP is easier to control than throughput since it can be observed directly, while throughput is usually controlled according to an estimated capacity considering process time, setup time, random outages, worker efficiency, rework, and other factors that affect production capacity. In fact, if the input rate is smaller than the production line capacity, then throughput is equal to input, considering an ideal system, with no defects along the way. Otherwise, throughput is equal to capacity and WIP builds with no limit (HOPP; SPEARMAN, 2004). When capacity is incorrectly estimated, input can easily exceed the true capacity. They point out that this is particularly true when seeking high utilization rates.

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[1] KRAJEWSKI, Lee J. et al. Kanban, MRP, and Shaping the Manufacturing Environment. Management Science, v. 33, n. 1, p.39-57, Jan. 1987. Institute for Operations Research and the Management Sciences (INFORMS). DOI: 10.1287/mnsc.33.1.39.

For this reason, they stress that systems that control WIP are substantially more robust to control errors than systems that control throughput. In a *kanban* system, there is a limitation on the size of each queue, so that when the limit is reached the upstream process stops producing. In the CONWIP system is the overall WIP that is limited, so there is less blocked processes and an increased variation in the size of the queues. For Hopp and Spearman (2004), a simple overall bound on WIP will promote the same benefits as the ones often assumed for *kanban* and that the throughput rate of a closed queuing without blocking is greater than the same system with blocking. This means that the benefits of a pull environment are related to the WIP cap than to the practice of pulling itself.

Concerning these first assumptions, Hopp and Spearman (2004) defined a pull systems as the extent to which work in process is limited at a low level in the production system. It is not an absolute definition, since it depends how sharply the WIP limit is imposed, and how low it is possible to be. This will determine how much the production system will benefit from the pull production.

Bonney *et al.* (1999) defined push and pull systems according to how the control information flows, like Rother and Shook (1999). Their study was based on a series of simulations comparing both systems and one of the conclusions was that, provided batch sizes are not allowed to grow and the resources are not overloaded, push systems performed better than pull systems. Although using a different definition, the conclusion of Bonney *et al.* (1999) corroborates the idea of Hopp and Spearman (2004) that the benefits of the system come from controlling WIP.

For Hopp and Spearman (2000) the benefits of limiting the WIP level are:

- Reducing manufacturing costs – disruptions in the line, such as machine failures, quality problems, etc. would not cause an explosion of the WIP.
- Improving quality – quality is both a precondition and a benefit of just-in-time. Since the higher the quality, the lower the WIP levels can be, a continual effort at WIP reduction will demand a continual quality improvement.
- Maintaining flexibility – as a pure push system can release work to a very congested line, it will generate a loss of flexibility in several ways:
  - parts that have been partially completed cannot easily incorporate design changes;

  - it is hard to make a priority or scheduling changes, as parts may have to be moved out of the line to make way for a high-priority part; and
  - finally, if WIP levels are high, parts must be released to the plant floor well in advance of their due dates. Because customer orders become less certain as the planning horizon is increased, the system may have to rely on forecasts of future demand to determine releases
- Facilitating work ahead – It is possible to work ahead of the schedule if the system is doing so well that the WIP levels are falling faster than they were supposed to.

Hopp and Spearman (2000) also highlight that reduction of variability in cycle times is one of the benefits of this approach. However, this should be seen as a required condition without which is not possible to design a production system with a limited and low WIP. It is worth acknowledging that this would be a characteristic of this system, but as a cause not as a consequence, which means that different strategies have to be taken to achieve this variability reduction.

The study of Pettersen and Segerstedt (2008) corroborate the benefit of reducing variability. According to the simulations carried out by those authors it was possible to see that an increase in WIP would not improve the throughput rate much but it would increase the variation in the lead-time.

It is important to emphasize that there are no pure push or pure pull systems. As stressed by Hopp and Spearman (2000) if a job is scheduled to be released by Material Requirement Planning (see section 4.3.1), but the information about a line congestion makes it wait longer, then the effect is a hybrid push-pull system. Conversely, according to the same authors, if a *kanban* system generates a production card for the start of a job that cannot be released because of anticipated lack of demand, this would be a hybrid system as well. In this regard, Bonney *et al.* (1999) reveal that even the Toyota System, the classical pull system, uses push information flow for the vehicle and pull information flow based on *kanban*s to ensure the availability of other parts on the assembly track.

It is worth noting that Hopp and Spearman (2000) disconnect hybrid system from the push-pull interface. While the latter refers to the point in the production process where there is a change in the production strategy (from push to pull and vice versa), the former refers to an overlapping of both systems in the same set of processes. Another important insight of Hopp and Spearman (2004) is the relationship between the client interference, regarding make-to-order, or make-to-stock systems, with the push or pull systems, as illustrated in Figure 3.7. Those authors show that there is no predetermined answer for the type of system, being possible to have a pull system using forecast or a push system based on a customer order.

	Make-to-order	**Make-to-stock**
Push	MRP based on a customer order	MRP with forecast
Pull	*Kanban* with *takt*-time and orders	*Kanban* with takt-time and forecast

Figure 3.7: Examples of push and pull systems (HOPP; SPEARMAN, 2004)

Tommelein (1998) emphasizes the importance of maintaining flexibility. In that study, the level of uncertainty hinders the possibility to anticipate what should be done. The adoption of a pull strategy enables a flexible schedule. However, she realized the existence of the matching problem in the construction industry, i.e., sometimes the components produced do not match with what is required on site. In this situation, there is a need to anticipate what should be produced, still based on a pull strategy.

Therefore, pull production can be applied at strategic or tactic levels, it can be achieved when a *takt time* is established to set the output of the plant to be equal to demand (HOPP; SPEARMAN, 2004). This would define a strategic or market pull, although it does not ensure a pull system at the operational level.

3.2.4 Transparency

Based on the observation of the communication between managers and operators in a factory, Greif (1991) pointed out the use of visual communication as a means to separate the network of information and the hierarchical structure of order giving. According to Koskela (1992), visual management is concerned with one way of achieving transparency. It is an orientation towards visual control in production, quality and workplace organization (GREIF, 1991). The goal is to render the standard to be applied and a deviation from it immediately recognizable by anybody (KOSKELA, 1992). For Liker (2003) the Toyota Production System is grounded on visual management.

Ohno (1988) suggests the use of different tools for easily visualizing what is going on in the production process. The information he highlighted was: what the production needs, what the main production problems are, and if the design operations were working. This information provided a factual inclusion of the communication and control system in the production system itself (ALVAREZ; ANTUNES JR., 2001). The use of visual management tools increases the capacity for processing information and reduces the feedback time for action-taking; control can be integrated into execution (ALVAREZ; ANTUNES JR., 2001). However Ohno (1988) highlighted the problem of producing more information than needed. According to this author information also has to be controlled. The use of *kanban* card is an important example of a visual tool containing just the useful information for the users.

Andon is a visual management tool commonly used in the car industry, that points out the status of operations in an area at a single glance and signals whenever an abnormality occurs (LEI, 2008). In some plants the *takt time*, the execution progress of current operations, and what are the new products to be produced next are displayed (ALVAREZ; ANTUNES JR., 2001). An *andon* can indicate production status, an abnormality, and needed actions, such as changeovers (LEI, 2008). It also can be used to display the status of production in terms of the number of units planned versus actual output (LEI, 2008).

Autonomation, one of the pillars of TPS, is concerned with creating process transparent with the aim of ensuring the quality of the products under production. Besides the device to make the machine stop whenever it detects a problem, a device to prevent the production of defective products, named *poka-yoke* is often used (OHNO, 1988). Shingo (1989) stresses that *poka-yoke* is only an intervention, not a goal in itself. Once there is a decision determining if the source, self, or successive inspection should be relied upon, the same author reveals that poka-yoke is a fool proof device, avoiding the need for inspection.

3.2.5 Learning process

For Shook (2008), one of the most important accomplishments of Toyota was that it has learned to learn. Spear and Bowen (1999) stress that these learning capabilities are sometimes disregarded in the lean literature, turning some tools and practices as the fundamental contribution of the production system. For this reason, those authors defined a set of rules to summarize the most important features from TPS:

- **How people work:** all work shall be highly specified as to contents, sequence, timing, and outcome
- **How people connect:** every connection must be standardized and direct, unambiguously specifying the people involved, the form and quantity of the

goods and services to be provided, the way requests are made by each customer, and the expected time in which the requests will be met.

- **How the production line is constructed:** every product and service needs to flow along a simple, specified path. That path should not change unless the production line is expressly redesigned.
- **How to improve:** any improvement to production activities, to connections between workers or machines, or to pathways must be made in accordance with the scientific method, under the guidance of a teacher, and at the lowest possible organizational level.

The first rule is concerned with how people work; it reveals the importance of learning through the comparison of the actual practice to a given standard. The work at Toyota is highly specified, Spear and Bowen (1999) pointed out that it reveals the importance that Toyota’s managers gave to details. When describing how to make a worksheet, Ohno (1988) emphasized the importance of visual control through the understanding of the work at a glance. In this regard, he relates standardized work with visual control: one should arrive in the workplace and easily understand what has to be done.

It is worth emphasizing the difference between the standardized work vs. the “one best way” developed by Ford. The latter is not open for changes or adaptation, whereas Toyota’s standardized work, once established and displayed at workstations, must be the object of continuous improvement (LEI, 2008). Ohno (1988) stressed the need to engage production personnel in writing the work sheets, since they must be convinced of their importance. With this in mind, deviation becomes immediately apparent, enabling workers and supervisor to move to correct the problem right away and then determine how to change the specifications or retrain the worker to prevent a reoccurrence (SPEAR; BOWEN, 1999).

For Spear and Bowen (1999) this is one of the paradoxes of the Toyota Production System: to make a very detailed procedure in order to make the operation procedure adaptable to the way people are doing their work. From the formalized starting point, it is easy to understand when there are deviations and, so, it is possible to analyse if the steps of the standard procedure need to be changed or if there is a problem in the operation (SPEAR; BOWEN, 1999).

The second rule is concerned with how people connect. There is a standardization in the organizational structure for order giving (SPEAR; BOWEN, 1999). The same authors postulate that it is clear for everyone who provides what to whom and when. The person designated to assist someone must respond immediately, solving the problem within the worker cycle time. If he fails perhaps the request signal is ambiguous, or the designated assistant has too many other requests for help and is busy or is not a capable problem solver (SPEAR; BOWEN, 1999).

The same authors stress that this is how the system can be continually adjusted, making it flexible. For that reason, Toyota emphasizes the need to ask for help, what might be counterintuitive for managers who used to encourage workers to try to resolve problems on their own; but it avoids problems to remain hidden (SPEAR; BOWEN, 1999).

It is also important to acknowledge the importance of using the Language-Action Perspective (LAP) to understand people communication. According to LAP, people interact through language (WINOGRAD, 1988). It emphasizes that before performing an action, a person made a promise for someone else and it is possible to manage the work through the management of this commitments (MEDINA-MORA *et al.*, 1992). As this perspective is based on promises, it emphasizes a two-way communication in which the one requesting the action allow the one performing the action to negotiate. Koskela and Howell (2002) claim for the use of LAP as the theoretical basis for understanding the operations process.

The third rule is concerned with how the production line is constructed. Spear and Bowen (1999) emphasize the importance of analysing the flow of products. As Shingo (1989) pointed out, in production every product has a path that has to be understood differently from the operations flow. In this rule, the hypothesis embedded is that every supplier connected to the pathway is necessary, and any supplier not connected is not necessary (SPEAR; BOWEN, 1999). The same authors also point out that these three rules enable Toyota to conduct experiments and remain flexible and responsive.

The last rule is concerned with how to improve. Frontline workers are the ones who make the improvements to their own jobs, and their supervisors provide direction and assistance as teachers (SPEAR; BOWEN, 1999). Continuous improvement is implemented by means of an important learning process which Shook (2008) described using A3. According to that author, in the TPS an A3 refers to more than an international-size piece of paper. It reveals the way problem-solving should be presented in order to be understood by everyone through the same lens. This tool describes a set of elements presented in a logical sequence: the problem faced, its root causes, the goals of the problem-solving, the actions proposed and the means of judging success (SHOOK, 2008).

The same author also points out the role of the managers at Toyota to enable the learning process. Unlike traditional command-and-control leaders who rely on the authority of their position to instruct others, the Toyota leader is concerned more with responsibility (SHOOK, 2008). The A3 process clarifies this responsibility by placing ownership to the A3's author. Although this author might not have developed the solution collectively, it reveals his or her acceptance to take the responsibility to get decisions made and implemented (SHOOK, 2008).

Nevertheless Shook (2008) stresses that this kind of improvement method has emerged for facilitating important management processes such as strategy management and problem solving. Spear and Bowen (1999) emphasize the importance of this emerging process, since a company that starts using TPS methods may use completely different ones in the long-term, according to how it was adapted facing their own problems (SPEAR; BOWEN, 1999).

4 PRODUCTION PLANNING AND CONTROL MODELS FOR ETO PRODUCTION SYSTEMS IN CONSTRUCTION

This chapter discusses the suitability of a set of production planning and control models for ETO prefabricated building systems. Initially, some basic concepts on production planning and control for construction projects are presented. Considering the ETO context, a set of requirements for production planning and control is proposed. Those requirements are then used to assess six categories of production planning and control models: Material Requirement Planning (MRP), Theory of Constraints, Workload Control, card-based approaches (*kanban*, CONWIP, and POLCA), and the Last Planner System (LPS).

4.1 PRODUCTION PLANNING AND CONTROL IN CONSTRUCTION PROJECTS

According to Hoc (1988), planning is a decision making process based on the prediction of the probable outcome of a situation through extrapolation from past events. He points out that planning is a matter of **anticipation**, which can be seen as the setting of relatively distant goals, and the elaboration of procedures to attain them. Hoc (1988) also acknowledges that anticipation is often associated with **schematization**, which is the ability to abstract relevant data from details in a situation. Schematization enables individuals involved in decision making to increase their ability for control over a situation, despite the limited capacity of working memories (HOC, 1988).

Johnston and Brennan (1996) argue that in the traditional *management-as-planning* approach there is an underlying assumption that plans can be used as a control structure for action. This approach to management views a strong causal connection between the actions of management and outcomes of the organization (KOSKELA; HOWELL, 2002). In this approach, although the development of plans is important for management, there is a naive conception that these are effective means of managing on-going repetitive activity (JOHNSTON; BRENNAN, 1996).

For Johnston and Brennan (1996), this traditional managerial approach is based on a planning model that considers the developer of plans as an agent from outside the world that is been managed. This world is considered objective and stable where a high degree of continuity, predictability and causality is ascribed. The claim of those authors is that in real world there is a need for different assumptions for the management.

For Johnston and Brennan (1996), management should be based in a situated activity model, in which a prototypical agent that is embodied, modular, situated, distributed, parallel, interactional and whose purposeful behavior is emergent. It means that the agent is a functional part of the world with which it is in immediate contact and interaction. Those authors point out the importance of a decentralized structure of management. By modular, parallel and distributed, Johnston and Brennan are referring to the use of functionally complete sub-units which could independently sense, model and act and, because of their small size, would be able to implement a tight coupling between sensing the world and acting on it. Therefore the tasks of planning and control are distributed rather than centralized.

Due to the tight connection between the agent and the world, agent deals directly with the situations presented in the environment and not through a centralized symbolic representation of the world. The idea of the interactionism and emergence is the acknowledgement that the outcomes are achieved through the interaction of a number of relatively simple devices. Therefore, the agent behavior emerges from the environment and is not the explicit program of an action (JOHNSTON; BRENNAN, 1996)

Given this assumptions, Johnston and Brennan (1996) see the manager as a coordinator and enabler of autonomous activities. Those authors call this approach as *management-as-organizing*. For Koskela and Howell (2002) this should be a basic assumption for developing a suitable project management theory. This view is also similar to the discussion of Laufer, Denkar and Shenhar (1996), in which managers are not responsible for taking the best decisions but to ensure that the best decisions are made by managing the decision-making process.

The management-as-organizing approach should be the main underlying assumptions in the development of planning and control systems for production environments plagued by uncertainty and in non-repetitive operations, such as ETO prefabricated building systems.

Laufer and Tucker (1987) emphasizes that planning should contain both information about what should be done and how it should be performed, i.e., it should include both goals and methods. Moreover, the planning process should not be seen as disconnected from the control process. Hayes-Roth and Hayes-Roth (1979) consider planning as the first of a two-stage problem solving process, the second one consists of monitoring and guiding the execution of the plan to a successful conclusion. For Hoc (1988) planning is strongly related to control, since when there is a decision to act in the system, although it can be conditioned by this prediction, it usually has the effect of modifying the system towards more satisfactory goals.

Laufer and Tucker (1987) proposed a conceptual model that defines the main steps of project planning and control (Figure 4.1): planning the planning process, gathering information, preparing plans, diffusing information, evaluating the planning process. The figure reveals two different cycles. The first is concerned with the production planning control cycle within the project, which involves a continuous effort of monitoring and correcting action. The second one is longer and intermittent, and refers to the learning process within the company from one project to the other, or through different phases of the same project (LAUFER; TUCKER, 1987).

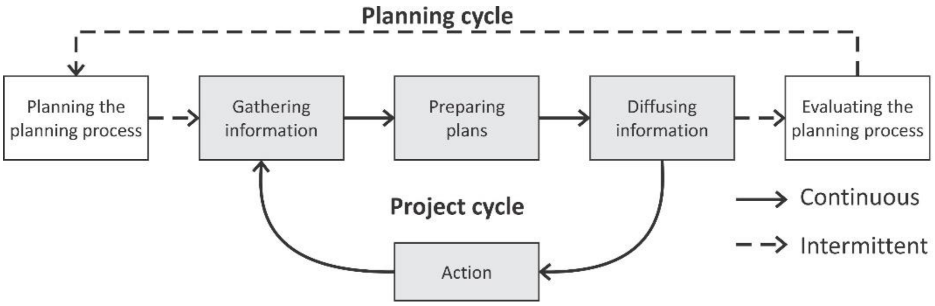

Figure 4.1: Planning and control process (LAUFER; TUCKER, 1987)

The planning accuracy, which can be understood as the extent to which plans materialize, is strongly affected by the degree of uncertainty in the project; the greater the uncertainty when plans are defined the lower planning accuracy (LAUFER; TUCKER, 1988). In this regard, those authors highlight the existence of the timing of planning dilemma: the influence of management, and so of the planning process, is greater the earlier it is defined, while the planning accuracy is higher when plans are defined as close as possible to the execution time.

In order to solve this dilemma, Laufer and Tucker (1988) argue that some decisions can be taken at an early stage, in relation to the start of production, as long as the level of detail is not high. For them, the impact of overly detailed plans are: (a) a costly planning process; (b) cluttered data, obscuring a clear overview of the project; (c) heavy updating requirements, which are time-consuming; and (d) high obsolescence, as detail plans decay much faster because some of the information is not based on reliable data. The need for updating the plans and the difficulty to understand a heavy detailed plan disrupt the two main capabilities of the planning process emphasized by Hoc (1988): anticipation and schematization.

As a result, Laufer and Tucker (1988) claim plans should be prepared at the early stages of the project with the lowest possible degree of detail, and then be increasingly detailed as the production process gets closer. Wight (1970) corroborates this idea by arguing that forecasts are more accurate in a short-term. Accordingly, the same author argues that, in a long-term horizon, forecasts can be accurate when dealing with a large grouping of items. When dealing with small grouping or individual items, there is a need to make the forecast closer to the execution.

For Laufer and Tucker (1988), the pace at which the level of detail increases varies according to the level of uncertainty. As shown in Figure 4.2, while in an environment with low uncertainty the level of detail may increase in a constant degree, in an environment with high uncertainty there is a need to remain in a low level of detail for a longer period and accelerate the detailing process closer to the execution.

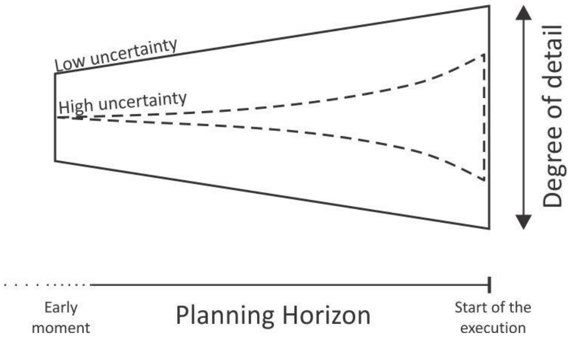

Figure 4.2: Influence of planning horizon on degree of detail, adapted from Laufer and Tucker (1988)

Laufer and Tucker (1987) suggest that the hierarchy of an organization mirrors the planning evolution: top managers are concerned with goals and means, middle managers are concerned with means and solutions, and low-level managers are concerned with the application of these solutions in practice. Each level should be concerned with a specific planning horizon that should fit the scope of their decisions (LAUFER; TUCKER, 1988).

Wiendahl, Von Cieminski, and Wiendahl (2005) developed a framework for understanding the main aspects of a production planning and control system to further analyse the common stumbling blocks that hinders the performance of the system. The production planning and control system of a company consists of all functions and tools used for planning and controlling the production processes in an organization (WIENDAHL; VON CIEMINSKI; WIENDAHL, 2005). They consider that the main scope of this system is the three value added processes: **source, make** and **deliver** and, therefore, it goes beyond company boundaries (from suppliers to customers). The six configuration aspects of production planning and control systems were (Figure 2.3):

- **Logistic Objectives:** concerns the strategic objectives of the company for the production, such as limitting WIP, maximum utilization capacity;
- **Process:** concerns the chronological order of planning and control activities, defining the workflow of order processing in terms of the information flow along the logistic process chain. It is also concerned with the work structuring, as discussed in the section 4.3.5;
- **Objects:** concerns the objects used for the planning and control activities. The most important ones are the items (raw materials, componentes or finished products), resources (machinery and personnel) and orders (like the customer orders); and
- **Functions:** concerns the activities required to plan and control the logistic processes in the stocks and in production. The fundamental activities are the definition of local objectives and targets, forecasting and decision-making, providing feedback on order progress as well as continuous improvement.
- **Responsibility:** concerns the definition of the people in charge of certain activities of the planning and control.
- **Tools:** aims to support the operational activities by using some degree of automation. This automation may enable staff to have more time available for decision making in the planning and control process.

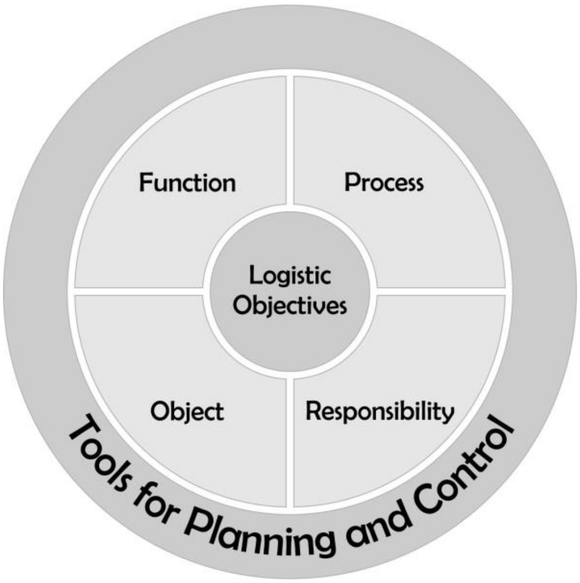

Figure 4.3: Configuration aspects of a planning and control system (WIENDAHL; VON CIEMINSKI; WIENDAHL, 2005)

The configuration aspects are centred on the idea of logistic objective (Figure 4.3). Although the definition of logistics is not explicit in that study, it seems to follow Baudin's (2004, p. 10) definition, in which "logistics is comprised of all operations needed to deliver goods or services, except making the goods or performing the services". In this view, Baudin (2004) points out that, for example, in a manufacturing plant bringing work pieces or tools to a machine is part of logistics, while cutting the metal is not. Therefore, the logistic objective of a production unit refers to the decision on which, when and how much products have to be delivered to the following PU (WIENDAHL; VON CIEMINSKI; WIENDAHL, 2005). This decision must be based on strategic guidelines, usually expressed in the main performance metrics used to evaluate the production unit.

Each production unit might require a different logistic objective, which should define the remaining configuration aspects of planning and control systems, as suggested by Wiendahl *et al.* (2005). In this regard, understanding the specific characteristics of the production system is fundamental to develop the most suitable set of tools for carrying out planning and control activities.

There are two stumbling blocks described by Wiendahl, Von Cieminski, and Wiendahl (2005), very relevant for the understanding of planning and control systems analysed in this investigation. The first is the 'missing position in system logistic objectives'. Those authors highlight the importance of defining consistent objectives, as well as communicating them to decision makers. For illustrating the conflicts between WIP level, utilization, throughput time, and schedule reliability, they developed Figure 4.4, based on the interaction of the logistics operating curves. Those curves “visually represents the correlation between a specific parameter of interest (the [logistic] objective or dependent variable) and an independent variable” (NYHUIS; WIENDAHL, 2008, p. 11).

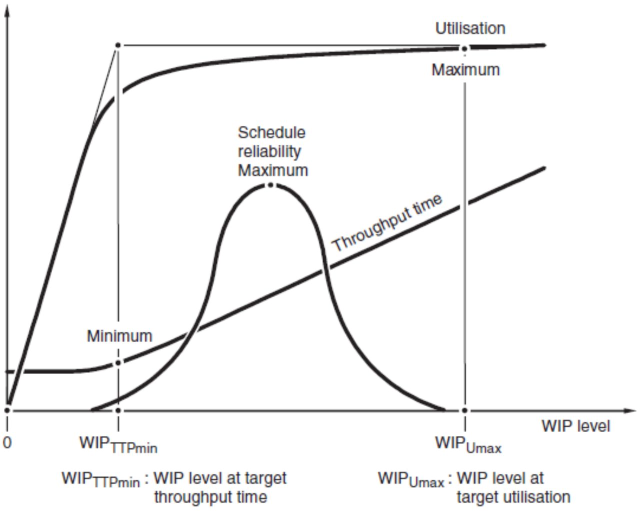

Figure 4.4: Logistics operating curves revealing the interdependencies between logistic performance measures (WIENDAHL; VON CIEMINSKI; WIENDAHL, 2005)

It is common to find production managers looking both for maximum utilization of capacity while striving to decrease throughput time. The operation curves reveal the interdependencies in between those strategies, and how the throughput increases in the case of using maximum utilization (WIENDAHL; VON CIEMINSKI; WIENDAHL, 2005). The same authors argue that it is not enough to communicate which is the most important metric; there is a need to check how incentives are given to the company employees.

The second chosen stumbling block is the ‘missing responsibility for inventories’. In this case, those authors use the example of an MTO company in which there was an unclear definition of interface, and there was no responsibility defined for the inventory levels of finished products. In that example, production receives customer orders and has to deliver up to a due date, while customer tends to ask for receiving as soon as possible, but end up postponing when realizing the products are not needed immediately, increasing inventory levels. For those authors, a possible solution would be to assign production the responsibility for finished products inventories.

4.2 CORE REQUIREMENTS

Considering the complexity of ETO production systems, and the high variety of products, particularly in construction, it is necessary to establish a specific set of requirements for planning and control systems. Based on a literature about planning and control for ETO environments (BERTRAND; MUNTSLAG, 1993; GOSLING; NAIM, 2009; KINGSMAN, 2000; SOMAN et al., 2004; STEVENSON; HENDRY; KINGSMAN, 2005), five general requirements were identified.

Any production process that starts from a customer order needs to estimate the lead-time to produce it, before the project starts. Kingsman (2000) emphasizes that failures to meet the promised delivery date might impact the amount of future business likely to arise from that customer. Bertrand and Muntslag (1993) stress that the quotation of one project needs to take into account the available capacity required from the remaining projects and as there are more quotations than actual customer orders, capacity and production planning becomes very difficult.

Soman *et al.* (2004) emphasize that the competitive priority for this kind of organization is often shorter lead times, although Kingsman *et al.* (1996) stress that some external factors such as the reputation for technical skills and quality, position of the company in the marketplace and financing options might also play a key role in winning an order.

In this regard, Soman *et al.* (2004) state that capacity planning, order acceptance and rejection, and attaining a high due-date adherence are key issues for any make-to-order system. Stenvenson, Hendry, and Kingsman (2005) stress that this capacity planning should be addressed at several levels, including the stage at which orders are first considered. Therefore, the customer enquiry stage is of particular importance for planning and control in this kind of production system. Therefore, the first requirement for a suitable planning and control system is:

> *1. Plan capacity at the customer enquiry stage in order to establish the due date of the project.*

Stenvenson, Hendry, and Kingsman (2005) highlight that capacity planning should not be made only at the costumer enquiry stage, since along the project the customer may make additional decisions about the design and the delivery time. After order confirmation there is also a certain period before the project is released to production, as stressed by Kingsman (2000). Therefore, Stenvenson, Hendry, and Kingsman (2005) consider the need to include the Job Entry and the Job Release Stage, focusing on due date adherence as a requirement for planning and control in make-to-order production systems. As the study of those authors is concerned with the MTO environment, their focus was on planning and controlling the manufacturing process at the operational level.

The job entry stage is an important feature for the production system, since it defines a point of confirmation for the production of the project. Bertrand and Muntslag (1993) deal with this issue in a wider approach, proposing a decision structure. The essential idea of having a hierarchical decision structure approach is to decompose a global problem into a set of smaller manageable sub-problems, in which each level should solve its own problem and give a feedback to the higher level (SOMAN *et al.*, 2004). For Hayes-Roth and Hayes-Roth (1979) this feedback process is important since, in their point of view, the planning process is opportunistic, which means that it is able to learn from operational level. According to those authors, although sometimes there is a need to adopt a top-down approach for defining plans, there are some decisions that emerge from less orderly opportunities.

As a result, the second requirement concerns a combination of the operational view of the job entry stage, from Stenvenson, Hendry, and Kingsman (2005), and the strategic guideline of a decision structure from Bertrand and Muntslag (1993) to provide bottom-up feedbacks from the production to the managerial levels. The idea is that there is a need for confirmation points before starting a production process:

> *2. Deal with uncertainty in process and product specification by confirming the need for producing the products.*

The confirmations highlighted in the second requirement refers to the trigger to start a given production phase. For a confirmation to be worthwhile, the production process needs to be flexible in terms of volume, which is defined by Suarez, Cusmano, and Fine (1995) as the “ability to change significantly both the production level and the composition of the production mix in a relatively short time span, in order to quickly respond to unexpected demand changes”.

The manufacturing plant is a critical process in this chain, since it is the first transformation process to use physical raw materials and design information as a resource. According to

Stenvenson, Hendry, and Kingsman (2005), any make-to-order system, such as fabricate-to-order or engineer-to-order, needs some specific operational controls that enables the production of non-repetitive products and, regarding the manufacturing plant, that is developed through variable routings. Specifically in an ETO production system, more than non-repetitive, components have to meet customer requirements. Those requirements sometimes affect even the routing for fabrication. Therefore the third requirement of the planning and control model is:

3. Deal with customer-oriented non-repetitive production and variable routings.

It is worth emphasizing that in an ETO environment the production process happens in different production units: design, engineering, manufacturing, and assembly, as described previously. The scope of an organization could be focused on only one of these production units. Bertrand and Muntslag (1993) point out that there is a need to develop control mechanisms both for the management of one project throughout the production units and for the management of the set of projects one unit has to produce, differentiating goods flow control, from production unit control, respectively. As this investigation is dealing with construction projects, it is rather used the term project flow control instead of goods flow control.

Differently from a traditional make-to-stock production system, the production process in an ETO environment needs to manage the hand-offs between each production unit, such as from the conceptual design to engineering design and then to manufacturing and to assembly. The project flow control (PFC) is concerned with this overall coordination of the chain. This differentiation is analogous to what happens in manufacturing when dividing processes from operations, as proposed by Shingo (1989). Given this, the fourth requirement is:

4. Promote a distinction between project flow control and production unit control.

As stressed by Wiendahl, Von Cieminski, and Wiendahl (2005), the manufacturing plant tends to strive for the best utilization of shop capacity as a matter of a quicker return on investment on machinery. This can result in a disconnection of goals and of information flow between the various production units within an organization (WAHLERS; COX, 1994; WIENDAHL; VON CIEMINSKI; WIENDAHL, 2005).

Bertrand and Muntslag (1993) stress the need to promote this alignment by managing the interface between production and sales. According to those authors, the sales department is responsible for ensuring sufficient product demand and for accepting customer orders, while production is responsible for providing production capacity and ensuring that the customer order is completed on schedule. However, they emphasize that sometimes there is a conflict between the required and the available resource capacity due to the lack of flexibility in the production capacity. A possible solution would be to use the order generation to determine planned input and output, as well as the planned order sequence (WIENDAHL; VON CIEMINSKI; WIENDAHL, 2005). For the aforementioned reasons the last main requirement for a planning and control model for the ETO environment is:

5. Manage the interface between production and sales.

Conditions and circumstances may change during the customer order. Customer may change his original specifications; a number of other customer orders may have been accepted while the negotiations were taking place; the capacity requirements of previously accepted orders appear to be greater than originally anticipated; the order negotiations extend over an extremely long period of time, leading to changes in the original estimates of the total capacity requirements (BERTRAND; MUNTSLAG, 1993). Because of these conditions there is a need to continuously revise and reconfirm the relevant conditions between Sales and Production (BERTRAND; MUNTSLAG, 1993). In TPS, the main connection between sales and production output is established by the *takt* time, which plays a key role in the definition of the necessary capacity of the manufacturing plant, and also in the synchronization of operations (HOPP; SPEARMAN, 2004).

The requirements described above have been used to understand the suitability of a set of planning and control models for dealing with an ETO production system. They are also a source for the development of the final planning and control model of this research. It is worth noting that this selection is not meant to be a definitive and limited selection of requirements, but it is rather a contribution for the development of planning and control models based on a management-as-organizing approach, striving for integrating plans between production phases.

4.3 PLANNING AND CONTROL MODELS FOR ETO

According to Ackoff and Sasieni (1968), a model is a simplified representation of the reality, based on the assumption that a large number of variables are required to understand a phenomenon accurately, but the selection of some of these variables is enough to explain most of it. A model can also be understood as one of its definitions in the dictionary: “a thing used as an example to follow or imitate” (STEVENSON, 2010).

Different models have been used for describing the planning and control systems at an abstract level. Each of these might be better suitable to one or more specific production situation. It may also concern to different hierarchical levels, which means that different models can be merged to provide a complete a planning and control system of a company. The idea of naming planning and control systems as models is the possibility to provide a more general discussion rather than focusing on real systems adopted in specific organizations. These discussions are an attempt to explicit the underlying assumptions of each model.

Stenvenson, Hendry, and Kingsman (2005) carried out an extensive literature review in order to assess the applicability of six planning and control models for a make-to-order situation: MRP, Theory of Constrains, Workload Control, *kanban*, CONWIP and POLCA. The analysis of Stenvenson, Hendry, and Kingsman (2005) was a starting point for selecting the planning and control models to be assessed in this research work.

As the focus of Stenvenson, Hendry, and Kingsman (2005) was make-to-order production systems, some models were mostly focused on manufacturing plant management, such as the *kanban*, CONWIP and POLCA. These approaches are card-based methods for controlling the production in the manufacturing plant, developed from the *kanban* approach, and cannot be considered as complete planning and control models. In this regard, although there are some differences among these methods, they are going to be analysed as Card-based approaches mainly because the benefits for the entire production process of an ETO organization are based on its underlying ideas.

In this context of ETO prefabricated building systems, besides the aforementioned approaches, there is a possibility to use project-based approaches, such as the Last Planner System, which is based in different assumptions when compared to the management approaches used with an MRP system. The LPS was included in the analysis, because it has been successfully used in a large number of construction projects, not only in the construction phase (ADAMU; HOWELL, 2012; ALSEHAIMI; TZORTZOPOULOS; KOSKELA, 2009; BALLARD, 2000; HAMZEH, 2011; KALSAAS; SKAAR; THORSTENSEN, 2009; KIM; JANG, 2005), but also in the design phase (HAMZEH; BALLARD; TOMMELEIN, 2009; KEROSUO et al., 2012; WESZ; FORMOSO; TZORTZOPOULOS, 2013). Other project-based management approaches, such as PERT and CPM, were not included because they are based on the similar assumptions of MRP.

Figure 4.5 summarizes the selected planning and control models, including their objectives, and scope. This latter information indicates whether the model is able to manage a project throughout different production units, or it is focused on one of them.

		Objective	**Scope**	**References**
MRP		To manage the start of a production order by forecasting demand of products so that all the resources of a product can be early predicted, as well as the lead time for its completion.	Throughout the production units involved within an organization	(BERTRAND; MUNTSLAG, 1993; HOPP; SPEARMAN, 2000; ORLICKY, 1974)
TOC		To keep all the production processes in the same pace. The rhythm is given by the major constraint of the line. All the processes become connected. A continuous effort has to be taken in order to continuous improve the performance of the main constraint.	Manufacturing	(GOLDRATT; COX, 2007; GOLDRATT; FOX, 1986; GOLDRATT, 1988, 1994; LOCKAMY; COX, 1991; RAHMAN, 1998)
Card-based approaches	***KANBAN***	To control the trigger to start the production of a component in one station through the request of this component by the next. The unit of control is the component	Manufacturing	(ANTUNES JR. et al., 2008; HOPP; SPEARMAN, 2004; OHNO, 1988)
	CONWIP	The same as *kanban*, but the unit of control is the final product.		(SPEARMAN; WOODRUFF; HOPP, 1990)
	POLCA	The same as *kanban*, but the card is concerned to a pair of cells rather than particular parts within a cell		(SURI; KRISHNAMURTHY, 2003; SURI, 1998)
Workload Control		To control WIP, by confirming the need for producing a product, through different confirmation sources: client, resources, and plant capacity.	Throughout the production units involved within an organization	(HENDRY et al., 2008; KINGSMAN, 2000; LAND; GAALMAN, 1998; STEVENSON; HENDRY; KINGSMAN, 2005)
LPS		To use workers' promises to do the work as a basis to control activities. There is a need of an early process to make resources available for production by systematically removing their constraints.	Construction site installation and design	(BALLARD; HOWELL, 1997, 2003; BALLARD, 1994, 2000)

Figure 4.5: Overview of the basic assumptions of each planning and control method

In the following sections, each of those models are briefly explained and assessed according to the requirements that have been proposed for ETO situations. The description of the models is mostly based on the main functions of planning and control systems, as suggested by Wiendahl, Von Cieminski, and Wiendahl (2005): source, make and deliver.

4.3.1 MRP/MRPII/ERP

Material Requirements Planning (MRP) is a computer-based management system, developed in the early 1960s, due to the complexity and tedium of scheduling and inventory control (HOPP; SPEARMAN, 2000). MRP quickly became the predominant production control system in the manufacturing industry in the United States. Manufacturing resource planning (MRP II) was the first development, which further became Enterprise Resource Planning (ERP) (HOPP; SPEARMAN, 2000). For Slack, Chambers, and Johnston (2007), this development reflects the increasing need to integrate information systems at the supply chain level. However, Stenvenson, Hendry, and Kingsman (2005) state that the core planning and control assumptions underpinning these models have developed less rapidly. In this regard, the aforementioned authors argue that the same assumptions from the first version of MRP have been applied in more advanced versions of that model. Therefore, the terms MRP, MRPII, ERP are going to be referred as MRP systems.

MRP uses product information in the form of a bill-of-material (BOM) together with demand information in the form of a master production schedule (SLACK; CHAMBERS; JOHNSTON, 2007). This product demand may be based on customer orders or on a demand forecasting (SLACK; CHAMBERS; JOHNSTON, 2007). The bill-of-materials defines the relationship between a finished product and its constituent parts, called lower-level items, as shown in Figure 4.6 (HOPP; SPEARMAN, 2000). The demand for components by the finished products generates a **dependent demand** for lower-level items, while the demand for finished products by the customer is an **independent demand** (HOPP; SPEARMAN, 2000).

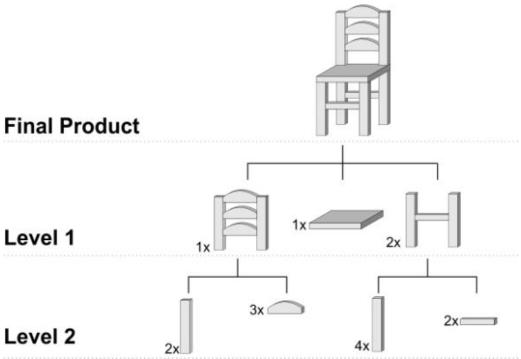

Figure 4.6: Example of a Bill-of-Materials

According to Hopp and Spearman (2000), one important contribution of MRP is that it differentiates the dependent from the independent demand, so that production can meet dependent demand through a schedule that explicitly track how to meet independent demand. Therefore, the basic mechanism of MRP is to work backwards from a production schedule of external orders to the internal dependent demand (HOPP; SPEARMAN, 2000). MRP can be generally understood as a push system, since the trigger to start a task comes from the previous process, based on a schedule. However, it can be seen as pull system if there is some mechanism in production for controlling the release of orders according to actual WIP (HOPP; SPEARMAN, 2004).

Although for Stenvenson, Hendry, and Kingsman (2005) MRP has been successful in reducing inventory levels and improving customer service levels in many instances, there is some criticism related to some basic assumptions of this model. It assumes that production stages lead times are fixed and predictable, as if the lead time for replenishing a component had a dedicated production stage that just produces that element (GRAVES, 1987). Ioannou and Dimitrou (2012) also challenge the MRP assumption of fixed lead time, as the main limitation of MRP. For them, lead times should be derived from the existing workload in the system.

Moreover, since MRP is focused on breaking the products into its components, it is possible to argue that this model understands production according to the transformation model (KOSKELA, 2000). For this reason, it has all the drawbacks resulting from the adoption of the transformation conceptualization, such as the trend to increase WIP level (HOPP; SPEARMAN, 2000).

4.3.1.1 Applicability of the MRP

Bertrand and Muntslag (1993) argue that using MRP systems to manage engineer-to-order production is counterintuitive. Stenvenson, Hendry, and Kingsman (2005) emphasize that although it is widely used, the fact that almost any kind of production system can be modelled into an MRP software platform, does not mean that MRP is really fulfilling the necessary requirements. As pointed out before, there is much uncertainty in ETO production systems, while in MRP it is assumed that batches are formed by well-known discrete standard products (BERTRAND; MUNTSLAG, 1993). As the product is not completely specified before the design is ready, there is a need to assume part of the bill-of-materials required for the project for the MRP system. Therefore, the dependent demand created may be subject to change, increasing uncertainty.

In this regard, Little *et al.* (2000) claim for a project-related variant of MRP suitable for ETO production systems. Those authors highlight that the due date for a new order should take into account the existing workload and the forecast capacity for all production units. Although MRP systems can provide an analysis of the utilization of future capacity, it is not suitable for verifying the real capacity in use. Therefore, the first requirement regarding the evaluation of the required capacity is just partially fulfilled.

Turner and Cochran (1993) stress that when there is uncertainty over methods, it means that the fundamental building-blocks of project management cannot be defined in advanced, such as the work breakdown structure (WBS), which is related to the tasks required to complete the job and their sequence. Analogously it is possible to infer that if the WBS of a given project cannot be defined, in a manufacturing environment the BOM would also be unsuccessful, which means that MRP would not be suitable when there are uncertainties over methods. Ioannou and Dimitri (2012) emphasize by assuming a definite bill of materials and constant lead times the MRP becomes not suitable for dealing with uncertainty in product specification and, therefore, does not fulfil to the second requirement.

Regarding the applicability to non-repetitive products and variable routing, MRP is able to fulfil this requirement as long as the specification of the product and the routings needed in the plant could be established at the beginning of the project. It means it is applicable for Repeat Business Customizers environments. However, when components are highly customised, such as the case of Versatile Manufacturing Companies, the model is not applicable.

During the emergence of the Enterprise Resources Planning (ERP) there was the development of the client/server information technology architecture, in which it was possible to integrate virtually all of a corporation’s business applications with a common data base (HOPP; SPEARMAN, 2004). Jin and Thomson (2003) pointed out that a major benefit of this system is that it supports the management of work orders by tracking them from inception to receipt of payment towards various cost centres or contracts. Therefore, the system is capable of providing project flow control.

However, it lacks effectiveness concerning the production unit control since the model defines the bill of materials at the beginning of the project, using a detailed component unit since then. Jin and Thomson (2003) reported some cases in which companies used phantom items in order to use MRP without product definition. However, this approach caused serious problems later when trying to relate purchase and work orders to products and contracts. For this reason, the distinction between project flow and production unit control is only partially fulfilled.

Regarding the link between production and sales, the functionalities of the ERP platform enable the definition of goals according to actual data regarding the sales. The use of this information is a matter of management strategy, more than the system capabilities. Nevertheless, Stenvenson, Hendry, and Kingsman (2005) point out that the evolutionary process from MRP to ERP does not seem to have eased the problem of integration and implementation, eased data requirements nor tackled the key characteristics of the make-to-order industry that differentiate it from more repetitive manufacturing environments.

4.3.2 Theory of Constraints

The theory of constraints is a bottleneck-oriented concept, developed by Eli Goldratt during the Eighties, evolving from the Optimized Production Timetables system (OPT). According to Goldratt (1990, p. 5), a constraint is “anything that limits a system from achieving higher performance versus its goal”. Therefore, all production systems have at least one constraint, otherwise it would have unlimited profits. The same author also defines that a constraint should be seen as an opportunity for improvement, which is possible to be understood through the analysis of the five steps to apply his approach (GOLDRATT, 1990, p. 6):

1. **Identify the system's constraints:** Goldratt (1990) stresses that identifying a constraint also means to prioritize it according to its impact on the overall goal.
2. **Decide how to exploit the system's constraints:** the aim of this step is to make sure that a physical constraint will be as effective as possible and that a managerial constraint should be removed (RAHMAN, 1998).
3. **Subordinate everything else to the above decision:** the pace of the constraint is established throughout all the process (GOLDRATT; COX, 2007), so that the non-constraints must support the maximum effectiveness of the system (RAHMAN, 1998). Goldratt (1990) also emphasize the need for a continuous improvement effort, since there must always be a way to reduce the limiting impact of the constraints.
4. **Elevate the system's constraints:** rigorous improvement efforts are needed on the most critical constraints (RAHMAN, 1998). Improving constraint performance can lead to improvements in the overall system performance (RAHMAN, 1998).
5. **If in the previous steps a constraint has been broken, go back to step 1:** In the last step, Goldratt (1990) stresses the need to be aware of a set of rules derived from the current constraint. According to that author it would mean a policy constraints. When a constraint is removed there is a need to review those rules.

The TOC has two main components: (a) the philosophy of TOC, consisting of the just mentioned five steps of on-going improvement, the drum-buffer-rope (DBR) scheduling methodology, and the buffer management information system; (b) a generic approach for investigating, analysing, and solving complex problems, called thinking process (RAHMAN, 1998).

Regarding the Drum-Buffer-Rope (DBR) approach, Goldratt and Cox (2007) define the drum as a 'drumbeat' for the entire plan limited by a constraint, which can be the production rate of the bottleneck or the capacity-constrained resource (CCR). The former is concerned with a physical limitation that limit the system, while CCRs are resources which constrain the system due to management policies and procedures (GOLDRATT; FOX, 1986). The concept of drum can be related to the rhythm given by the *takt-time* in the lean philosophy. The difference is that the latter is established according to the required demand, while the former by a system constraint.

Lockamy and Cox (1991) explain that an inventory buffer, named by Goldratt as a time buffer, is positioned in front of CCR or other constraint to shield it from disruptions at upstream processes. To avoid this inventory from increasing beyond acceptable levels, there is a need to control the rate at which raw materials are released to the plant. Therefore, there is a need of the ‘rope’ to ensure that the release of materials is tied to the actual production rate of the CCR (GOLDRATT; FOX, 1986).

The flow model described by Koskela (2000) is aligned with the idea of the drum-buffer-rope approach. One of the main rules of the theory concerns the importance of balancing flow instead of capacity (GOLDRATT; FOX, 1986). For Antunes Jr. (1998b) manufacturing managers may let their plants capacity unbalanced because it is easy to buy some capacity or even because of a strategic interest. The same author stresses the importance of assuming this unbalanced capacity, in order to focus the management efforts on synchronizing the flow of products.

In TOC there are two important sets of performance measurements: the operational and the global measurements (RAHMAN, 1998). The former refers to the measurement of some outputs such as (a) throughput rates, the output of the system; (b) Inventory, to analyse the money invested waiting to sell; and (c) Operating Expenses, money required to turn inventory into throughput (RAHMAN, 1998). The latter refers to (a) Net Profit, total throughput minus the operating expense; (b) Return on Investment, the net profit divided by inventory; and (c) Cash Flow, which makes it visible if there is enough cash in the company (RAHMAN, 1998). The contribution of the TOC regards the focus on those metrics, instead of focusing on the reduction of operating expenses, it focuses on increasing throughput for, then, reduce inventory. The operating expanses become the less priority (RAHMAN, 1998).

From TOC, Goldratt developed the critical chain production management (CCPM), applying the manufacturing principles for project management (GOLDRATT, 1997). In that approach, instead of having one buffer after each activity from the critical path, there is a project buffer located at the end of the schedule (GOLDRATT, 1997). By using buffers, Goldratt claims for a reduction in the cycle time of each activity. This should be achieved by avoiding multi-tasking. Therefore, the principle behind this cycle time reduction is the reduction of WIP levels. In a multi-project environment, Leach (2014) claim for the control of WIP at the organizational level, avoiding releasing new projects when there is a large number of projects already taking place.

The CCPM acknowledges three types of uncertainty in project planning, namely “task time uncertainty”, “path time uncertainty”, and “resource uncertainties”, As it is based on the TOC, the CCPM focuses on throughput and constraints (YEO; NING, 2002).

4.3.2.1 Applicability of the TOC

The ability to plan the capacity at the customer entry stage is possible through CCPM from TOC. Since this project management approach is based on scheduling the activities and re-understanding buffers position, it is possible to plan the use of capacity and define a due date at the customer order intake stage.

Although the CCPM is said to be focused on dealing with uncertainty, it addresses the uncertainty on task durations, sequencing and required resources. The product specification is not addressed in this approach. As a result, neither is the idea of collaboratively confirm the need for producing the projects. Therefore, this requirement was not fulfilled.

Mabin and Balderstone (2003) reveal some benefits in manufacturing-based applications of the TOC, such as lead-time reduction, cycle time reduction and increased revenue. Wahlers and Cox (1994) showed that these benefits are also possible in a highly customized ETO production systems. A major criticism to TOC is the limited applicability of a bottleneck-oriented model to complex production environments (SIMONS; SIMPSON, 1997 *apud* STEVENSON; HENDRY; KINGSMAN, 2005).

In a complex job shop[1] configuration, products routines vary according to the product specifications, turning the dominant bottlenecks dynamic. As a result, in comparison to MRP, TOC will perform better if there is a dominant bottleneck, but MRP outperform when there are highly customized products (STEVENSON; HENDRY; KINGSMAN, 2005). For this reason the model was considered as partially fulfilling the requirement of non-repetitive customer-oriented production.

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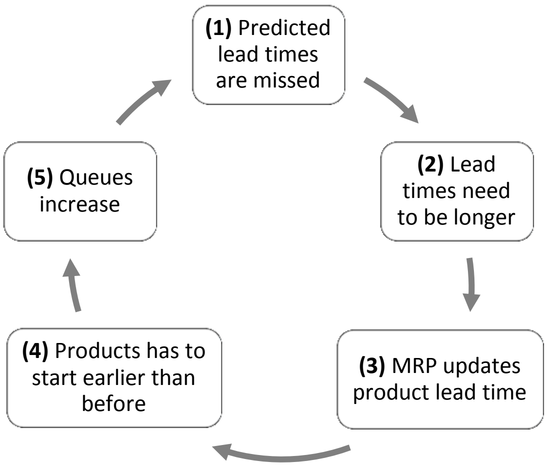
[1] A pure job shop is a shop configuration in which routing sequences are random; jobs can start and finish at any work centre allowing complete freedom and customization, very common to ETO situations.

Using the CCPM, the TOC is capable of dealing with the project flow, since this management approach is focused on the critical chain of the project, instead of focusing on the bottleneck. Leach (2014) highlights the ability of the CCPM in dealing with a multi-project environment. Applied in the plant, the TOC is focused on the management of a production unit, focusing on the flow of products. Therefore, the model is able to provide a differentiation between project flow and production unit control.

The role mechanism from the drum-buffer-rope method is a means for integrating the supply chain and production. Regarding this control over the production process, Wahlers and Cox (1994) argue that the theory of constrains is able to provide a connection between the production and the sales department. Therefore, the theory of constraints is not a complete model that deals with all requirements of an ETO production system. However, it can be useful to control the pace of the manufacturing process for this kind of system. Stenvenson, Hendry, and Kingsman (2005) stressed that it continues to be an option widely considered by practitioners and has been used effectively in ETO in highly customized environments, when there is only a flow shop floor configuration.

4.3.3 Workload Control

Workload Control (WLC) is based on the input/output control proposed by Wight (1970). According to Wight, a key problem in the management in most manufacturing plants is the lack of lead time control, in spite of all the different control tools that have been developed. The main assumption of Wight (1970) for the input/output control is the vicious cycle presented in Figure 4.7.



(1) Most of the companies do not understand the fundamentals of the lead time control. Lead time is just assumed to be known, but is not controlled.
(2) Lead time concerns the sum of the setup time, running time, moving time, waiting time and queueing time. According to Wight, the latter is where the products spend most of the time. Queues, or work-in-progress, increase lead times.
(3) Any planning method needs to use lead times to predict due dates.
(4) If an MRP is used, when the system assumes that lead time have increased, orders will be placed earlier than before.
(5) Placing product earlier means an increasing in backlog and, therefore, in queues
(1) **(closing the cycle)** The redefined lead time is not going to be achieved

Figure 4.7: Vicious cycle in the misunderstood lead-times controls, according to Wight (1970)

Through this assumption, Wight (1970) argues that this chaotic situation prevents managers from knowing which are the jobs that should be done first, since all jobs are late, according to the existing production planning and control system. The aim of an input/output control is to ensure that the amount of products is enough and that the right ones have been done (WIGHT, 1970).

Workload Control is based on the need of addressing that the right products are going to production. Jobs are only released onto the shop floor if released workload levels will not exceed preset limits, while the jobs in the pool cannot stay too long in order to reduce lead times (STEVENSON; HENDRY; KINGSMAN, 2005). Kingsman (2000) argues that the first aim of this model is to process the jobs in a way that the promised delivery dates can be achieved using the machines and workforce capacities available. The second aim is to determine if the lead times for the new customer are possible, along with the actions that are necessary to achieve particular delivery lead times, such as obtaining extra capacity, movement of operators, and subcontracting (KINGSMAN, 2000).

According to Stenvenson, Hendry, and Kingsman (2005), Workload Control was specially designed for make-to-order industry. It uses a pool of orders to reduce shop floor congestion, making the shop floor more manageable, consisting of series of short queues (STEVENSON; HENDRY; KINGSMAN, 2005). Kingsman (2000) explains that the term Job Pool comes from the managers practice to hold up jobs that, although have all the materials available, are not released to the shop to allow batching jobs into efficient production packages. So, it is assumed that there is a standard time, a pool delay, that jobs normally wait once the material has arrived, before being released to the shop floor (KINGSMAN, 2000).

The same author remarks that, in this model, there are workloads, or backlogs of work, for every work centre on the shop floor. These workloads are the sum of the queue of jobs in front of the work centre and the indirect work of all jobs at upstream work centres (KINGSMAN, 2000). In accordance to what Bertrand and Muntslag (1993) and Little *et al.* (2000) have proposed for engineer-to-order production systems, Kingsman (2000) emphasize the need of four levels at which the control of work can be carried out in the WLC method:

- priority dispatching,
- job release,
- order acceptance, and
- order entry at enquiry stage.

In order to deal with the situation of a customer taking a long time to consider and accept the bid made in response to an enquiry, Kingsman (2000) added the “order acceptance” stage that had not been mentioned in previous research. The idea of this stage is to establish a time limit after which the bid lapses. Figure 4.8 summarizes the relationship between levels of control along the production process. Kingsman (2000) stresses that the products can be found in one the following stages, as addressed in Figure 4.8:

(1) a bid made in response to a customer enquiry and awaiting the customer decision,
(2) a confirmed order awaiting the arrival of its raw material and/or having the design and manufacturing configuration being finally specified,
(3) a confirmed job, with its material having been delivered, in the production planner’s office awaiting release onto the shop floor,
(4) a job currently being processed at some work centre on the shop floor.

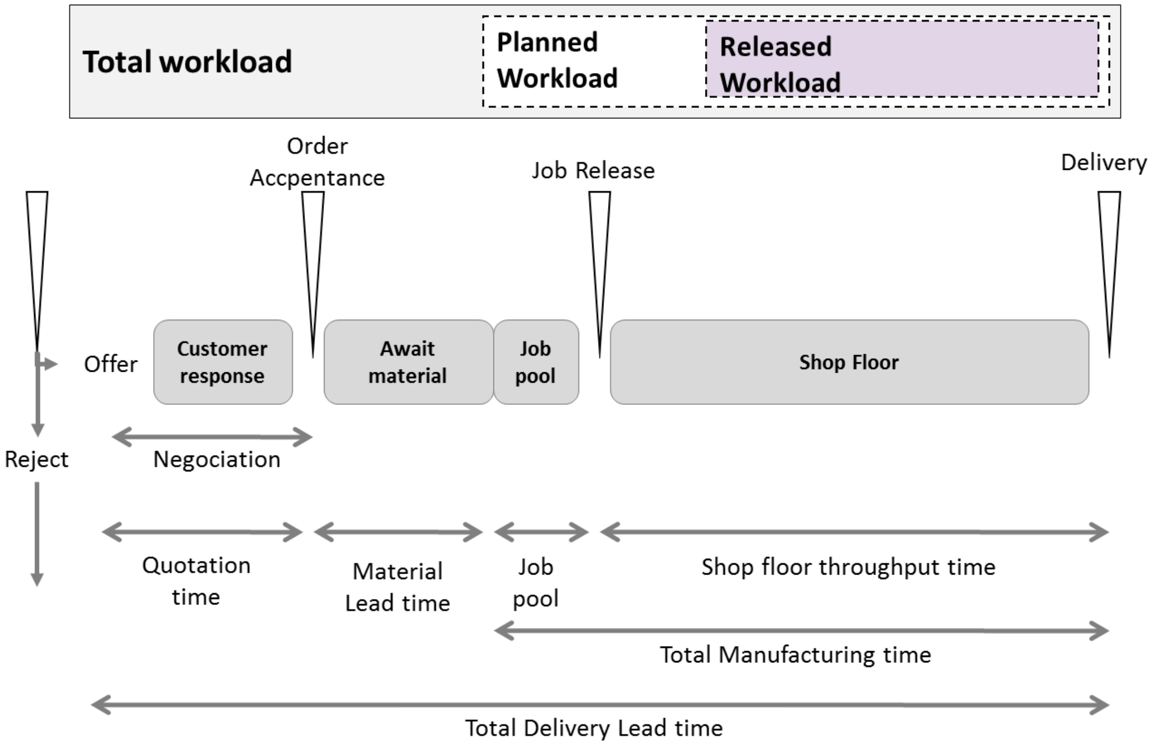


Figure 4.8: Components of the delivery lead time and workloads (backlogs) with controlled order entry and job release (KINGSMAN, 2000)

It is worth emphasizing that there are three different points of confirmation in WLC, according to Kingsman (2000) explanation. The first is concerned with the customer that needs to approve the job that had been bid, after that, there is an internal confirmation regarding materials. The last confirmation is related to the amount of WIP in the plant floor. According to Wight (1970), the items should be scheduled to be put in production at the planned rate and at the last possible moment so that their schedule dates can be made more accurate by forecasting over a shorter period of time.

The majority of the WLC concepts use periodic release in which the period length must be shorter than the smallest slack of the jobs in the pool in order to avoid lateness (STEVENSON; HENDRY; KINGSMAN, 2005). In this regard, workload control stabilizes the performance of the manufacturing process and makes it independent of variations in the incoming order stream (BERTRAND; VAN OOIJEN, 2002).

For Bertrand and Van Ooijen (2002), the main conclusions from the theoretical studies, carried out by Ragatz and Mabert (1988)[1], Philipoom et al. (1993)[2] and Van Ooijen (1996)[3] on the Workload Control model is that it leads to a decrease of average shop throughput time, regarding the time that elapsed between release of a work order to the shop and completion time of the work order. Kingsman (2000) emphasizes that the management of lead times using workload control methods based on controlling a hierarchy of aggregate loads of work is a better approach than using forecast lead times.

In summary, the main logistic objective of the Workload Control is to limit shop floor WIP, just as the card-based approaches. However WLC includes a mechanism to enable the customer to confirm jobs. In this case, it is possible to argue that the level of WIP is controlled by doing the right parts.

4.3.3.1 Applicability of Workload Control

The model was particularly designed for an either make or engineer-to-order production environments in which there is a job shop configuration, accommodating non-repetitive production and variable routings (STEVENSON; HENDRY; KINGSMAN, 2005). The same

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[1] RAGATZ, G. L.; MABERT, V. A.. An evaluation of order release mechanisms in a job-shop environment. **Decision Sciences**, 19, p.167-189.1988.

[2] PHILIPOOM, P.R.; MALHOTRA, M. K.; JENSEN, J. B.. An evaluation of capacity sensitive order review and release procedures in job shops. **Decision Sciences**, 24(6), p. 1109-1133. 1993.

[3] VANOOIJEN, H. P. G.. **Load-based work-order release and its effectiveness on delivery performance improvement**. (PhD thesis, Eindhoven University of Technology). 1996.

authors also emphasize the effectiveness of the method to reduce WIP and control lead times. Since the system takes into account the total backlog of the shop (KINGSMAN, 2000), it is possible to argue that it does enable an evaluation of the required capacity at the costumer enquiry stage.

The confirmations for dealing with uncertainty are in the kernel of the model. Therefore, it is able to deal with the uncertainty in product specification According to Kingsman (2000) description, it is possible to manage projects at a higher level, while it is in the job pool. It means that the model is able to promote a distinction between project flow control and production unit control. The relationship among production and the fluctuation on sales is not addressed.

4.3.4 Card-based approaches

The scope of card-based planning and control models is usually limited to the management of manufacturing plants. Stenvenson, Hendry, and Kingsman (2005) emphasizes the importance of a control method that is able to deal with the production of non-repetitive products through different plants routings. In this regard, the *kanban* system, as originally developed by Ohno (1988), does not fulfil this requirement. The main contribution of the *kanban* is to play the role of an operational control tool that enables production to be pulled at Toyota (HOPP; SPEARMAN, 2000). Some other methods that were developed from this system, such as CONWIP (SPEARMAN; WOODRUFF; HOPP, 1990) and POLCA (SURI, 1998) are able to cope with the ETO situation. Therefore, the main concepts presented in this section are concerned with the *kanban* system.

There are different types of *kanbans*. A common one is a piece of paper contained in a rectangular vinyl envelope with a set of information such as pickup information, transfer information, and production information (OHNO, 1988). In order to avoid mistakes during production, that author established some rules for the use of *kanban*, as shown in Figure 4.9. Antunes *et al.* (2008) emphasize the control role of the *kanban* system, since any problem regarding production programming or industrial engineering, such as a broken machine, is immediately perceived in the plant, unlike the traditional systems of orders and assembly.

Functions of *kanban*	Rules for Use
1. Provide pick-up or transportation information.	1. Later process picks up the number of items indicated by the *kanban* at the earlier process.
2. Provides production information.	2. Earlier process produces items in the quantity and sequence indicated by the *kanban*
3. Prevents overproduction and excessive transport.	3. No items are made or transported without a *kanban*
4. Serves as a work order attached to goods	4. Always attach a *kanban* to the goods.
5. Prevents defective products by identifying the process making the defects.	5. Defective products are not sent on to the subsequent process. The result is 100% defect-free goods.
6. Reveals existing problems and maintains inventory control	6. Reducing the number of *kanbans* increases their sensitivity.

Figure 4.9:Functions and rules for using the *kanban* system (OHNO, 1988, p. 30)

For Moura (1992[1] *apud* ANTUNES JR. *et al.*, 2008), besides the idea of a control system for the flow of materials within the plant, the application of *kanban* can be extended to the supply chain, such as in the study carried out by Ballard and Arbulu (2004) in a large construction project. In this regard, Antunes *et al.* (2008) emphasize the importance of understanding the key role of a *kanban* system for plant logistics.

4.3.4.1 CONWIP

When describing CONWIP, the main idea of Spearman *et al.* (1990) was to make it possible to have the benefits from a pull system and that could be used in a wide variety of manufacturing environments. It is strongly related to what Wiendahl, Von Cieminski, and Wiendahl (2005) calls logistic objective. The key idea of CONWIP is to keep a certain level of work-in-progress constant (CONstant Work In Process), so that that the main benefits of pull system are achieved (see section 3.2.3), such as (SPEARMAN; WOODRUFF; HOPP, 1990, p. 886):

1. The chances for early detection of quality problems are improved, since when WIP levels are lower, so are flow times. So, if a process produces defective items, it soon reaches a subsequent operation where the defect can be noticed.
2. It is easier to manage the shop floor. When WIP levels are low, operators waste less time searching through WIP for the next job to process. The chances for damage or an incident are also decreased.

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[1] MOURA, R. A. **Sistemas de produção: Conceitos e práticas para projetos e gestão da produção enxuta**. São Paulo: IMAM, 1992.

3. Reduced WIP makes it harder to hide or tolerate: machine failures, defects, yield losses, theft, and unnecessary idle time.

CONWIP uses cards to regulate the flow of work through the production line. The difference from the *kanban* system is that CONWIP uses job number specific cards that stay with a product or batch through the whole length of the process, making it a more manageable method when there is high variety (STEVENSON; HENDRY; KINGSMAN, 2005). Hence, the card is attached to a container of parts at the beginning of the line, each of which containing roughly the same amount of work (SPEARMAN; WOODRUFF; HOPP, 1990). When the container is used at the end of the line, the card is removed and sent back to the beginning where it can be attached to another container of parts (SPEARMAN; WOODRUFF; HOPP, 1990). The same authors explain that the main queue rule in the line is “first in system first served” (FSFS), except for rework which is given the highest priority.

The CONWIP basic assumptions have much to do with the Theory of Constraints and with Workload Control. Spearman *et al*. (1990) emphasize the need of controlling throughput levels, in accordance to the TOC metrics, as stressed by Wahlers and Cox (1994). Spearman *et al*. (1990) also highlight the importance of ensuring a target throughput level and the point at which actions are taken if production is expected to be above or below the target. CONWIP also adopts the TOC rule of balancing flow, not capacity, as stated by Goldratt and Fox (1986)

Like in Workload Control, CONWIP is also considered as an input-output control conceived in its logical extreme (SPEARMAN; WOODRUFF; HOPP, 1990). Bertrand and Ooijen (2002) argue that CONWIP is able to provide a practical method to implement this kind of input/output control at the shop floor level. Therefore it is possible to argue that CONWIP and Workload Control can be adopted for the same production system, but at different hierarchical planning levels.

4.3.4.2 POLCA

The Paired-cell Overlapping Loops of Cards with Authorization (POLCA) is a hybrid push-pull material control and replenishment system developed by Suri (1998), to be used in Quick Response Manufacturing, an approach to reduce lead times. POLCA is a hybrid System because it incorporates some features from MRP regarding the release of materials on the shop floor, and of *kanban* in terms of communication between cells (SURI, 1998). Suri

(1998) emphasizes that this control system has been developed for highly engineered production, small batches and high product variety.

Figure 4.10 shows the routing of an order using POLCA cards; through the pair of cells cards the system enables routing flexibility. It is worth noting that in the POLCA system, the shop floor layout is not limited to a linear flow, so that products can go through cells in various sequences (SURI, 1998).

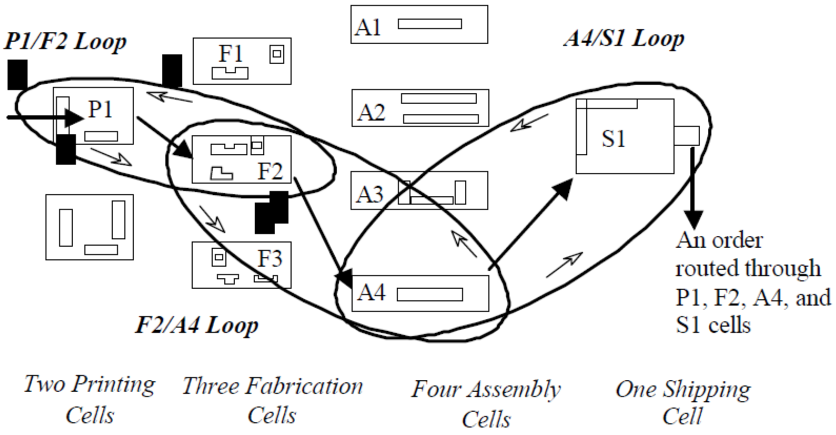

Figure 4.10: Overview of POLCA cards flow for a particular order (SURI, 1998)

Suri (1998) assigns four features of the system that enable a company to customize its products while having control over congestion and excessive WIP:

1 Release authorizations are created via high level material requirement planning;

2 Card-based material control methods are used to communicate and control the material movement between the cells. Within the workstations of a cell it is possible to use *kanban*;

3 Production control cards, called POLCA cards, are not specific to a product or a batch of products like in *kanban* or CONWIP. They are, instead, assigned to a pair of cells. Within the planning horizon, if the routing for any order goes from cell A to cell B, then the pair of cells A and B is assigned a number of POLCA cards, called A/B cards; and

4 The POLCA cards for each pair of cells stay in the cells with a job during its journey through both cells before it loops back to the first cell in the pair.

4.3.4.3 Applicability of the card-based approaches

Both CONWIP and POLCA have some advantages over the *kanban* system for an engineer-to-order environment, due to the possibility of dealing with non-repetitive production (HOPP; SPEARMAN, 2004; STEVENSON; HENDRY; KINGSMAN, 2005). Stevenson, Hendry, and Kingsman (2005), however, highlight that POLCA is better suited for the need of variable routings, since CONWIP limits the WIP of the overall production flow. However, Ede (2010) reveals some limitations of the model, it is only suitable for a shop floor configured as a network of loosely connecter cells without strong variation in workload per product.

Since CONWIP and POLCA are shop floor control methods, they do not tackle the need of evaluating the required capacity at the customer enquiry stage. In fact, Ovalle and Marquez (2003) claim adaptation of CONWIP to a more strategic level, by extending the application of the method to the supply chain, in which the production line of each firm works similarly to a work centre that is part of a global line of supply. Those authors found some advantages of using CONWIP for keeping a constant WIP throughout the whole supply chain in comparison to a fully integrated supply chain.

Regarding this limitation, Spearman *et al*. (1990) and Suri (2003) claim that CONWIP and POLCA, respectively, can be used in association with the MRP. Spearman *et al*. (1990) argue that while in the latter the capacity are assumed to be constant, the feedback of cards provides a means of avoiding excess WIP, based on the actual performance of the production line. They also highlight that these approaches will also benefit from unusual increase of performance by allowing more work to start if jobs are being finished quicker than expected.

Using any card-based approach there is a postponement in the decision of when each part should be produced in each workstation. It happens because the link between processes is clearly defined as well as the production flows according to the needs (SPEARMAN; WOODRUFF; HOPP, 1990). In this regard, Antunes *et al.* (2008) highlight that a card-based approach has much flexibility concerning to changing in the product mix, making it is possible to effective give a response to demand oscillation. Therefore, these approaches are able to deal with uncertainties in processes and even in product demand.

The card-based approaches do not formally address a distinction between project flow control and production unit control. By contrast, there is a need to promote this sort of differentiation since the whole projects have to be divided into small batches to be produced in the work centres. Both the project as a whole and the batches within the work centres has to be controlled and, therefore it is possible to infer that the card-based approaches are able to promote this distinction.

The relationship between fluctuations on sales demand and production control may be helped by the use of card-based approaches since it reveals the actual capacity of the system through the control of the number of cards, but it does not provide a mechanism to enable this sort of synchronization.

4.3.5 The Last Planner System

The Last Planner System™ (LPS)[1] was developed as a planning and control model capable of dealing with the uncertainty in construction industry. Ballard (1994) assumed that construction requires planning done by different people, at different places within the organization, and at different times during the life of a project. The name of the system refers to the last person at the operational level responsible for assigning the specific job that has to be carried out, therefore the last planner.

Aslesen and Bertelsen (2008) remark that the system is based on the assumption that the complex and dynamic construction environment makes it both production and the upstream flows uncertain. Therefore, reliable planning cannot be made in detail much time before execution. This system can be understood as a mechanism for transforming long-term[2] planning into what can be done, thus forming an inventory of ready work, from which short-term plans can be formed (BALLARD, 2000). This mechanism is a major change in relation to traditional project management in which what should be done is sent directly to the execution process. This difference is schematically represented in Figure 4.11.

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[1] Last Planner System is a trademark from Lean Construction Institute

[2] In this research long-term planning refers to a plan that includes the project as a whole. In a multiple project environment, it refers to all projects within the company. The middle and short-term refer to a smaller slack of time in which the plan is focused.

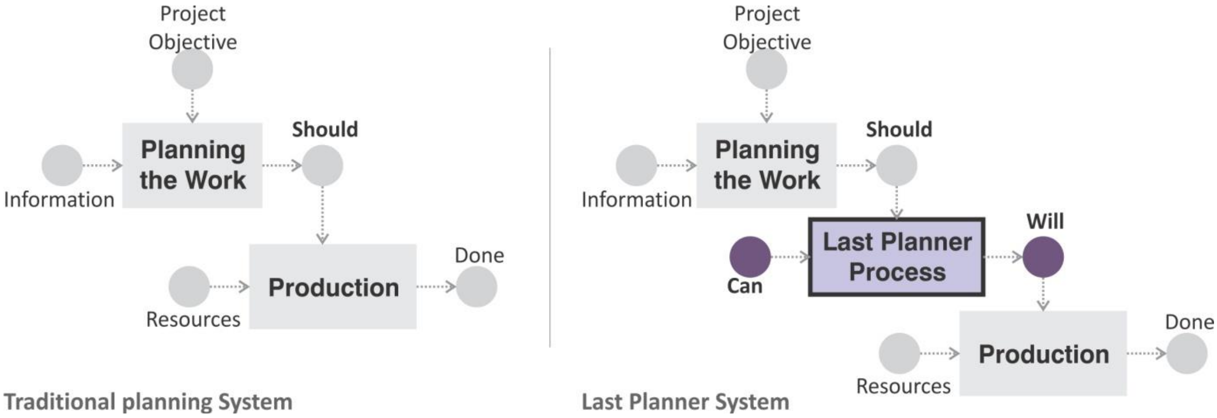


Figure 4.11: Traditional and Last Planner Planning systems (BALLARD, 2000)

The process of "Planning the work" is based on an analysis called work structuring, which indicates a set of activities that reveal how work should be performed, including project design and supply chains, all the production processes for fabrication and site assembly (LCI, 2007). Work structuring is a fundamental level of process design, defining the amount of work will be released to the PUs; how they are sequenced; in what unit they are delivered; where to include buffers; and when should be performed (BALLARD, 1999).

The definition of the activities that "can" be produced is part of a long process. Ballard and Howell (2003) argue that there is a need to develop a phase scheduling, validating activities lead times and sequencing of the master. This phase scheduling is based on a collaborative consensus between the production team working backwards from a milestone of the master schedule. From the phase scheduling, it is developed the look-ahead, which refers to a workflow control level (BALLARD, 2000). The main idea of the look-ahead planning is to plan activities at a more detailed level, in relation to long-term plan, identifying and removing the existing constraints for the activities that have been planned.

These are the main definitions for the production unit control, in which the only concern would be matching the work of the backlog with the capacity of the crews. It is similar to the backlog of ready work used by the Workload Control method, named pool of jobs. Therefore, Ballard (2000) acknowledges the difference between the workflow control and the production unit control.

Ballard (2000) emphasizes that the Last Planner System enables the production processes to achieve a basic stability through learning cycles and keeping commitments. Starting from this backlog, the process called in Figure 4.11 as "Last Planner Process", is concerned with a meeting where the work is assigned to crews through negotiation, when they commit to do the work (BALLARD, 2000). Slivon *et al.* (2010) emphasize the importance of this promises made in public for the performance of the system.

The main metrics of the system are the percentage of plans completed (PPC), and the causes for the non-completion of work packages (BALLARD, 2000). The same author highlights that the analysis of those reasons provides a mean to enable learning incorporated in the control process.

4.3.5.1 Applicability of the LPS

The system is able to provide an evaluation of the required capacity at the beginning of the project through the use of the master plans developed during the long-term planning. A decision making structure is the basic assumption, in which the most detailed decision about the production is made by the “last planner”. The main goal of the system is to deal with the uncertain environment of the construction industry. In this regard, it fulfils the requirement of dealing with the uncertainty in product specification.

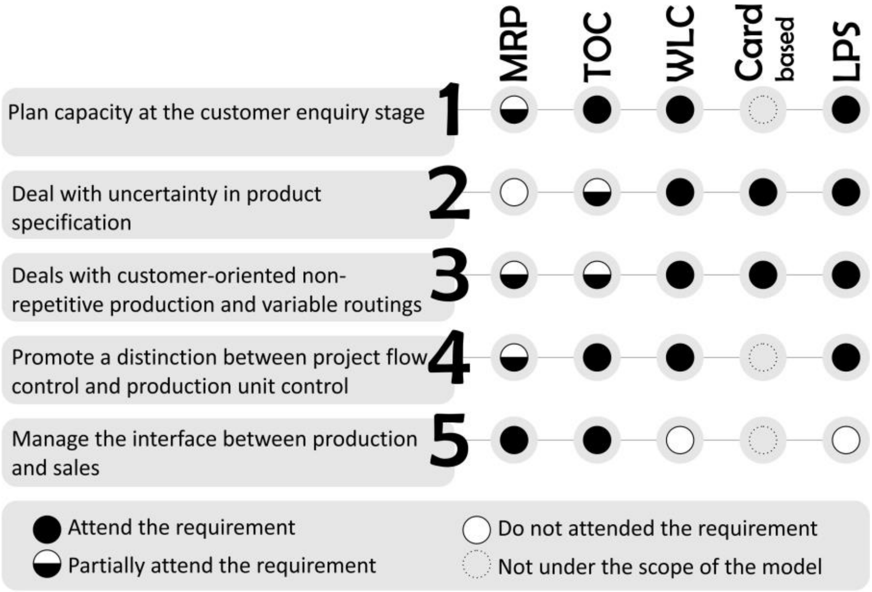
As it was developed for the construction industry, based on a series of handmade and non-repetitive activities, the model fulfils the requirement of dealing with a customer-oriented non-repetitive production. Ballard (2000) highlights the differentiation between workflow control and production unit, which meets the project flow and production unit control differentiation. The link between production and sales is not addressed.

4.4 DISCUSSION

The assessment of the five production planning and control models according to the requirements is summarized in Figure 4.12. It must be pointed out that there is a clear differentiation between strategic models, such as MRP and the more operational ones, such as the card-based approaches. The idea of using the category of a requirement “not under the scope of the model” was to stress the need of combining some models in order to develop suitable planning and control systems for the ETO environment.

Regarding the need to enable an evaluation of the capacity planning at the customer stage, although the MRP tools are able to address an evaluation of the capacity, Bertrand and Muntslag (1993) argue that this planned use of capacity is fairly different from the real one. Therefore, it is just partially fulfilled. However, as suggested by Suri (2003), the use of

POLCA to manage the plant connected to an MRP for the overall process would take advantage of a push/pull interface. In this situation, the first requirement could be fulfilled through an integration between those models.



		MRP	TOC	WLC	Card based	LPS
Plan capacity at the customer enquiry stage	1	◒	●	●	◌	●
Deal with uncertainty in product specification	2	○	◒	●	●	●
Deals with customer-oriented non-repetitive production and variable routings	3	◒	◒	●	●	●
Promote a distinction between project flow control and production unit control	4	◒	●	●	◌	●
Manage the interface between production and sales	5	●	●	○	◌	○

● Attend the requirement
◒ Partially attend the requirement
○ Do not attended the requirement
◌ Not under the scope of the model

Figure 4.12: Assessment of the planning models based on the set of five requirements

As discussed before, the main problem of using MRP for an engineer-to-order production system is that this model is not able to deal with uncertainty in the process. As pointed out by Jin and Thomson (2003), it is hard to make the BOM of the MRP flexible enough to cope with the time for defining the product specifications during the design and engineer production process, while this definition is required before that process. All the other models provide some mechanisms to deal with this kind of uncertainty, but TOC that partially fulfilled that requirement. This was because this model requires an understanding of the plant routines, as well as the cycle times in order to calculate the main bottleneck and establish the pace for the manufacturing plant.

In order to manage an engineer-to-order situation, planning and control system must be capable of managing hand-offs among production units, which is provided through the project flow control. This seems to be another important implication why MRP is so widely used in this environment, despite all the critique over its applicability. Besides the fact that there is a wide range of software availability, there is no other planning and control model that fulfils all the requirements for an ETO production system.

The Last Planner System was the only method that was not devised for managing manufacturing plants. Nevertheless, it fulfils most of the requirements for engineer-to-order environment. LPS provides an important contribution regarding the incentive on engaging the operational level in the development of the plans. More than being able to commit to do the work, team members participate in high levels scheduling, which helps all the stakeholders to be aware of interdependencies between activities. As stated by Crichton (1966), interdependencies are an important source of internal uncertainty. Using this participative approach, together with the different planning levels, LPS can be seen as a robust model to deal with both external and internal uncertainty.

The Workload Control provides important insights related to the confirmation of orders by clients. The model lacks some basic requirements such as how to integrate production units, by assuming an engineer-to-order environment can be limited to the manufacturing plant. The contribution of the card-based approach refers to the way WIP can be managed either in between processes, such as in the *kanban* system and POLCA, or looking at the system as a whole, such as the CONWIP, those systems provide important mechanisms to avoid a high level of WIP.

5 RESEARCH METHOD

This chapter describes the research approach that has been adopted in this investigation, as well as the steps involved in the research process. The first section discusses the positioning of this investigation as design science research (DSR). The second and third sections refer to the research strategy followed by the research design, emphasizing the learning cycles that are typical of an action-research investigation. The fourth section concerns the description of the companies involved in this research. A detailed description of the activities developed in each empirical study is presented in the fifth section, as well as the sources of evidence that have been used.

5.1 DESIGN SCIENCE RESEARCH

This research work can be classified as design science research, also known as constructive research, or prescriptive science, in opposition to descriptive research, that is typical of the natural and social sciences (MARCH; SMITH, 1995). This approach is concerned with devising a solution concept that serve human purposes, often named as artefact or construction (MARCH; SMITH, 1995).

Despite the emphasis on practical contributions, design science research must have also theoretical contributions to the existing body of knowledge (VAN AKEN, 2004). However, those theoretical contributions are typically at a lower level of abstraction, if compared with descriptive theories from the natural sciences. Van Aken (2004) uses the expression “mid range theories” to name such theoretical contributions.

Holmström, Ketokivi and Hameri (2009) argue that a strong connection exist between prescriptive and descriptive research. They describe the main steps involved in the production of knowledge in design science research, which are divided into two stages, namely exploratory and explanatory research (Figure 5.1). The former is concerned with the conception and refinement of the artefact, i.e., the phenomenon under analysis is artificial and has to be created by the researcher, while the latter consists of understanding a phenomenon, which includes the artefact that has been devised, at an abstract level. Then, it is possible to achieve the explanation theories, which are typical of natural sciences.

Holmström, Ketokivi and Hameri (2009) argue that exploration and explanation are highly complementary. While both research phases need to be based on data, the design scientist must first create the artificial phenomenon so that data to be analysed can be obtained (HOLMSTRÖM; KETOKIVI; HAMERI, 2009).

Research Type	**Research Phase**	**Objective**
Exploration (Design Science)	Solution Incubation	Development of an initial solution design
	Solution Refinement	Refinement of the initial solution design, solve the problem
Explanation (Theoretical Science)	Explanation I	Development of substantive theory; establish theoretical relevance
	Explanation II	Development of formal theory; strengthen theoretical and statistical generalizability

Figure 5.1: exploratory and explanatory research phases (HOLMSTRÖM; KETOKIVI; HAMERI, 2009, p. 70)

Holmström, Ketokivi and Hameri (2009) also points out that design science research deals with ill-defined problem, also known as wicked problems, in which the development of a solution is part of the understanding of the problem. However, it must be emphasized that in design science research problems are not discovered, but are constructed: “we may discover a symptom, but symptom does not equal problem” (HOLMSTRÖM; KETOKIVI; HAMERI, 2009).

Vaishnavi and Kuechler (2007) claim that it is precisely in the exploration of this wicked problems, where there are conflicting or sparse theoretical bases, that design science research excels. According to Holmström, Ketokivi and Hameri (2009) as design science research deals with these ill-defined problems, a common contribution of this approach is to frame problems in unique ways.

March and Smith (1995) state that the artefacts developed in design science research need to be assessed against criteria of value or utility, which is part of the exploration phase. According to Holmström, Ketokivi and Hameri (2009), the following step is to understand the theoretical relevance of the solution. This is where the explanation research starts, involving an examination and evaluation of the solution from the theoretical point of view. Therefore, those authors claim design science research should achieve at least the level of abstraction of explanation I (Figure 5.1).

DSR have some specific outputs, around which the research aims are defined. March and Smith (1995) proposed a set of outputs, which was extended by some more recent papers (PURAO, 2002; SEIN *et al.*, 2011; VAISHNAVI; KUECHLER, 2007; VAN AKEN, 2004) with the idea of developing “better theories”, as follows:

- **Constructs:** constructs or concepts form the vocabulary of a domain. They constitute a conceptualization used to describe problems within the domain and to specify their solutions (MARCH; SMITH, 1995).
- **Model:** a model is a set of propositions or statements expressing relationships among constructs (MARCH; SMITH, 1995).
- **Method:** a method is a set of steps (an algorithm or guideline) used to perform a task. Methods are based on a set of underlying constructs (language) and a representation (model) of the solution space (MARCH; SMITH, 1995).
- **Instantiation:** an instantiation is the realization of an artifact in its environment (MARCH; SMITH, 1995).
- **Technological rules**: “a chunk of general knowledge, linking an intervention or artefact with a desired outcome or performance in a certain field of application” (VAN AKEN, 2004, p. 228). The same author state that a technological rule is not a prescription for a specific situation, but a general prescription for a class of problems. It is not a universal law, since its use is limited to a certain domain.

Vaishnavi and Kuechler (2007) highlight two distinct ways by which design science research contributes to better theories. The first concerns the methodological contribution related to the development of the artefact. The second refers to the capability of this artefact to expose the relationships between its elements.

5.2 RESEARCH STRATEGY

The artefact being developed in this investigation is a planning and control model for ETO prefabricated building systems. This model was conceived, developed, implemented and assessed in collaboration with a steel fabricator. This company was willing to improve its management processes. For this reason, the implementation process was carried out with a strong participation and engagement of a large team of managers and technical staff from a steel fabricator company. There has been a strong participation of the company in the development of the model, and several learning cycles, similar to the one described by Susman and Evered (1978). Therefore, the research strategy adopted is similar to an action research.

According to Eden and Huxham (1996), action research is a strategy for obtaining, at the same time, knowledge and change in social systems. In this approach, there is an involvement with members of an organization over a matter which is of genuine concern to them (EDEN; HUXHAM, 1996). There is a learning cycle, involving five stages: diagnosing, action planning, action taking, evaluating, and reflection (SUSMAN; EVERED, 1978) (Figure 5.2). This research strategy was originally developed in the Social Sciences.

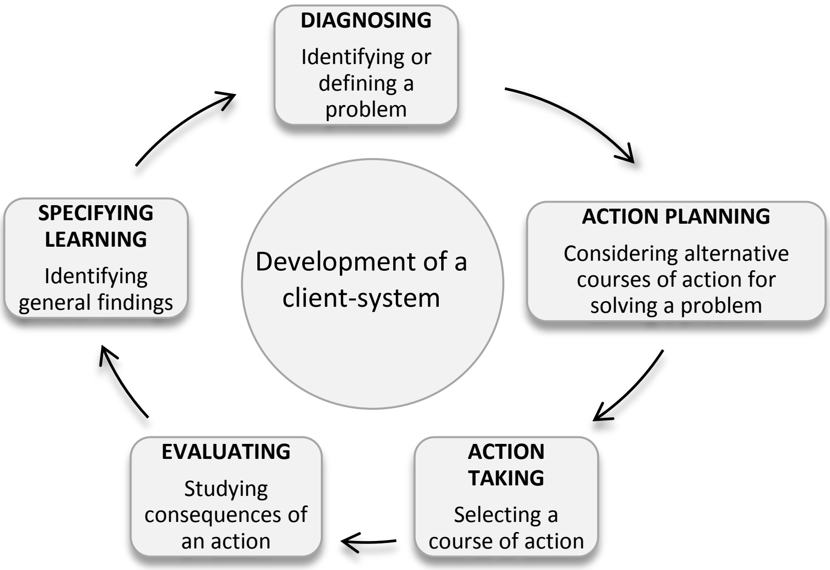


Figure 5.2: Cyclical process of action research (SUSMAN; EVERED, 1978)

In this investigation, the design science is understood as a model of knowledge production, and the action research as one of the possible ways to achieve this type of knowledge production. Although in different levels of abstraction, a common action research strategy from the social sciences would not struggle to define an artefact and develop knowledge from the use or assessment of this artefact, as in the design science research. Cole *et al.* (2005) highlight the synergies between both approaches and argue that design science research benefit from the mature body of evaluation and other criteria of performing action research.

Regarding the connection between action research and design science research, Järvinen (2007) pointed out some similarities between them: both research approaches typically involve doing actions, evaluating the results, and producing knowledge. Järvinen (2007) highlights that a common difference is that in the former, action is carried out in collaboration between action researcher, in what Susman and Evered (1978) referred as the client system, while in design science research a study is initiated by the researcher interested in developing a technological rule for a certain type of issue (VAN AKEN, 2004).

For Sein *et al.* (2011) the researches such as this investigation should be framed as an action design research, because in this environment of development of a solution in collaboration with the practitioners there is no clear separation between building and evaluating the artefact. The action design research was developed to support the research from IT development, but it is based on similar principles of the action-research, such as the need of sharing and collaboration between researchers and analysed environment, mutual influential roles (SEIN *et al.*, 2011).

A different point of view is presented by Holmström, Ketokivi and Hameri (2009), who argues that the goal of most action research projects, and of other similar research strategies, such as action science, action innovation research, participatory action research, participatory case study, academe-industry partnerships, is to develop "a means to an end", i.e., an artefact to solve a problem.

By trying to reframe the research strategy of a set of studies from action research to design research and vice-versa, Cole *et al.* (2005) suggest the idea of: (1) adding a "reflection" phase to DSR to enhance learning; (2) adding a "build" phase to the action-research to concretize learning, turning the output of the AR into a DSR artefact; and (3) developing an integrated approach combining both. These can be considered as a DSR strategies in which the interaction of design efforts and the contextual factors are both contemplated (SEIN *et al.*, 2011).

A major difference between a traditional action-research research project and the research approach adopted in this study is that one of the outputs of this investigation is an artefact, i.e., the production planning and control model, just as mentioned in the second idea from Cole *et al.* (2005).

5.3 RESEARCH DESIGN

In this research, three different empirical studies were carried out. The main study was conducted in a steel fabricator company from Brazil, named Company A in this thesis, in which the integrated planning and control model was developed and where most of the learning cycles took place. The other two empirical studies were carried out in two companies: (1) a Heating, Ventilation and Air Conditioning (HVAC) contractor, also called mechanical contractor, and (2) a steel fabricator from the USA, named companies B and C, respectively. The role of those two studies was to refine the model, based on the understanding of ETO prefabricated building systems in different contexts.

Figure 5.3 shows the differences in the scope and illustrates one of the complexity dimensions that each production system deals with, regarding the number of concurrent projects. Company A usually carries out a large number of simultaneous projects (around 200), being in charge of design, fabrication and site installation. Company C also produces prefabricated steel structures, being responsible only for fabrication and site installation, although it is able to provide customized solutions. Compared to Company A, Company C works with a much smaller number of simultaneous projects (around 5). The empirical study in Company B was an opportunity to understand integrated planning and control for a different prefabricated system. That study was focused on a specific project, in which that company was in charge of design, fabrication and site installation. It is worth noting that Figure 5.3 pointed out only a single project of Company B, which was the focus of this investigation, but not the total number of simultaneous projects typically carried out (around 6).

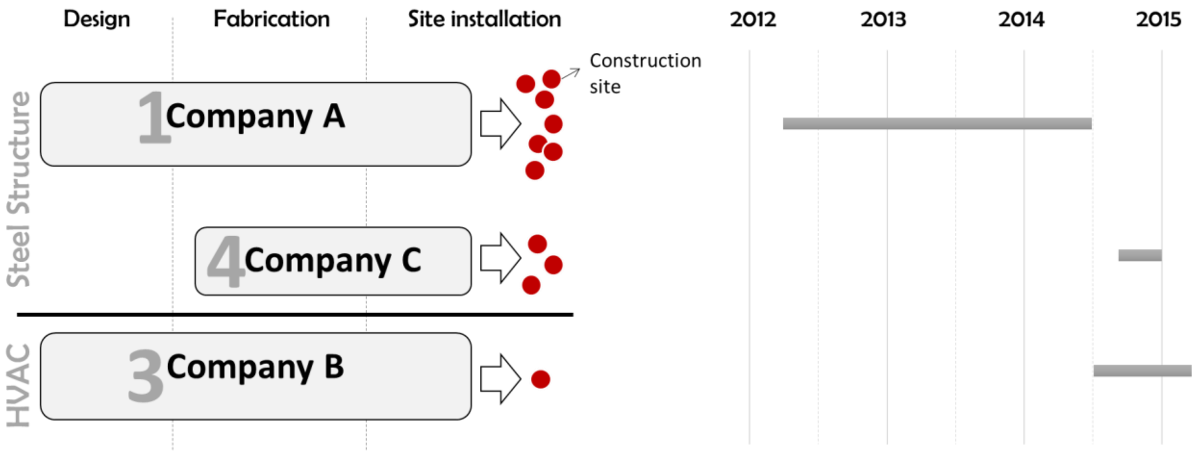


Figure 5.3: Scope and time of the empirical studies

Figure 5.4 illustrates the role of each empirical study. As mentioned above, the study in Company A was the most important one for the development of the model. In company B, it was possible to implement some elements of the model, promoting a short learning cycle in specific project. In Company C, in turn, the empirical study was mostly descriptive, and the contribution to the model comes in the form of comparisons to good practices from a different context.

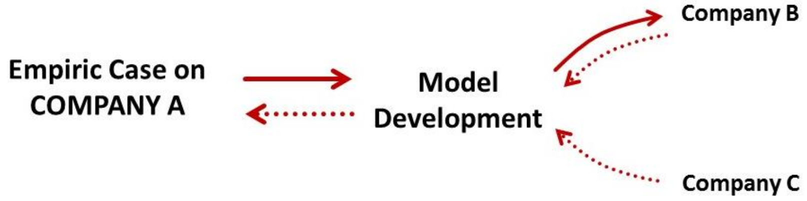


Figure 5.4: Role of the empirical studies in the development of the model

The research process in Company A was divided into four phases, following the main phases of the design science research, as suggested by Vaishnavi and Kuechler (2007): (a) Awareness of the problem; (b) Suggestion; (c) Development and evaluation, and (d) Conclusion (Figure 5.5). Here it was made an adaptation of the phases from the aforementioned authors, as suggested by Sein *et al.* (2011), including the development and evaluation in the same phase, because of the close interaction those phases have in an action-research strategy. There was no sharp separation between those phases, as they did not form a linear sequence of steps but rather an iterative process to develop and improve the solution, through a series of learning cycles, as mentioned by Susman and Evered (1978).

It is worth noting some of the characteristics of the design science research: while the decisions about the implementation process were made collaboratively with the company, there was an internal process for the researcher of building the model. Both of these processes were undertaken simultaneously, although with some delay in order to absorb the changes that were taking place.

As in any Design Science research project, the problem is ill defined at the beginning, being necessary to do a kind of initial descriptive study, focused on understanding the real problem in-depth. Whereas the research progressed, the researcher started to get a different level of understanding of the problem. This is why the research design was divided into five steps highlighted in the Figure 5.5. Only the last step is not related to the study on Company A.

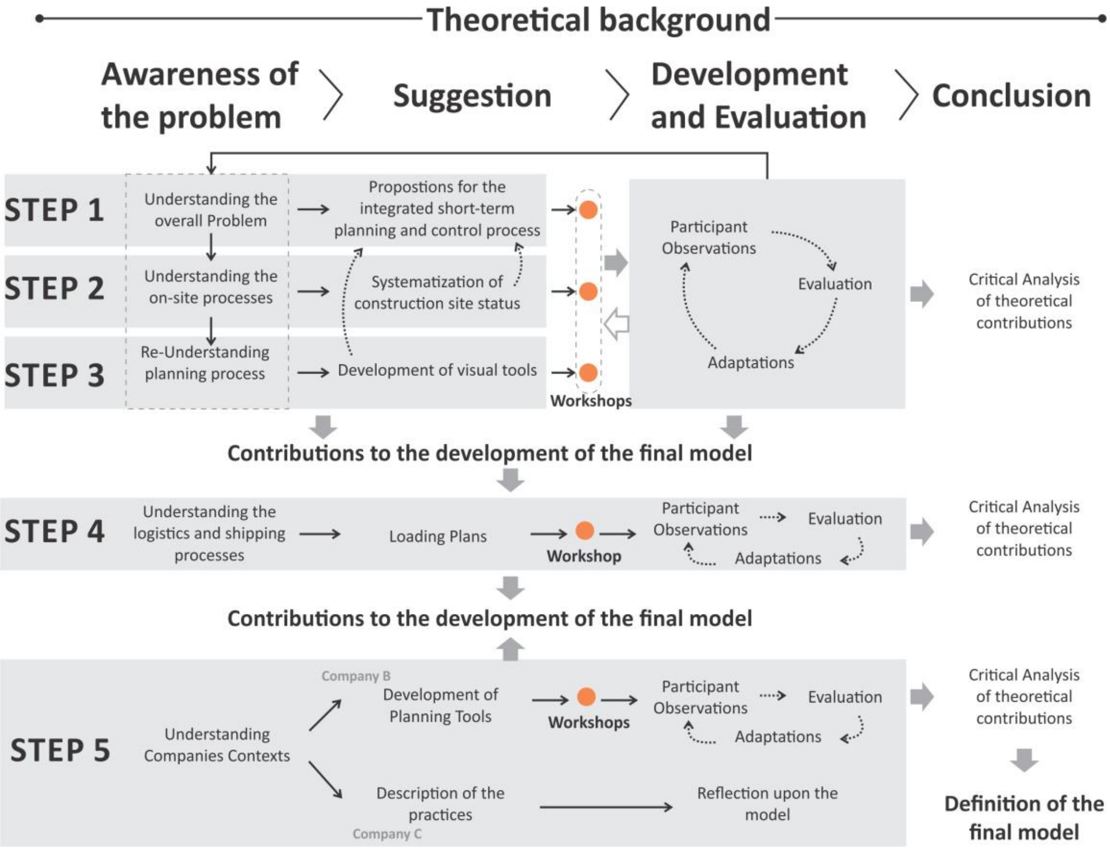


Figure 5.5: Research Design

Step 1 focused on a decision-making level in which representatives from different production units could discuss the main hand-offs. **Step 2** focused on the overall planning and control system, looking at different levels and processes and other levels of that system. **Step 3** focused on the use of visual management tools and metrics to enhance the control of the overall system. **Step 4** focused on some specific issues in the shipping process, which was the interface between the plant and the construction site. This step was carried out separated in time from the previous steps, after a period of analysis and abstraction.

Company A had been involved in the implementation of Lean Production concepts and techniques for 8 years so far. In fact, several process improvement initiatives related to that philosophy have been undertaken in parallel with this research project. There were some important changes introduced by the company in the production planning and control in different production units, which were not directly related to this research, but provided important contributions.

For achieving a further level of understanding, there was a need to make a comparison with production planning and control systems of slightly different environments. This was made in **Step 5**, based on two studies carried out in the United States, in Companies B and C. Those studies were carried out as part of a research project of the Project Production Systems Laboratory (P^{2}SL) at the University of California at Berkeley. This research lab is devoted to the development of knowledge and tools for achieving a lean project delivery system, based on the principles from the lean production for project and production management. The main criteria for this selection were companies engaged in the production of ETO products for building systems, either of steel structures or not. The aim of these studies was to provide a broader view of the problem, and how the instantiated model could be abstracted for a wider applicability. The research process of this phase is discussed in the next section.

Since the beginning of this investigation in 2012, six workshops involving the research team, and the representatives of the company were carried out in Company A for discussing the data collected in this investigation. In the study of Company B, two workshops were carried out. Those events were an important source information and reflection, and played the role of creating trust between the researcher and the company technical staff.

The action research promotes a straight relationship among practitioners and researchers, and therefore, after a certain level of maturity in the understanding of the company problem, there is a development of trust and the researcher participation become more common. Somekh (2005) highlights that this relationship is important to create knowledge as a foundation for improvement, since this knowledge comes from working in partnership with participants to reconstruct and transform their practices. Figure 5.6 presents the most important milestones of this research, including these workshops. Detailed information about the workshops is presented in section 5.5.1.3.

Moreover, the workshops were concerned with sharing knowledge in order to create a common understanding of the problem. This was important because this type of research needs people from the company engaged in the implementation. Therefore, the presentations of the results emphasised the impact of the proposed changes and the existing barriers for implementation.

Both in Company A and B, there were two types of learning cycles in the implementation process. One was defined by the workshops: the feedback obtained in each workshop had a strong influence on the following learning cycle. Changes were implemented, assessed, analysed, and then presented in a workshop. Shorter learning cycles from one week to the next also took place, resulted from the participant observations of the researcher in regular planning meetings, and as part of the company routines.

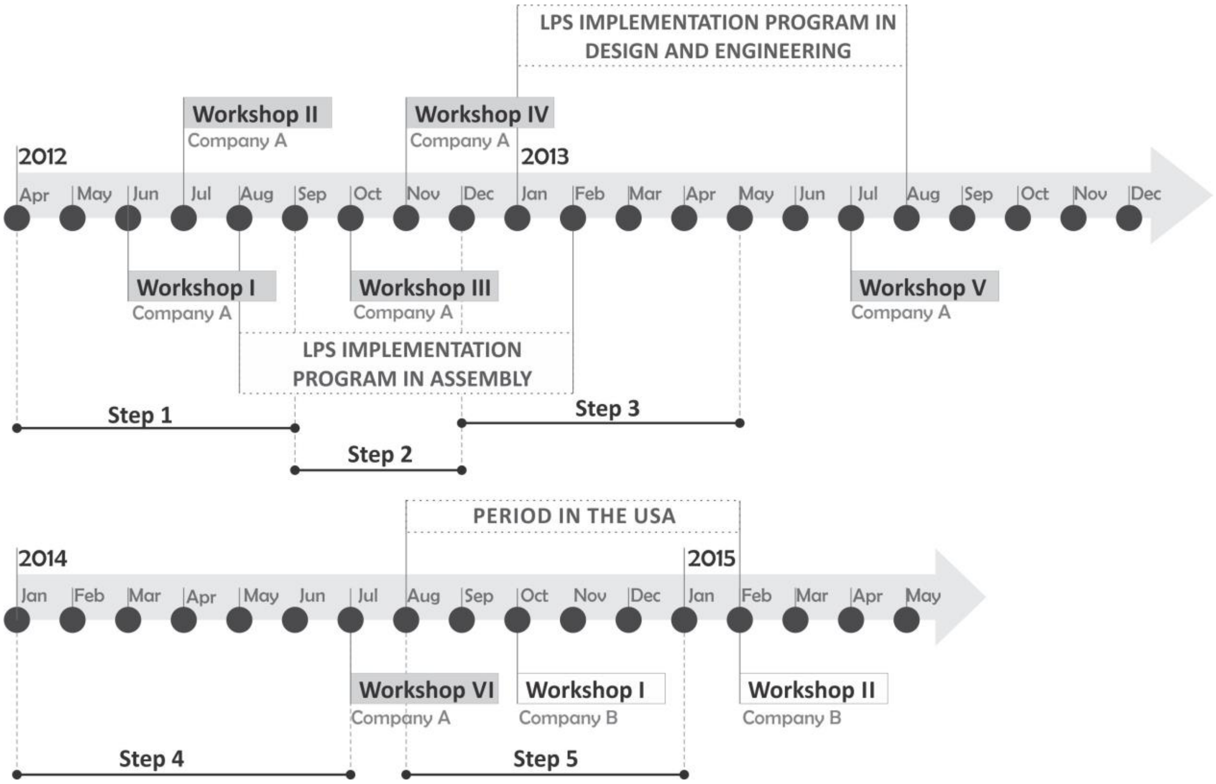


Figure 5.6: Main activities in the empirical study A

The investigation in Company B followed the same main phases of the one in Company A. It can also be framed as an action research, since some planning tools were collaboratively developed to enhance the communication between the subcontractor superintendents, the different fabricators, and with the general contractor (GC) of the project. Due to the nature of the planning and control system investigated in that study, it was not possible to apply the model, only some of the principles used for its development.

This study started with the understanding of the problem. The phase of suggesting a solution was based on the participant observations of the planning and control processes and meetings concerning the problems on synchronizing fabrication and site demand. Some tools were developed to plan this synchronization and were assessed through a workshop. The contributions influenced the further development of the final model.

The study carried out in Company C was a descriptive study, based on in-depth interviews, plant visits and document analysis. For this reason, the research process does not present the learning cycles and the implementation phases as shown in the previous empirical studies. From the preliminary understanding revealing the peculiarities of the production system, it was observed some of the practices that turned that production system very efficient in comparison to similar ones. The contributions of this study were summarized for the final reflection upon the model.

5.4 DESCRIPTION OF THE COMPANIES

Here the main description is from Company A, since they were the focus of this investigation. The description of companies B and C is more succinct, highlighting the most important characteristics for the understanding of this work.

5.4.1 Company A

Company A is the largest steel fabricator in Brazil: it has more than 2000 workers, three manufacturing plants, around 200 simultaneous contracts, and annual revenue around $300 million dollars. It is divided into three different business units: (a) light steel structural systems for warehouse and industrial buildings; (b) high rise buildings; and (c) heavy structures for bridges and off-shore platforms. This study is focused on the operations of the first one. Figure 5.7 presents the main departments directly involved in production planning and control, highlighting the ones formed by production units (Design and engineering, Manufacturing Plant, and site assembly). Those departments are highlighted in Figure 5.7.

The Planning Department is in charge of producing long-term project plans, from design to the delivery of components on site. It is divided in three groups, each of which has its own coordinator. The first group is the project flow, which manages the master schedule initially agreed with the client and defines the amount of products that need to be produced per month for each production unit, excepted for the erection process which has a distinct department for its planning and control. The second group is in charge of planning and controlling plant production, while the third is responsible for making the cost estimation of the projects.

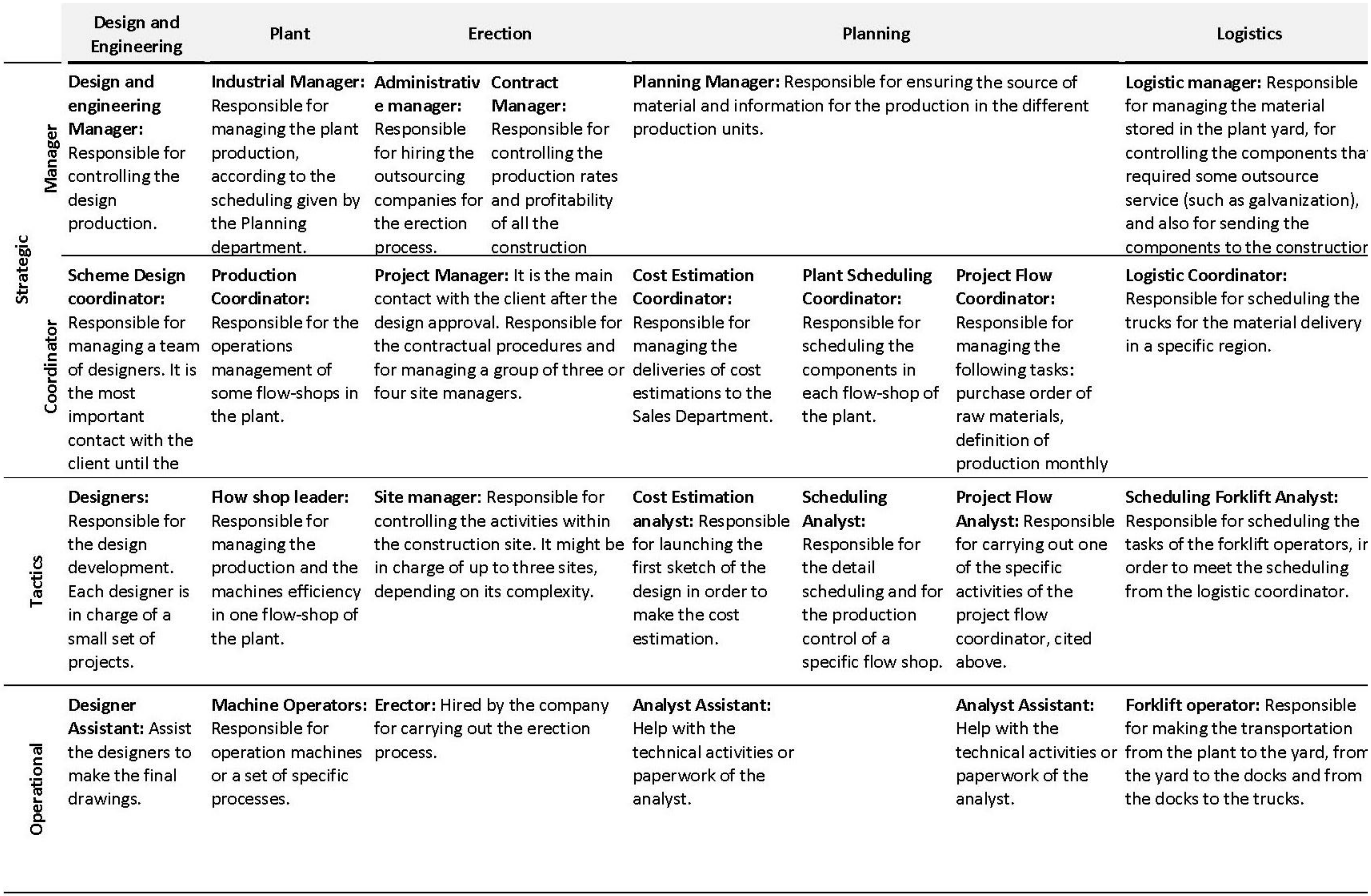
Main departments		Responsibilities
Planning	Project Flow	Analyse the need of raw materials, centralize the master schedule of all projects, control the production of each production unit, and
	Plant Scheduling	Define and control plant scheduling, according to the projects received by component specification
	Cost Estimation	Make a sketch and cost estimation of the projects under negotiation with the sales department
Auditing		Monitor the production in each production unit in terms of tonnages.
Purchasing		Buy raw materials required by the production planning and control department
Sales		Sell the projects to customers
Continuous improvement		Manage the improvement projects
Design and engineering*		Develop the conceptual design of buildings, and the detail design of components
Component specification		Name components according to the type of machine it will demand from the plant, match the components to the raw materials, and ensure that the Plant Scheduling will receive only the projects that are able to be produced, according to schedule and raw materials availability.
Manufacturing Plant*		Manufacture components
Logistics		Store and organize the plant yard, manage outsourcing
Expedition		Ship and provide invoice of the components
Site assembly*	Contracts	Manage the needs of the clients, while projects are under production. Commonly more focused on the Erection phase, since they are also responsible for supervising site managers.
	Administrative	Plan and control the assemble process on site

*** Compounded by Production units**

Figure 5.7: Roles of the main departments

The Continuous Improvement Department revealed the lean culture of the company. This department was established in the beginning of this investigation, during the first semester of 2012, in order to compile the improvement project efforts that had been carried out separately in each department. The constitution of this department was very important for this research. The supporters of the implementation process and the multipliers of the concepts discussed were from this department.

The structure of the company is hierarchically organized. Each business unit had a specific director. Each department has one manager, who is supported by a team of coordinators and so forth. Each department have also tactics and operational positions. Figure 5.8 presents a detail description of the positions in the departments that are most relevant for this research study.



		Design and Engineering	Plant	Erection		Planning			Logistics
Strategic	Manager	**Design and engineering Manager:** Responsible for controlling the design production.	**Industrial Manager:** Responsible for managing the plant production, according to the scheduling given by the Planning department.	**Administrative manager:** Responsible for hiring the outsourcing companies for the erection process.	**Contract Manager:** Responsible for controlling the production rates and profitability of all the construction	**Planning Manager:** Responsible for ensuring the source of material and information for the production in the different production units.			**Logistic manager:** Responsible for managing the material stored in the plant yard, for controlling the components tha required some outsource service (such as galvanization), and also for sending the components to the constructior
	Coordinator	**Scheme Design coordinator:** Responsible for managing a team of designers. It is the most important contact with the client until the	**Production Coordinator:** Responsible for the operations management of some flow-shops in the plant.	**Project Manager:** It is the main contact with the client after the design approval. Responsible for the contractual procedures and for managing a group of three or four site managers.		**Cost Estimation Coordinator:** Responsible for managing the deliveries of cost estimations to the Sales Department.	**Plant Scheduling Coordinator:** Responsible for scheduling the components in each flow-shop of the plant.	**Project Flow Coordinator:** Responsible for managing the following tasks: purchase order of raw materials, definition of production monthly	**Logistic Coordinator:** Responsible for scheduling the trucks for the material delivery in a specific region.
Tactics		**Designers:** Responsible for the design development. Each designer is in charge of a small set of projects.	**Flow shop leader:** Responsible for managing the production and the machines efficiency in one flow-shop of the plant.	**Site manager:** Responsible for controlling the activities within the construction site. It might be in charge of up to three sites, depending on its complexity.		**Cost Estimation analyst:** Responsible for launching the first sketch of the design in order to make the cost estimation.	**Scheduling Analyst:** Responsible for the detail scheduling and for the production control of a specific flow shop.	**Project Flow Analyst:** Responsible for carrying out one of the specific activities of the project flow coordinator, cited above.	**Scheduling Forklift Analyst:** Responsible for scheduling the tasks of the forklift operators, ir order to meet the scheduling from the logistic coordinator.
Operational		**Designer Assistant:** Assist the designers to make the final drawings.	**Machine Operators:** Responsible for operation machines or a set of specific processes.	**Erector:** Hired by the company for carrying out the erection process.		**Analyst Assistant:** Help with the technical activities or paperwork of the analyst.		**Analyst Assistant:** Help with the technical activities or paperwork of the analyst.	**Forklift operator:** Responsible for making the transportation from the plant to the yard, fror the yard to the docks and from the docks to the trucks.

Figure 5.8: Functions description according to the organizational hierarchy

Regarding the Site Assembly department, unlike the other departments, this has two managers, one in charge of administrative issues and the other focused on controlling production rates. Site assembly coordinators are the ones who are responsible for managing projects once the detail design starts. Therefore, those coordinators are project managers.

One of the most important changes implemented based on the Lean Production concepts and principles was the implementation of kaizen workshops [1], which involve teams of workers or managers who are put together for a week to think and test process improvements. At the end of this process there is a formal presentation in which all managers and the director of the unit analyse the proposed solutions. Since the beginning of these projects, there had been around 300 improvement projects. Although not all projects are fully implemented, those events develop an opportunity for sharing knowledge among the different hierarchical levels of the organization.

One of the most important changes promoted by a kaizen workshop was the reduction of batch size, by dividing a project into stages, as shown in Figure 5.9. Each stage is also broken into sub-stages, which contains a set of specific products that can be assembled independently. Design and production control should be mostly based on those sub-stages, after the conceptual design is approved by the client. The manufacturing plant needs a lower level of control, which is called packing-list (PL). PL is a set of similar materials that can be put in sequence in a machine to be produced. It is worth emphasizing that the PL is a subdivision from the sub-stage.

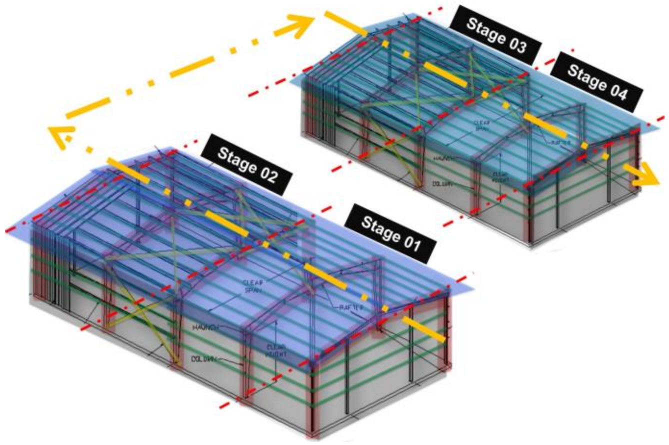


Figure 5.9: Reduction of batch size by dividing the building into stages

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[1] **Kaizen workshop:** The company followed the protocol from the LEI (2008, p. 41): “A group kaizen activity, commonly lasting five days, in which a team identifies and implements a significant improvement in a process”.

One important characteristic of the contracts that affects the planning and control system is the payment conditions. In general, when a project is sold, a deposit of around 7% is required. The second payment, is made when the materials are shipped to the construction site summing up 75% of the project, paid according to the amount of material delivered. The remaining 25% is paid as long as the stages are delivered in the construction site.

5.4.2 Company B

Company B has a manufacturing plant in the state of Utah, US. The whole corporation has annual revenue of between $20 and 50 million dollars. The study in this company was situated in a large commercial building of approximately 300.000 m^2, to be built in 3 years. Due to the size and location of the building, there were important logistics constraints. As there was not much space for storage in the construction site, there were many prefabricated and components that has to be delivered in a just-in-time basis.

In this project, Company B was working under a design-assist type of contract, in which they were involved since the early designs, before knowing whether they would get the job, to make contributions regarding design, procurement and construction processes (GIL *et al.*, 2001). In this kind of contract the liability over the mechanical engineering design remains with a mechanical engineering team responsible for meeting client needs. Because of this type of contract, the design of the HVAC system required different levels of approvals: within the company; with the mechanical engineers; and, finally, to be coordinated with the other systems of the building by the GC. The project was located in the State of California, where some protective laws avoided the company from fabricating their products on their own plant, located out of the state.

Company B adopted a matrix organizational structure. There were small functionally divided teams. In this project, their scope was divided into the dry side and the wet side. The former refers to the ductwork and machines dealing with air, while the other refers to the piping, dealing with water. Each of those sides had a project manager, responsible for the detailing design teams. There were also two other project managers, one focused on design and fabrication issues, who was in charge of sending components to the site, and the other was responsible for the delivery of materials on the site and equipment management in the construction site.

5.4.3 Company C

Company C is a Steel Fabricator, mainly focused on the fabrication and erection of structural system of the building. The Company also work with some complementary modular elements for the structure. The main competitive advantage of the company was the development mass customized production strategy through a modular chassis for the structural system. Company C has estimated annual revenue of U$ 10 million dollars.

Company C developed a simple set of connections to facilitate on-site erection process. Their process of product development was marked by move from the high-density residential building to the industrial market. This move triggered the development of a different type of connection to be able to attend the new customer. The company has important innovations in the steel structure products, making their demand to growth. For dealing with this changing capacity requirement, Company C has struggled to develop licensee fabricators of their type of products. This reveals an awareness of the supply chain integration instead of in-house vertical integration.

5.5 RESEARCH PROCESS

5.5.1 Research process in Company A

The main phases described in the research design (problem awareness, suggestion, development and evaluation, and conclusion) configure different approaches carried out by the researcher in the company environment. These different approaches lead to the collection of different sorts of sources of evidence. Therefore, they are described in relation to those phases. However, the description based on the phases does not match the timeline of the research. For this reason, this section describes in more detail what had been done in each step, in order to provide an overview of this research process, before explaining the sources of evidence.

The research process in Company A refers to the 4 first steps highlighted in the research design. Step 1 lasted from April until September 2012. Initially, a set of interviews was carried out and data were collected and analysed in a first attempt to understand the problem. The main sources of evidence were semi-structured interviews and the analysis of a database of performance metrics used for assessing each production unit. In the first workshop, the results of the initial diagnosis were presented and discussed with representatives of the company.

During Step 1, the researcher also attended a kaizen workshop from the Logistics Department. In this event, some important decisions for the production planning and control meetings were made, which set the background for the beginning of this investigation. The most important decision was to start to implement a short-term planning and control meeting for integrating the different production units.

The second workshop was an attempt to establish a connection between that new meeting and some guidelines from the literature on production planning and control. The concepts discussed on that workshop were related to the management of uncertainties and short-term planning in the Last Planner System. The role of the researcher in this moment was to propose a procedure for the new meetings that were taking place. Both workshops in this step made contributions to the action planning process.

After the second workshop, most of the implementation of this phase took place. The analysis of these changes in the planning meetings and its impacts revealed that there was a need to investigate the different processes that were influencing this meeting. This need was realized after the second workshop, during the LPS implementation program with the site managers. The implementation in the site assembly triggers the program in the Design and Engineering Department. Those programs were carried out along Steps 2 and 3. Although they were not the focus of the research, they resulted in important changes in production planning and control at an operational level that were relevant for the development of the model.

Step 2 lasted from September 2012 to December 2012. This phase was strongly based on participant observations, the researcher was able to participate and collect data from a tactical planning process focused on the prioritization of the construction sites, and also made some visits to the construction sites as part of the LPS implementation program. The third and fourth workshops were held during this period. The third one was concerned with the operational problems identified in the assessment of the planning and control system, while the fourth provided an overview of the model and the discussions were related to the applicability of the first version of the model.

Step 3 lasted from December 2012 until May 2013. It was focused on about improving the integrated planning and control process, using visual management tools. The need for such tools emerged after the production units got some maturity in developing different procedures and using the Last Planner System at operational control levels. The main aim for developing the visual tools was to provide a transparent overview of what was happening in the production units. The fifth workshop was focused on a conceptual discussion regarding the main requirements for the integrated production planning and control model.

After this period, the researcher was away from participating on company A routines for some months. During this period most of the data were analysed, structuring the knowledge achieved so far. The researcher was not totally away from the company, it was on this period that the fifth workshop was carried out.

Step 4 lasted from January 2014 until July 2014. It was focused on a new empirical study started in a specific project, which will be also called project X, with a focus on logistics, including both the plant yard logistics, where the loads were shipped to construction sites, and on-site logistics. This study was benefitted from a special client of the company who was requesting a better organization in the materials delivery on-site. As the client had already produced some projects with Company A, they explicitly demanded an improvement on the material issues

This phase was more analytical than the previous ones, but it was possible to implement some plans and visual tools. It also contributed in terms of identifying opportunities for further research studies. Three teams of researchers worked collaboratively for this sake. Two at the construction site, looking at logistics management of the site (BORTOLINI, 2015) and the development of standardized procedures for the site assembly process (SANCHES, 2015). One at the plant yard, in which this researcher worked together with the researcher Ana Etges.

5.5.1.1 Awareness of the problem

This phase refers to the initial phase of understanding the company production system and initial data collection. The first contact of the researcher with the company system was with a series of semi-structured interviews, carried out with all the departments that seemed to affect the planning and control system. These interviews were compounded by open questions guided by the following structure:

- Describe the main steps of your work routine.
- How does your work of [Department the person is from] relates to the remaining departments?
- How are you measured?
- What are the challenges of your routine?

Those interviews provided an overview of the company production system, and guided the choice of data to be collected in order to understand the problems or what was hindering the production system to perform better. In this regard, the sources of evidence ranged from: primary data collection on archive records, Secondary data collection on archive records, documentation analysis, and participant observation. The archive records are quantitative data collected by the company, as described by Yin (2003). Here a differentiation was made regarding primary or secondary. The former required an effort from the researcher to become visible. The data that was already available from the company was considered secondary data. Figure 5.10 explains the aim of each of the sources of evidence used in the first 3 steps of this research.

Source of evidence	From	Aim
Semi-structured interviews for the initial understanding	Project Flow Coordinator	Understand how the projects flow among the departments and what were the main interactions between them. The questions concerned the main routines of work, the main problems faced, how do they interact with the project flow and how their work was planned and control
	Representative of the project flow specialists	
	Plant scheduling coordinator	
	Representative of the Scheduling specialists	
	Industrial manager	
	Plant production coordinator	
	Flow shop leader	
	Representative of the logistic team	
	Expedition coordinator	
	Project manager	
Primary Data analysis on archive records	Total of work-in-progress in the system	The aim of this data was to reveal the work-in-progress in the company and the problems it generates.
	Waiting time of the materials on plant yard	
	Waiting time of the materials on construction site	
Secondary Data analysis on archive records	Amount of tonnages produced by each production unit	Compare performance to the effectiveness of plans. There was also a need to convert commonly used metrics to number of sub-stages rather than tons.
	Adherence to the plan in terms of sub-stages	
Document Analysis (qualitative data)	Contracts	Basic understanding of the planning and control system
	Instructions for site managers	
	Shared presentations	
	Planning and control tools	
Participant observation	Initial planning meetings	Basic understanding of the planning and control system
	Short-term planning meeting integrating all teams from design and engineering production unit.	Understanding of the impact of changes in the production planning and control system.

Figure 5.10: Aims of each main source of evidence from Steps 1 to 3

Based on previous studies and on the perception of some of the managers, the decision was to collect data on the amount of work-in-progress in one of the plants of the company, since this was considered to be a major problem. The first analysis was focused on counting the number of projects that each production unit was working on. As the amount of material at the plant yard was large, the focus of data collection turned into the length of time that the materials had to wait before being shipped, and the reasons for such a long waiting.

During the fourth step of this research there was a new data collection, shown in Figure 5.11, related to the logistics and shipping processes. In this phase, direct observation was used to enable a detailed chrono-analysis of the operational processes in the company shipping process at the dock. Another important analysis made an analysis of the company records of some metrics regarding the time and cost of having the trucks in the yard for long periods.

Source of evidence	From	Aim
Direct Observation	Recording the loading process at the dock	Develop a chrono-analysis of the shipping process.
	Material flow in the yard	Understand the logistics processes.
Secondary Data analysis on archive records	Time spent by the trucks in the company	Understand the impact of the long waiting times by the trucks.
	Amount spent on daily rates for truck drivers	
	Causes for the payment of daily rates	

Figure 5.11: Aims of each source of evidence from Step 4

5.5.1.2 Suggestion of the solution

Vaishnavi and Kuechler (2007) highlight that this phase concerns an abduction of the solution from the previous understanding of the researcher. It is in the next phase (development) that the solution is correctly adapted to the context. The workshops of this investigation played both the roles of proposing new implementations and evaluating the ones previously made. They became the main and formal place to discuss the solutions under development. The main topics discussed in these workshops can be seen in Figure 5.12. The weekly informal meetings also played a key role to define, improve, and test planning methods and tools in a shorter term.

Workshop Date	Participants	Scope
1. June 13th, 2012	· Unit director · Planning Manager · Planning coordinator from the plant · Planning coordinator for the project flow · Continuous improvement coordinator · Erection manager · Erection administrative · Trainee	- Report the diagnosis and discuss how the production process could be pulled
2. July 2nd, 2012	· Planning Manager · Continuous improvement coordinator · Planning coordinator from the plant · Planning coordinator for the project flow · Representative of the Planning team · Erection manager · Erection administrative	**Concepts:** - Discussion about the benefits of batch size reduction - Production planning and control concepts, focused on the short-term planning. **Proposition:** - Proposition of some tools to implement previously decided changes in planning meetings **Discussion:** - Work strategy
3. October 4th, 2012	· Planning coordinator for the monthly goals · Logistics coordinator · Logistics manager · Expedition coordinator · Continuous improvement coordinator · Planning team ▪ design and engineering control ▪ responsible for the monthly goals	**Concepts:** - How and why collect the main causes of problems in the production - Production planning and control concepts, focused on the medium-term planning. **Assessment:** - Discussion about the benefits of batch size reduction - Production planning and control concepts **Discussion:** - Use of dashboards - Different metrics
4. November 7th, 2012	· Unit director · Design and Engineering manager · Continuous improvement coordinator · Representatives of the Planning team ▪ design and engineering control ▪ responsible for the monthly goals · Planning coordinator for the project flow · Erection manager · Erection administrative	**Concepts:** - Production planning and control concepts, focused on the medium-term planning. **Assessment:** - Main problems in current practices **Discussion** - Planning and control model design
5. July 5th, 2013	· Continuous improvement coordinator · Design and Engineering manager · Design and Engineering coordinators · Planning coordinator from the plant · Planning coordinator for the project flow	**Concepts:** - Applicability of production planning and control systems to the ETO production system **Discussion:** - What kind of features can be seen in the company, what can be absorb from the literature - Assessment of the planning and control model design
6. June 5th, 2014	· Unit director · Continuous improvement manager · Continuous improvement coordinator · Representatives from the Planning Department · Coordinator from the shipping process · Leaders of the loading process	**Assessment:** - Results of the development of loading plans and of the planning and control of construction site layouts **Discussion:** - Possibility to apply good practices of the project for the company as a whole

Figure 5.12: Main scope and participants of the workshops

Through the short interactions from one week to the next, it was possible to take into account the needs of the company in the development of the solution proposed. The last (sixth) workshop is the only one related to the implementation in the logistics. It was actually concerned with the discussion of that implementation process. However, it has also played the role of suggesting procedures by trying to abstract those practices emerged from the case of a specific project to the company as a whole.

5.5.1.3 Development

The development and evaluation refer to the implementation process. For Vaishnavi and Kuechler (2007), this phase is based on the deduction on the solution, because it is based on facts from the implementation process that makes this solution emerge. For this reason, there was a need to collect some new data in this phase, in order to tackle the impact the changes were making in the company production system. The task of evaluating was continuously made through the discussion in the workshops. As pointed out by Sein *et al.* (2011), when the solution of the design science research is developed through the collaborative and learning cycles from an action-research approach, there is a continuous assessment of the solution.

Figure 5.13 highlights the sources of evidence from this phase. A different series of semi-structured interviews were carried out, in order to systematize how people understood the changes in their routines. It was based in one simple question: '*what are the strengthens and weaknesses of the new design of the planning and control processes of the company?*' During the short-term integrated planning meetings it was developed and collected a metric regarding the adherence to batch sequence.

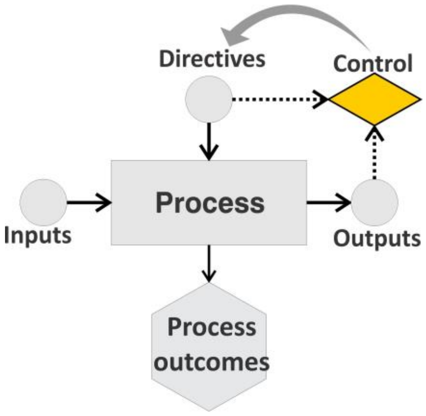
Another important source of information was the Last Planner implementation program. In the site assembly process, this program provided some important information about how components were getting in the site and how the communication between the site manager and the manufacturing plant were carried out. It also revealed the way site managers were able to control their construction sites (each site manager could manage up to three sites each time).

Source of evidence	From	Aim
Semi-structured interviews for assessing the changes	Project Flow Coordinator	Understand how the main changes influenced their work, what were the main problems faced and the main suggestion for improvement.
	Representative of the project flow specialists	
	Plant scheduling coordinator	
	Representative of the logistic team	
	Expedition coordinator	
	Project manager	
Participant observation	Short-term planning and control meetings integrating the different production units	Analyse the implementation of tools and methods previously discussed
	Meeting with project managers to share construction sites status	
	Last Planner System implementation program in the site assembly process	Ensure that the concepts developed in the research were also achieving operational levels.
	Last Planner System implementation in the design and engineering production unit	
Primary data Collection	Aggregated version of the adherence to the target metric	Understand if the adherence were improving and what was the source of the extra production
Secondary data Collection	Causes for non-completion	Analyse the problems and the way causes had been collected

Figure 5.13: Sources of evidence for the development and evaluation phases

In Step 4 there was the implementation of a plan to organise the loading process, and some visual tools. The process of understanding the problem and proposing the solution was carried out in close collaboration with the logistics team, mainly two of their analysts responsible for the loading process. Differently from the wider case, the embedded one was closer to the operational level of production.

An important tool used for developing and discussing of existing planning and control models is the one presented in Figure 5.14. Since the model adopts some of the core ideas of the Last Planner, the same notation adopted by Ballard (1994) was used. It is, in fact, a simplification of the notation used by Ballard and Howell (1997); Ballard (2000); Ballard and Howell (2003). This notation have an important advantage in relation to common flowcharts because it differentiates the directives from the inputs of a given process, and highlights what is the role of the output of a process for the next one.



Circles – play different roles in the system, such as the directives of a given process or its inputs and outputs. It is related to products of a work such as information, materials or final products.

Rectangle – is related to work processes; it means that there is an application of expertise to known problems with reasonably known outcomes.

Diamonds – concerns a control mechanisms, which will change the management process in order to increase the match between planned and executed.

Hexagon – the process outcomes refer to the consequence of the deliberations made by the process

Figure 5.14: Model design notation

5.5.1.4 Evaluation

March and Smith highlights that while natural science seeks to understand reality, design science creates things and, for that reason, should be assessed against a value or utility criteria. As the artefact emerged from a real problem, its utility should be situated on this context (VAISHNAVI; KUECHLER, 2007). The utility of a planning and control model has to be assessed according to its effectiveness of achieving its main goals. Four main criteria were used to assess the utility of the model decentralized and collaborative plans, control of the WIP, use of transparent plans, and the focus on the final product. The variables are summarized in Figure 5.15.

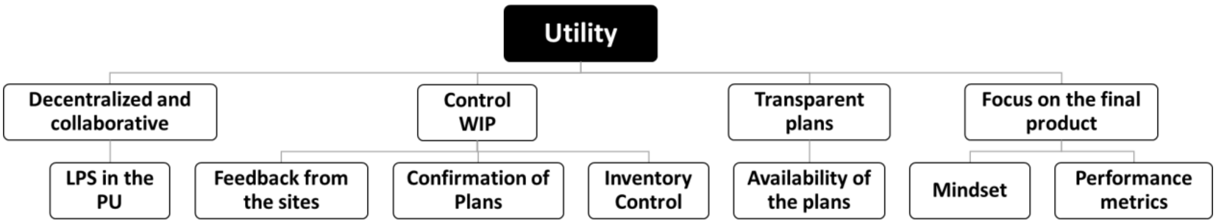


Figure 5.15: Utility construct for model validation

The development of decentralized and collaborative plans is a fundamental step towards a management-as-organizing approach. It is only by avoiding the centralization of information and planning activities that it is possible to learn from what happen in the production level. The use of the Last Planner System is a valuable mean to achieve this goal.

The control of the WIP is important to create a manageable environment, and, as discussed in section 3.2.3, to make the system benefits from pull production. The evidences for this control also revealed how it should be carried out. Using feedback from the construction sites is an important step for producing what is required by the last production process on this chain. The confirmation of the plans is important in different hierarchical levels to avoid the focus only on volume production and ensure the need for the ones that have been produced. The inventory control refers to an overall control of the finished products, to be able to analyse when there is a need to take actions to decrease it.

The use of transparent plans is related to the two previously described constructs, it makes each production unit aware of what is planned by the others. This awareness helps the PU to develop their own plans, decreasing the need for informal data collection in between the production phases, and increasing the integration among them. The transparency can be seen through the extent to which this plans are available.

The focus on the final product is also a fundamental concern in an ETO production system, since this is what the final customer is willing to receive within the time and cost previously established. This focus requires a change of the cultural mindset in the steel industry that attribute the success of the production system to the amount of material fabricated, instead of in customer attendance. This mindset shift can also be seen through the type of performance metric used.

5.5.1.5 Conclusion

This phase is concerned with a theoretical contribution that emerge from the research process, which Holmström (2009) named as an explanation phase. In this regard, there is a need of a critical analysis of the final results through a reflection upon the results obtained in the evaluation and on the research process as a whole, connected with the literature. The final conclusion and discussion of the theoretical contributions of the final model is only possible through a cross-analysis between the other empirical studies.

5.5.2 Research process in Company B

The study on Company B was held from September 2014 until February 2015. The author worked collaboratively in the HVAC contractor project office, understanding the demands from the GC and the capacity of the different fabricators. For this reason the phases of this research process is similar to the one in Company A. Although it was a smaller study, the researcher became part of the company routine, as what happened in Company A.

5.5.2.1 Awareness of the problem

As a mechanical contractor, in this study the author needed to understand the product and the way it interacts with the remaining trades of the construction process. The case of Company B was important to reveal the challenge of a trade that is not from the critical path of the construction, to adapt their production method to achieve the pace of other trades. Figure 5.16 shows the aim of the main sources of evidence used for understanding Company B problem.

Source of evidence	From	Aim
Semi-structured interviews	Vice-presidents	Understand the production process and the company workflow.
	Dry-side project manager	
	Pricing analyst	
	Dry side superintendent	
	Wet side superintendent	
Document Analysis	GC schedule	Analyse the main constraints, lead-times, and the windows for delivering or installing the components.
	Internal schedule	
	Internal look-ahead plans	
Direct observation	Piping Fabrication facility	Understand the characteristics and main constraints of the fabrication and shipping processes.
	Ductwork fabrication facility	
	AHU fabrication facility	
Participant Observations	Weekly planning meetings with the GC	Understand the way the work was organized and how were the interactions between the GC and the subcontractors.
	Logistics meeting with the GC	
	Design coordination meetings with the GC	
	Internal weekly planning meeting	

Figure 5.16: Aims of each main source of evidence in Company B

The semi-structured interviews were guided by the following questions:

- Describe your role in the company
- How is the workflow of the products in this project?
- How different is this process in this project from the other projects of the company?
- What are the plans you rely on to produce your work?
- How are you controlled?

This phase of Company B changed the aim the researcher has previously thought for this study. At first, the idea was to analyse some good practices from a different ETO industry to analyse the applicability to the model development. Given their demand on better understanding the activities on the site and the impact of them in the release of the design for fabrication, the study had changed its focus to incorporate this demand.

5.5.2.2 Suggesting and developing the solution

In Company B, the learning cycles occurred in a weekly basis, according to what were the demands from the construction site. In this study two workshops were carried out, the first as a validation of the first understanding of the researcher regarding Company B procedures. In this opportunity the first analyses regarding a problem in the ductwork delivery was also discussed. The second workshop was the discussion of the final results and the possibility for next steps. The participation and scope of the workshops can be seen in Figure 5.17

Workshop Date	Participants	Scope
1. October 15th, 2014	· Company Vice presidents · Dry side superintendent · Lean implementer	- Report the first diagnosis; - Discuss the analysis of the ductwork; - Find out the scope of the following analysis
2. February 2nd, 2015	· Vice presidents · Dry side superintendent · Project manager of the dry side · Project manager of the wet side · Responsible for the schedule update · Project manager for the submittals · Detailing designers	- Present the result of the analysis made - Understand the main problems they face with the interaction with the GC - Understand how the analysis helped

Figure 5.17: Main scope and participants of the workshops in Company B

The researcher was in the project office of Company B at least two times a week. Because of this close interaction it was possible to develop and evaluate the solutions in a short-term basis. Nevertheless, the workshops were important as a formalization of the knowledge developed during this period.

5.5.3 Research Process in Company C

In Company C the phase of understanding the problem was the main part of this empirical study. The company offers a huge amount of information on the web, the starting point for understanding their production process came from there. Another important secondary source of data was the previous studies carried out on the company in partnership with P^2SL.

For this reason, in the first visit to the company headquarters there was already some previous understanding. The plant of the company was visited twice, when it was possible to understand the production processes. Three people were interviewed: the president, vice-president, and a construction manager, in a semi-structured fashion in order to understand the product development process, the company capabilities and the peculiarities of this production environment. The semi-structured interviews were based on the following guide:

- How do the agreements with other steel fabricators works?
- What is fabricated in this facility and what is not?
- How far can they ship the products that are fabricated in this plant
- Do you develop special connections if a specific design requires?
- How often does it happen that the client interferes (i.e., request design changes) during the manufacturing process?
- What are the common lead time from customer order to start the erection
- What are the main performance metrics used for measuring results?

- How do you batch the products to go to the site?
- How automated does the construction site has to be?

Company C presented a different way of dealing with the complexity inherited in the steel structural system. The study in this company was used for the understanding of the practices that differentiate this production system. The reflection phase is related to the abstraction of those practices to the final development of the model, acknowledging the peculiarities of the context.

6 STUDY ON COMPANY A

This chapter presents the results of the main empirical study of this research, carried out in Company A. First, the existing planning system is described, pointing out the main problems that were identified in the early stages of this investigation. This initial phase refers to the effort of framing the problem. Then, the implementation process is described, divided in the learning steps pointed out in the research design. Third, a discussion about the learning from this phase of the research is presented.

6.1 EXISTING PLANNING AND CONTROL SYSTEM

In order to facilitate the understanding of the existing planning system this section is divided into six parts. First, the overview of the process is presented followed by the way products are divided into batches along this process. Both these sections are the basis for presenting the existing planning and control system of the company. Fourth and fifth sections refer to some important topics on this system: the role of the logistics department in increasing WIP, and the efforts already made to integrate the planning and control system. Finally, a summary of the existing system is presented.

6.1.1 Overview of the process

Figure 6.1 presents an overview of the process, including the main activities that the projects need to pass through, as well as the milestones that the project manager needs to be aware. In fact, this process map was devised by the company for training project managers, so that these could have an overview on how projects flow through the production units and how these units interact with each other.

During the **bidding process**, there is a strong interaction between the Bidding division of the Planning Department and the Sales Departments. The Bidding and the Project Flow divisions of the Planning Department are in charge of defining the long-term schedule, and checking if it is feasible to deliver the project within the client timeframe. When the client and the company come to an agreement, the deal is formalized through a specific documentation containing the main requirements of the project. This document is then sent to the Planning Department, finishing the bidding phase.

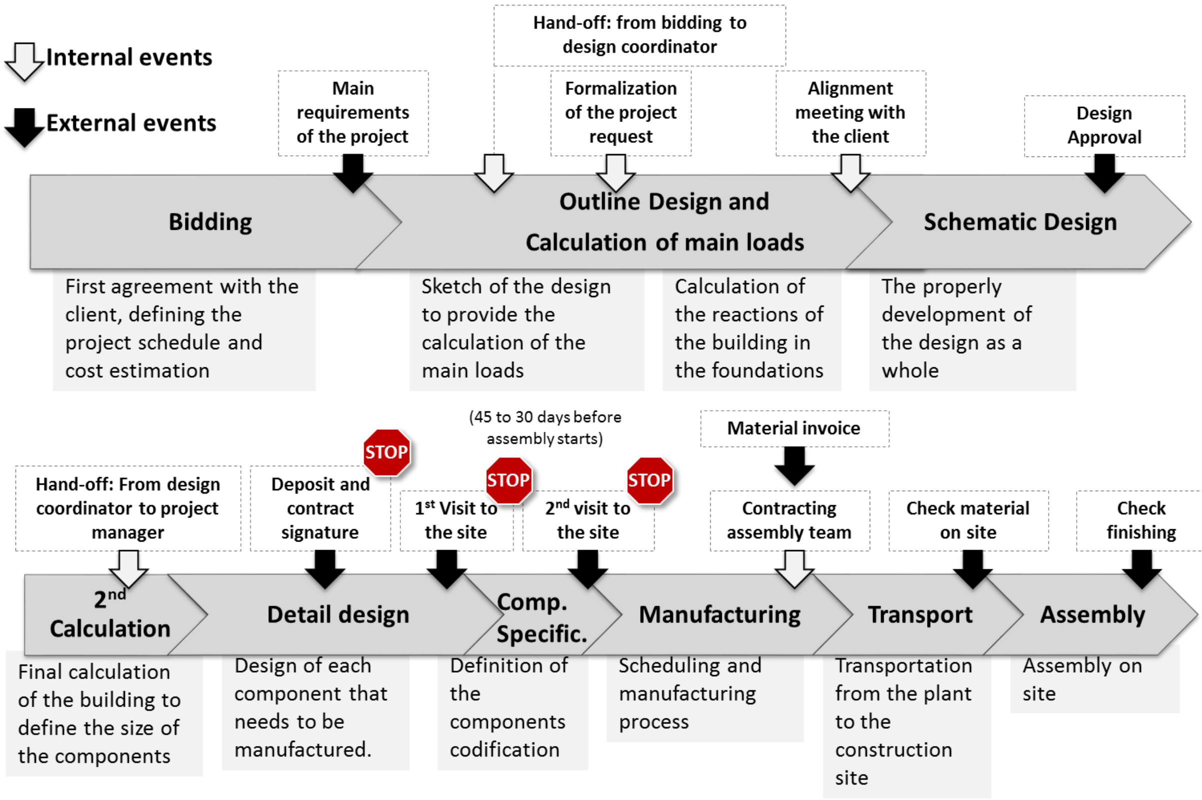


Figure 6.1: Main project stages and key milestones for project managers
(based on company documents used for training project managers)

When contracting a project, the client is normally responsible for the initial tasks at the construction site, such as preparing the ground, producing the foundations, and organizing a plot of land for storing components. Therefore, at the early stages of the design process, the steel fabricator needs to provide some information to trigger these processes.

The **outline design** phase concerns the first attempt to convert client requirements into product specification, defining the main geometry of the building. With this definition, the design team is able to **calculate the main loads**, providing the loads of the structure on the foundations so that the client can start its design and construction. This phase ends up in a meeting with the client to approve the geometry of the steel structure developed so far. The **schematic design** concerns the development of this geometry until the project is ready to be detailed. The **detail design** should start only after the client approves the previous design phase. This evaluation is often made by exchanging information electronically, not through a meeting. This approval process usually takes around10 days.

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There are two important hand-offs in the first four process stages. After the bidding phase, the main contact for the client changes from the sales person to the design coordinator. After the design approval, the project manager becomes the main contact for the client. These hand-offs are carried out through an internal meeting in which the main people involved in the project participate, with the aim of avoiding loss of tacit knowledge acquired in the relationship with client.

The **second calculation** phase is critical, since the cost estimation of the project is checked against what was negotiated in the bidding phase. If the initial estimation assumed more tons than the actual one, it means that the company will have an extra profit. However if the project is heavier than the initial estimation, the profit margin will be lower than expected. In this situation, the project is usually interrupted, requiring an approval from the company top management to continue. When this difference is considered too large, the company try to renegotiate the project price. This calculation is also a trigger for buying thin hot-rolled steel, one of the main raw materials for producing components. Thicker plates are bought according to a forecast, since its lead-time is longer than 2 months.

Before detail design finishes, the project manager needs to be sure that the client had already made the initial payment and that the contract had been signed. Otherwise, the project is not allowed to go forward, and the components to be manufactured. The project manager may also need to stop the project if the construction site is still not ready to start the erection of the structure. In fact, the project manager makes two visits to the site, 45 and 30 days before the site assembly activities should start. If a problem is detected, the detail design and manufacturing of components can be stopped until the problem is solved so that neither the design nor the manufacturing process should go on. Those visits are called **preliminary analysis of the site**, and the aim is to avoid the fabrication of components that cannot be delivered or assembled on site.

Before the manufacturing starts there is a process called **component specification** (comp. spec. in Figure 6.1), in which the components defined in the detail design are named and addressed to the right machine in the plant. After **manufacturing,** a major concern is to deliver the products on site, because of payment conditions.

When materials are delivered to the site, the client is usually supposed to pay 75% of the weight of the manufactured components. This contractual rule create an incentive for the company to increase work-in-progress, by producing the heavier components first, although it is the final building that is sold to the client. This resulted in a large amount of inventory at the plant yard and in construction sites, leading to material handling challenges. In order to deal with this situation, the company created some countermeasures to avoid sending just the heavy components to the site and not all the required components to start the site assembly process. The main countermeasure refers to the start of the **transportation** phase; it is a rule that components can only be sent to the site when the whole sub-stage is already produced. This rule can only be broken with the permission of the company's director. The project flow ends up in the construction site, where the site assembly processes take place.

6.1.2 Division in batches

Within each of the production units there is a different way of batching the projects, as shown in Figure 6.2. The Design and Engineering Department is divided into several teams. Each team is involved in the production of a set of projects. Sometimes a detail design team is in charge of the whole project, or a project is divided in a number of teams for the detail design phase. In any case, the design should be delivered in sub-stages for the manufacturing plant.

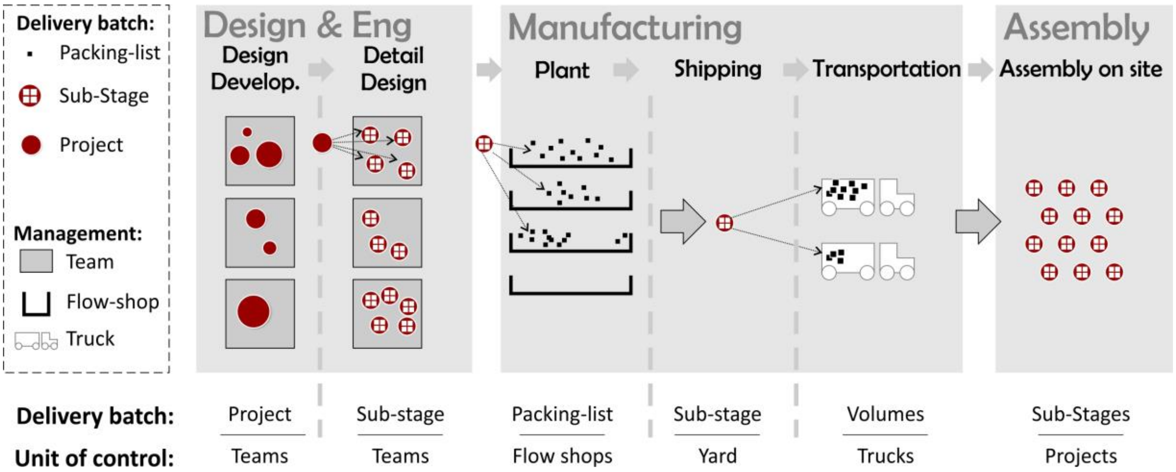

Figure 6.2: Division in batches for different production units

The plant is organized in flow shops[1] specialized in one or a small set of product types. For that reason, each sub-stage is divided into different set of products which are called packing lists. The different packing lists from the same sub-stage may be produced by different flow shops. The plant yard receives the products in batches of packing lists, depending on the size, organized in a package, called volume. Then, the products are organized in the yard according to the product type. There is a need to wait for the production of all the packing-lists for each

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[1] Stenvenson, Hendry, and Kingsman (2005) define a general Flow Shop as an assembly line where work travels in one direction but jobs are allowed to visit a subset of work centers, permitting limited customization.

sub-stage in order to start the shipment process. However, in most cases, it is not possible to ship a complete sub-stage in one truck. For that reason, in the loading process, components are organized according to the volumes packed after production.

Lastly, at the construction site each project should wait for the completion of the sub-stage delivery before starting an assembly batch. Deliveries and measurements at this phase are based on sub-stage completion.

6.1.3 The existing planning and control system

A value stream map was developed in order to understand the main activities related to the project flow, and identify waste, as shown in Figure 6.3. The main information used for developing this map was gathered in the first round of interviews, and the result was validated by the managers involved in the first workshop. The map uses average lead-times according to the perception of managers. Although much variability existed in those lead times, this map provided an overall picture to understand the impact of the existing planning and control system.

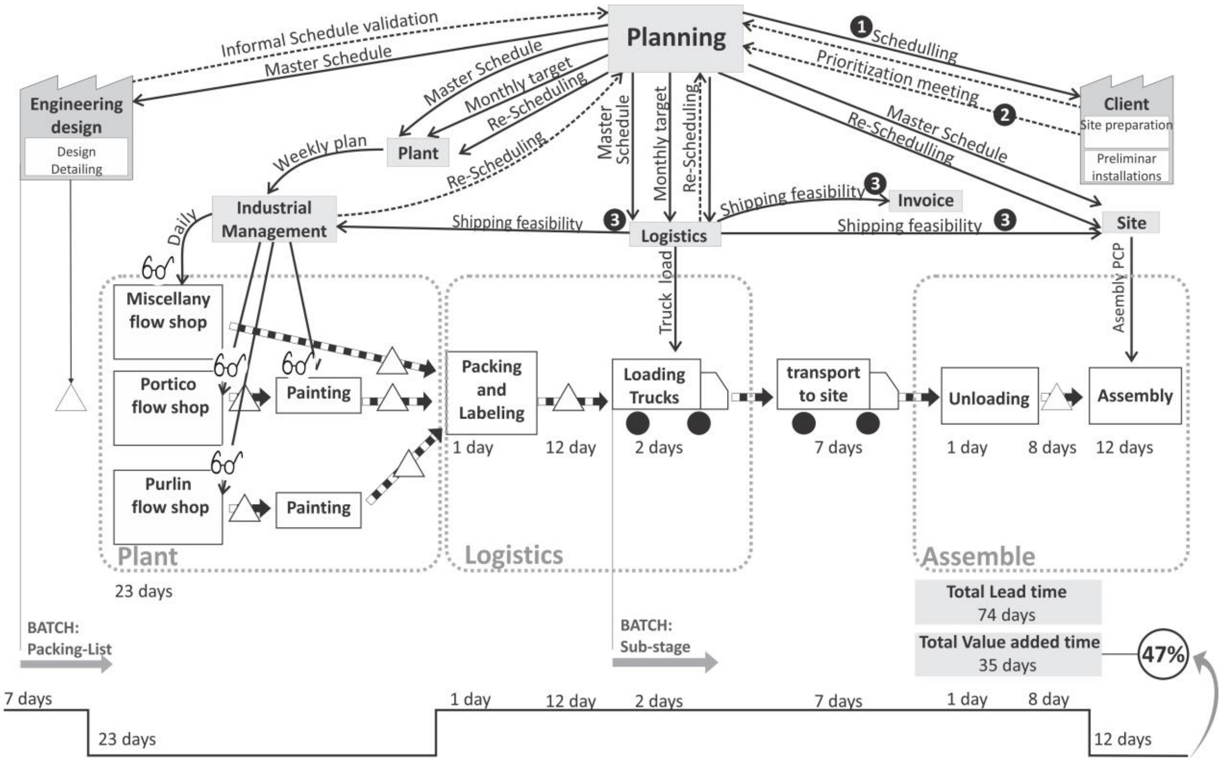


Figure 6.3: Value Stream Map of a generic project

The map starts after the detail design is finished. The production time of the plant was considered as a black box since the specific processes within the plant were not analysed in this study. Therefore, the ratio of value added time is quite high, 47%. Although the project flow through the production units is quite simple, the flow of information that supports it is much more complex. Figure 6.3 makes it evident that there is a centralized approach for decision making, around the Planning Department. In the figure, the planning in the centre concerns the project flow division of this department.

Starting from the scheduling with the client (see point 1 in Figure 6.3), the Planning Department is in charge of merging the master schedules from all the company projects into the ERP system, so that every department can access the most updated version of this schedule. Since this schedule is set with the client, the company is only able to change it, if the activities from the client side had some delay, such as design approval, payment, or site preparation. The project managers are the only ones who can give permission for an update in the master schedule, because of their close relationship with the client. However, each production unit might need to make adjustments in that schedule, at medium and short term levels, but this should not have an impact in the master schedule.

A major concern of the company is to maximize the utilization of capacity. This means that there is a strong effort in levelling the demand oscillation. Figure 6.4 presents the variation of sales along the year from three different years, in relation to the average of production the plant should achieve in terms of volume. The amount sold was converted to a percentage, using the plant target as a reference. During some periods, such as January or July, it is common to have a substantial reduction in sales. However, the company defines the monthly targets according to a strategic plan and not according to the actual sales. This situation encourages the different production units of the company to expedite production in order to have the increase the use of capacity.

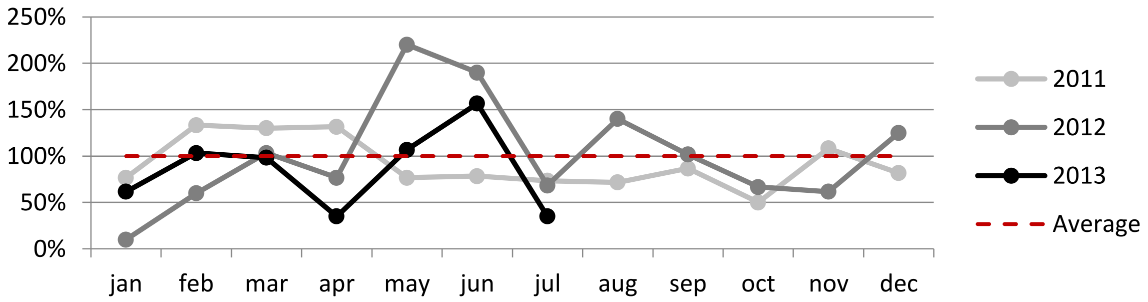


Figure 6.4: Demand oscillation

As discussed by Wiendahl, Von Cieminski, and Wiendahl (2005), a common strategy to increase the utilization of capacity is to increase the work in progress. The expedition of the production of some components, mainly the heavier ones, make the mechanisms for avoiding the storage of ready components to be useless, since the fabrication starts before the preliminary analysis of the site take place. In the case of some special clients with a long-term relation with the company, fabrication can start even before the client signs the contract, to be able to expedite part of the production. As a result, the strategy of increasing utilization of capacity requires the suppression of the mechanisms to cope with uncertainty. In order to have the large level of WIP projects are released too early. Although the Planning Department was aware of the need of confirming the production, the production incentives were hindering this process from occurring properly.

The Planning Department also carried out a weekly meeting, named Site Meeting, which aimed to increase the reliability of deliveries on site. This meeting involved representatives from different departments: design and engineering, manufacturing plant, logistics, accounting, and project managers. It was a long meeting (around 3 hours long), in which they discuss one-by-one the sub-stages that were late in each production unit. For each delayed item, a new date was established. However, there was no systematic control of what was hindering production, and not much effort was made to anticipate some problems in order to avoid further delays. The main contribution of the meeting for the participants was the information about the actual production due dates of the products.

Since the beginning of the investigation, the Planning Department had the policy of hiding information from the plan, based on the assumption that if a production unit knew when the batches were really needed, they would delay the delivery even more – this is often called as the “student syndrome”, as coined by Goldratt and Cox (2007). However, they were doing more than only adding a buffer for the final date. This approach was causing a series of unproductive processes such as the need for the Site Meeting.

The most important metric for the production units was the amount of weight produced, here also referred as the volume produced. Even the Logistics Department was seen as a separate production unit, which means they had their own targets, not necessarily the same as the manufacturing plant. Figure 6.5 presents an overview of the existing planning and control system of the company. It is clear that the main factor consider in the planning decisions is the need to maximize capacity utilization, expressed in terms of volume long-term target, for different production units.

The monthly target concerns the “should” directive for the production units. Although it was defined in terms of project sub-stages, the monthly targets were disregarded when there is some constraint to achieve the established goal. The plant and the shipping process were measured through different targets, revealing the awareness to build some work-in-progress between those processes. Besides, while the monthly targets defined a set of products, the site meeting would make the control over the master schedule. It was also observed a lack of feedback from the operational level.

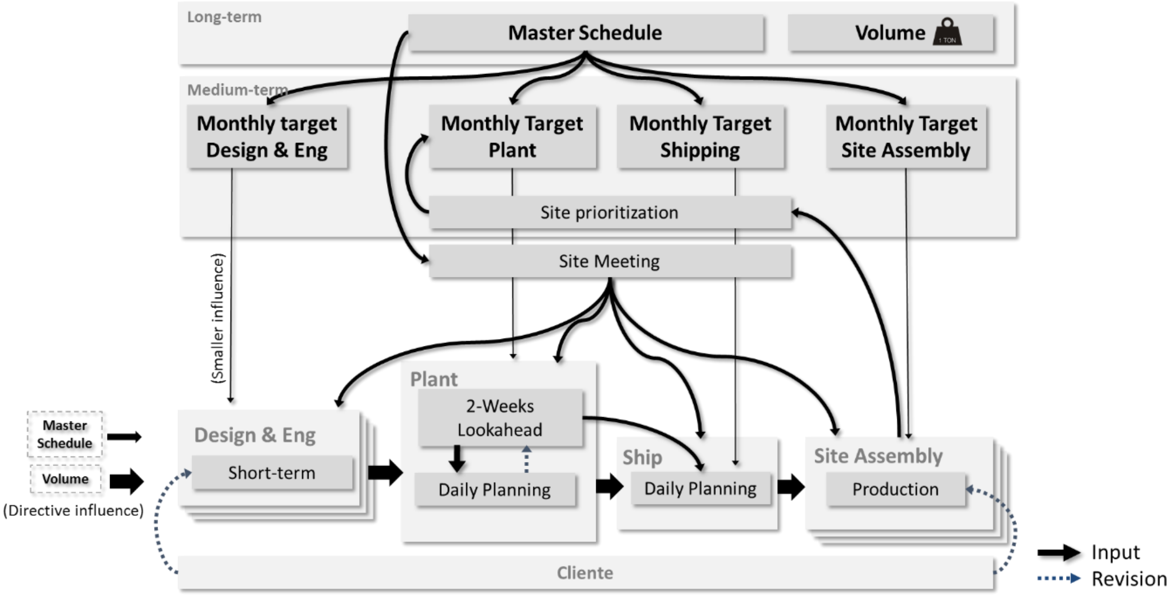


Figure 6.5: Overview of the production planning and control system

An important characteristic of the existing planning system was the lack of hierarchical control levels. The production in each unit would be checked against the master schedule, or monthly targets. The adjusted plans developed within the unit were considered only in the analysis of the volume produced; there were no adherence metrics in this level.

The total weight of steel components (in tons) was defined in the strategic plan of the company. The role of the Planning Department was to analyse the most suitable projects to be designed, fabricated, and delivered to the site in the following month, in order to accomplish that number. After this analysis, the Planning Department provided what should be produced to achieve the amount of weight required. Both those information defined the monthly target.

An important source of information for this decision was the preliminary analysis of the site. In a monthly meeting, called prioritization meeting, project managers and representatives from the Planning Department got together regularly in order to establish the project priorities in terms of site assembly (see point 2 in Figure 6.3). The Planning Department collected two different information about the projects, if the site assembly was in progress or stopped and general comments about the construction site. Then they would define if the production could be expedited or not. The prioritization meeting used to happen in the third week of the month, and the information from the sites were used to fill gaps of the fabrication plan, as follows:

a. In the last week of the month, the Project Flow analyst would define the target for the following monthly, based on a 10-day plan of the plant for the first week, and on the master schedule for the remaining ones;
b. The same analyst need to see if all the flow shops from the plant will be fulfilled with the products defined for the monthly target;
c. If yes, the prioritization meeting would be disregarded. If no, he would look at the most suitable projects to be expedited to see if some of them need the type of product required by the plant; and
d. A monthly target is, then, defined in terms of product, and sent to the production units.

Sometimes, the information from the prioritization meeting was not even used. It is worth noting that this was a very demanding meeting for some of the participants, who had to travel from the sites or from other offices to the company headquarters once a month. For this reason, they expected that the information provided in the meeting would be fully used in the plant scheduling. Several problems were created by the non-consideration of changes in the demands from construction sites, such as, for example, sending components to construction sites that had no teams available for the unloading, while another site had idle teams waiting for the same type of product. This kind of problem happened because of the centralized, pushed approach to planning and control without considering changes in the status of construction sites. The projects already scheduled in the master plan were supposed to follow that schedule no matter what was happening in the site.

At the manufacturing plant, there were two different production planning levels. The higher level was carried out by a section of the Planning Department dedicated to the plant, and the lower level by the management of the plant itself. After receiving the monthly target, the Planning Department defines the production sequence, trying to avoid too many setup operations and ensuring that the different flow shops will be fulfilled. Then, a 10-day plan is sent to the plant manager who could do some changes in the production sequence in order to keep a daily pace of production, avoiding variance on the throughput daily rate. Each sub-stage, requiring available raw materials, usually waits for one week to be scheduled and two weeks to be produced, resulting in a three-week lead time at the manufacturing plant.

During the production process, each unit might face some problems performing the projects required in the monthly target. Since the main metric is based on volume, each unit manager might decide to exchange a project from the target to a different one with a similar size. Therefore, each production unit had some degree of autonomy when deciding what should go for production: the heavier component, the easiest to fit in the truck, the project with better definitions from the client. By contrast, the most required component in the construction site was sometimes left aside.

Another reason for disregarding the status of projects in the monthly targets was he planning horizon. As the targets for the following month were defined at the end of each month, there was no rolling plan. Moreover, the targets were only established in terms of due dates, not lead times. Those practices would force production managers to decide what should be started by the end of the month, which would be finished at the beginning of the next period.

The problems related to the focus on volume is strongly related to the way the company is assessed by shareholders, and even internally to compare the performance between the business units. The way steel projects are priced is also directly related to the focus on weight.

6.1.4 Logistics and work-in-progress

The Logistics Department is responsible for shipping the components, considering that production batches should correspond to sub-stages. As mentioned earlier, this department is not able to ship a set of components if the sub-stage had not been produced completely. Therefore, this department needs to gather information from different sources to check whether a batch can be shipped: (a) when the batch will be finished; (b) whether the construction site is able to receive the components; and (c) whether all the documents and invoices are available (see point 3 in Figure 6.3). Consequently, the waiting time of batches in the yard ranges from a few days until months. The average waiting time estimated by the company was 12 days, considering that the shipment process takes two days to complete, and the delivery time depends on the site location. In order to avoid delays, the Logistics Department often decides to start the shipment before the plant had produced the components, so that shipment would finish just after the last component is delivered at the plant yard. Any problem in this fabrication would cause an inventory of loaded trucks, waiting to be able to go to the sites. For this reason, it was important to get information about when the sub-stages would be delivered available to schedule the shipment.

The main metrics adopted by the Logistics Department were not focused on effectively supplying construction sites, but on freight optimization (rate of utilization of capacity). Sometimes, although sub-stages have been fully produced, these may not fit a truck capacity, so the heavier items are shipped first, and the client is charged for those items. The remaining components are left for the following freight, even if it affects the site assembly schedule. The impact of that in the construction site sometimes is a yard full of components that are not possible to be assembled. Figure 6.6 shows the impact of this practice. The connected circles refer to loads that mix components from different sub-stages in the same truck and the arrows show the delivery due date on site.

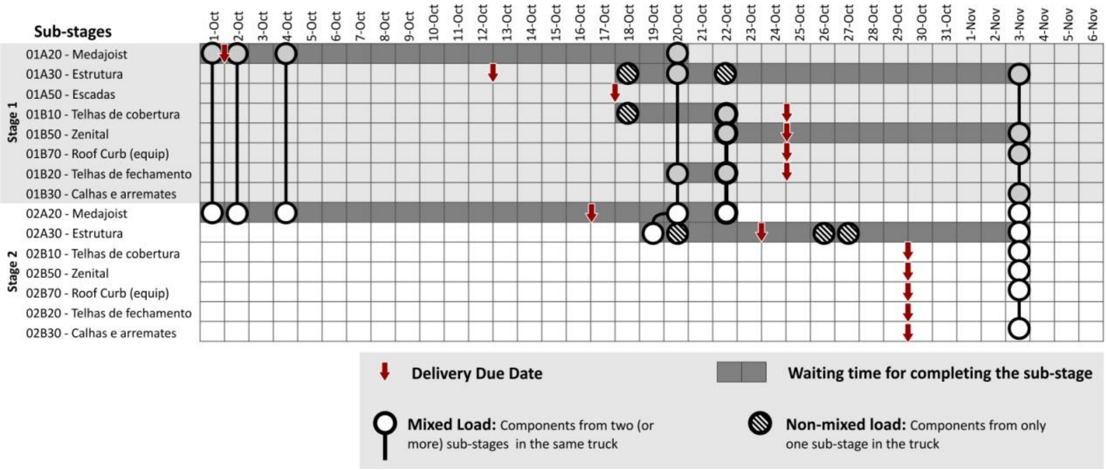


Figure 6.6: Impact of freight optimization in a construction site

The need for re-batching components, to some extent, makes the Logistics Department disconnected from the manufacturing plant, like an independent production unit, as discussed earlier. Figure 6.7, illustrates the result of this disconnection, through an analysis of how many sub-stages delivered by the plant are shipped in the same week. The overlapping of the circles demonstrates how many sub-stages were fabricated and delivered within the same week. The mismatch shown in the figure reveals the need to store a huge amount of material on the yard, before it is possible to ship.

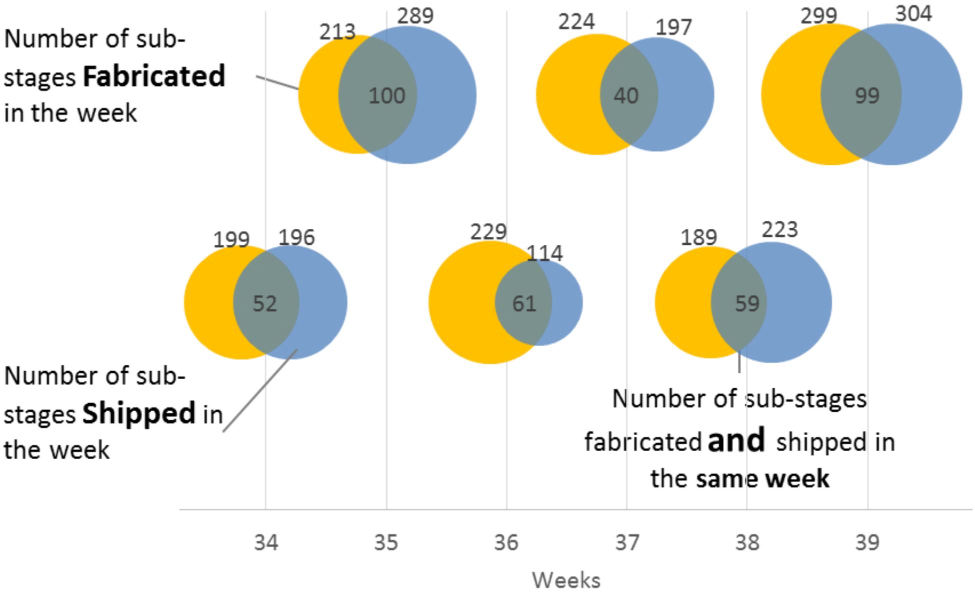


Figure 6.7: Fabrication vs. Shipment to construction sites

All those conflicts among production units reveal a misunderstanding of the idea of reducing the batch sizes at all stages, since one of the main performance measures of production units is the production volume rather than the completion of a sub-stage. This approach has traditionally made all company departments to be more concerned about the volume produced, than the delivery of a specific type of component. Due to this conflict, the company had not been able to reduce the amount work-in-progress as expected, despite of the decision of delivering design information, and components by stage (and sub-stages).

The amount of inventory at the plant yard was dynamic, changing in a daily basis. As the plant kept its production pace while the shipment process might vary a little more, it is normal to have some oscillation in this total amount. An important rate to control is the amount of completed sub-stages in the yard, because these are the materials ready to be shipped. The amount of inventory at the plant yard was monitored in different days of the month, for six months in this investigation, as shown in Figure 6.8. According to the Logistics Manager, their team were striving to achieve a maximum of 2 thousand tons of material, which he considered a bearable rate for a workable and safe yard. In fact, during the period of analysis the average amount was 2.192 tons, although the maximum amount reached more than three thousand tons. The proportion of ready to ship material in relation to the total amount of products in the yard was, on average, 27% for the analysed period.

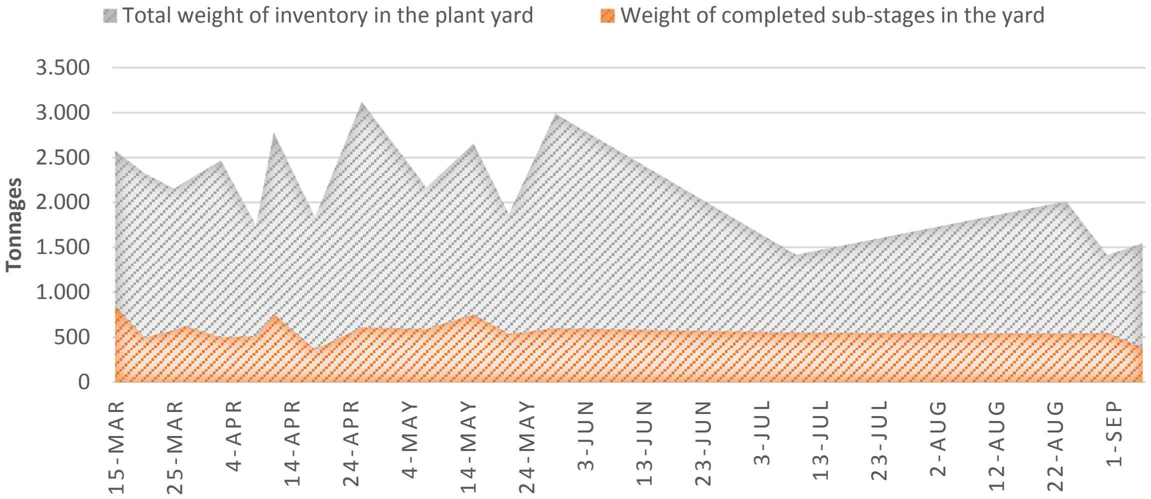


Figure 6.8: Amount of material in the plant yard in terms of tonnages

Figure 6.9 crosses the information about how long components have waited in the plant yard and if it was produced in advance, according to the master schedule, in terms of sub-stages. Since the types of components in the yard change in a daily basis, it was necessary to analyse one day of the yard, from May, 2012. Figure 6.9 indicates that most of the components stored were produced in advance, which means that there was not much time available for changing orders after making the preliminary analysis of the site. As mentioned above, the centralized production planning and control system did not take into account information from assembly sites in a systematic way.

The lowest unit of control from the plant was the packing-list (a set of packing-lists form a sub-stage), so some packing-lists from a sub-stage can be produced in delay, while others from the same sub-stage in advance, and can wait for a longer or shorter period of time in the yard. The worse situation considered in the analysis of the inventory in the plant yard was packing lists that were produced most in advance in relation to the master schedule. Out of the 361 sub-stages in the yard, 20 did not had any complete packing-lists, which means there was not yet available information of the production dates. These sub-stages were considered under production. Therefore, it was not possible to address for how long it was in the yard. In that day, 60% of the sub-stages were complete and, therefore, able to be shipped.

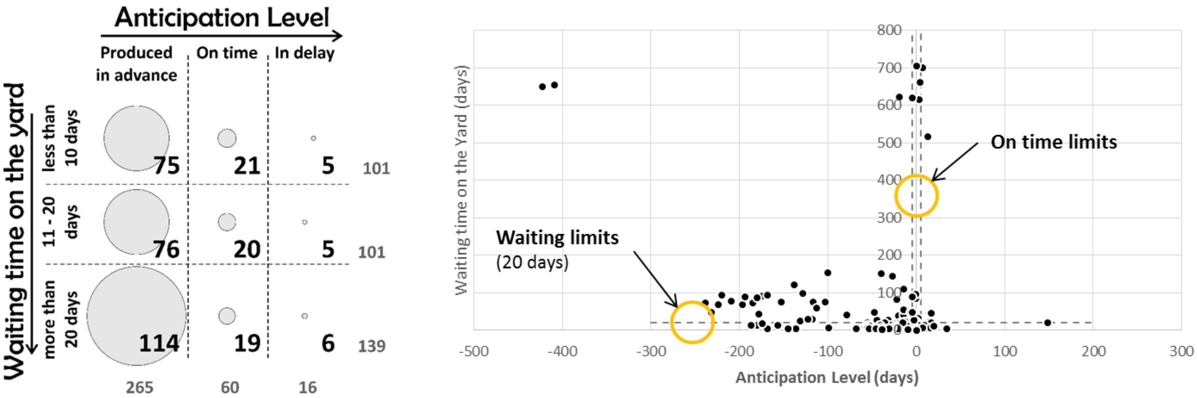


Figure 6.9: Analysis of the work-in-progress of components

The causes of the waiting time of the sub-stages in the plant yard for more than 20 days were collected. As shown in Figure 6.10, the lack of site conditions was the most frequent cause. This problem was addressed when the delays were: (a) the construction site has not enough space to store components; (b) there is no one to unload the components, since site assembly had not started yet; or (c) inclement weather. Regardless the last item, those problems revealed a lack of communication between the construction site and the Planning Department concerning some predictable situations. It also confirms the impact of producing in anticipation: mechanisms to confirm production are neglected.

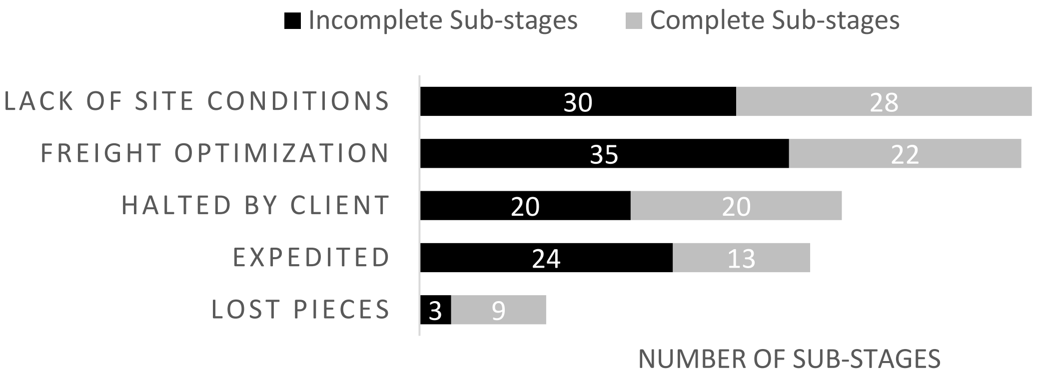
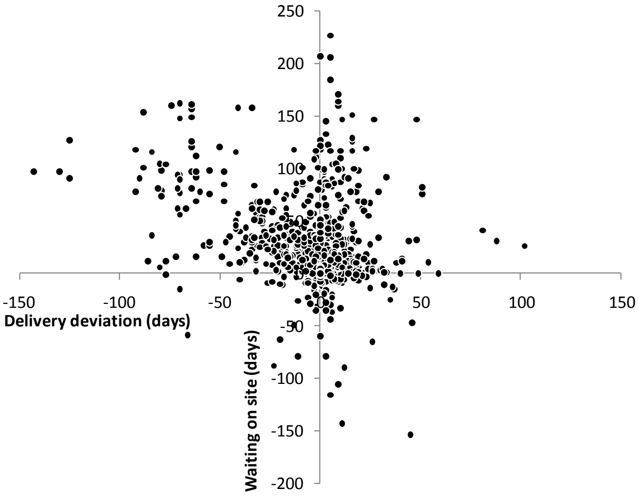


Figure 6.10: Causes for long waiting times

As mentioned in section 6.1.1, as clients are supposed to pay for the components that are delivered on site, there is much pressure to ship them as soon as possible. If necessary, even when there was not enough space on site, the Planning Department would press for an extra land to rent in surrounding areas, in order to store materials temporarily.

Figure 6.11 indicates the impact of this approach at the construction sites, through the relationship of the delivery deviation and the waiting time on the site (each dot is a sub-stage). For collecting this data, it was necessary to analyse the weekly reports from 35 construction sites, which were under development during the period of August and September of 2012. The delivery deviation considers the day of the last load of a sub-stage, while the waiting time considers the beginning of the activities of that sub-stage.



	Delivery in advance	On time	In delay	
Long wait on site (more than 10 days)	21%	30%	10%	**61%**
Quick wait (until 10 days)	3%	24%	7%	**34%**
Expedited use	1%	3%	1%	**5%**
	25%	**57%**	**18%**	

Figure 6.11: Impact of the delivery in advance in construction sites

The majority (61%) of the sub-stages have waited for more than 10 days, while 25% have been delivered in advance. Figure 6.11 indicates that site assembly was receiving materials before planned dates, was not contributing to quicker assembly process. The components were waiting for almost the same time in the site to be used. It illustrates the disconnection between the fabrication and site assembly priorities, and the amount of work-in-progress generated. There were even negative waiting times, which mean that only part of the sub-stage was available and the site manager decided to start the assembly process anyway. This is also an indication of disconnection between fabrication and site assembly: some sites received batches that were not necessary, while some waited for batches that were needed.

Moreover, there was a distortion in the performance metric used to monitor the causes for the delivery delays. This metric was based on the number of sub-stages delivered with some delay within a month period, not considering what should be shipped. Moreover, the metric gave the same weight for short and long delays. Figure 6.12 presents a comparison made in April 2012 between the number of sub-stages in delay and the delay time in days (on average and maximum). There was at least one-day delay in 132 out of 300 sub-stages shipped (44% of the sub-stages). According to the original metric, the main problem was the lack of site information, while when considering the impact in delay time, the main problem was the loss of components, which was a consequence of a crowded and badly organized yard. It is worth noting that the mechanism to avoid sending incomplete sub-stages does not work in this situation, since the components had been produced, but were not found to be shipped.

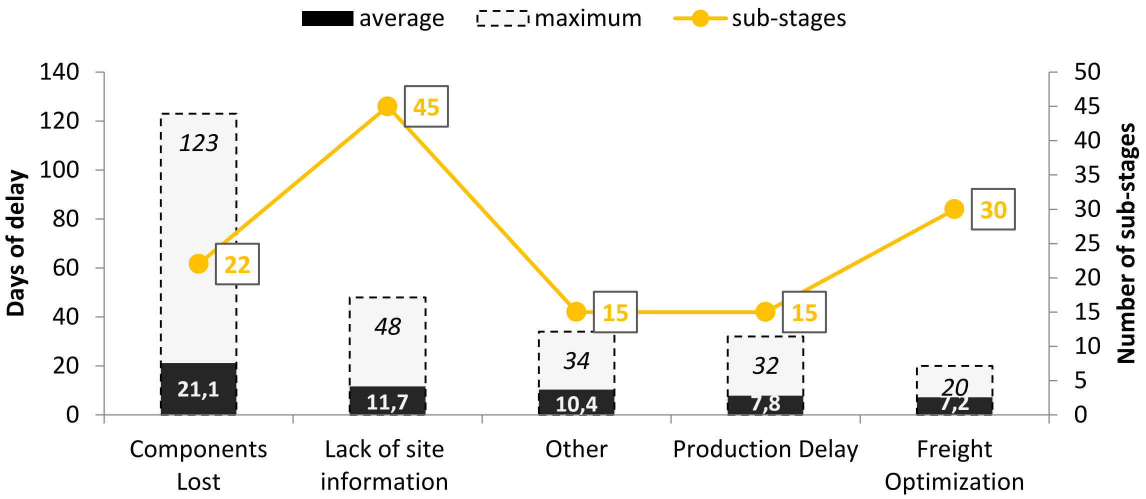


Figure 6.12: Average and maximum delays time (in days) compared to the number of sub-stages in delay for each type of problem

An important control problem was the focus on the due dates for each production unit, instead of lead-time controls. The main production control tool, available in the ERP system for every production unit, provided the delivery dates of different departments for each sub-stage of a project, but not the waiting times between production units.

6.1.5 Efforts for integrating production planning and control

The main consequences of the lack of integrated planning and control were made evident in the analysis of data from a single project. This project was chosen due to the fact that it was a fairly simple warehouse and also because it started after the design and engineering unit had begun to control activity durations, and that had already finished when this analysis started. Figure 6.13 presents and overview of the project, which had 15.960 m², two different buildings, which were divided into five stages.

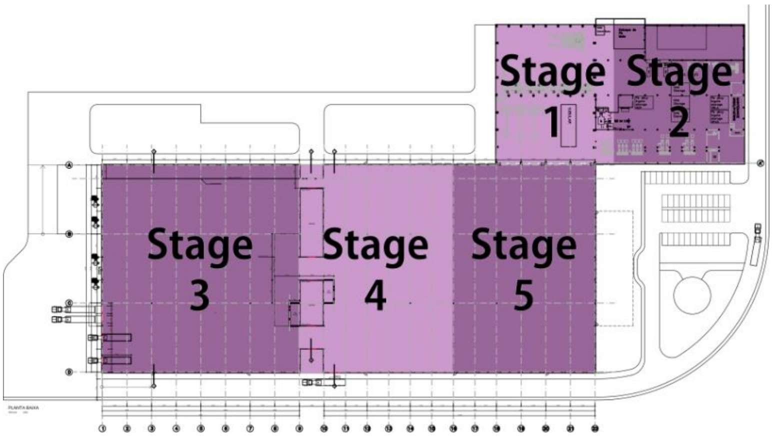


Figure 6.13: Layout of the project

Figure 6.14 shows the time for producing each sub-stage at the manufacturing plant, for loading trucks with the components (not considering the time for travelling), and for assembling them on site. During the production phase there is a mark representing when the first component of the sub-stage was finished. Based on Figure 6.14, it is clear that with the exception of one sub-stage of stage 1, all buildings were erected at the same time, indicating a high level of work in progress.

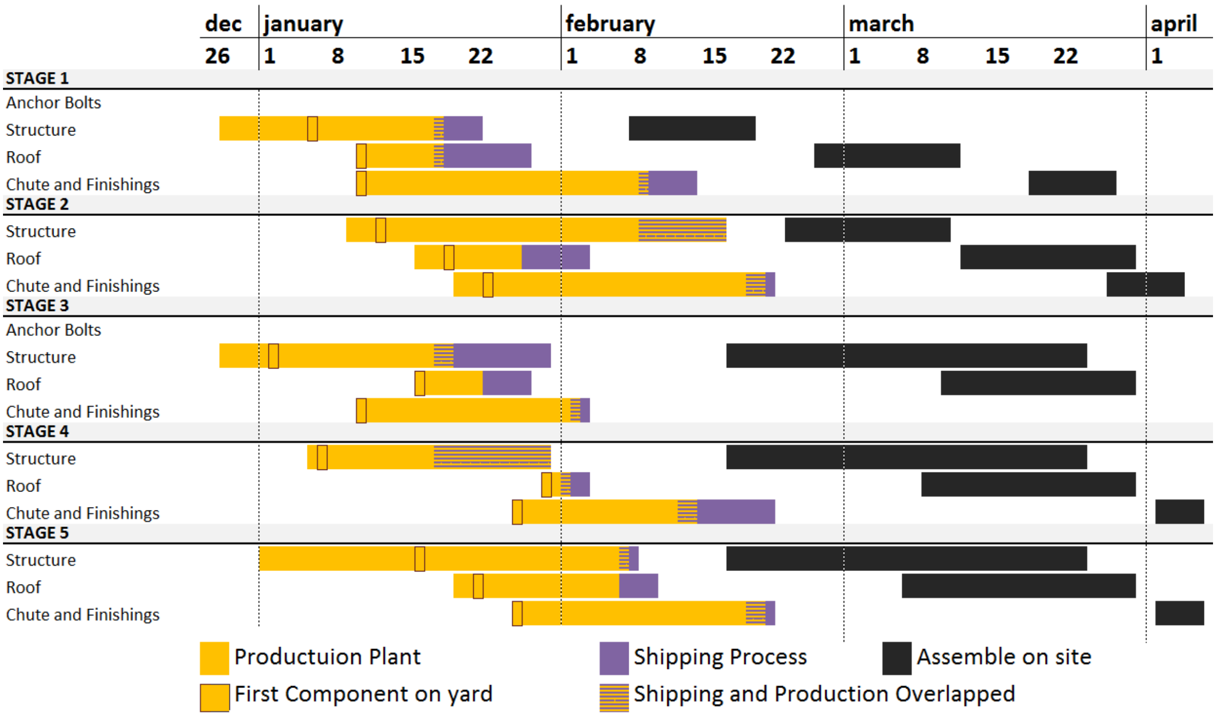


Figure 6.14: Time for producing, shipping and site assembly of each sub-stage

Moreover, structural sub-stages were produced at the manufacturing plant in the same period, and took longer than one month to be produced. This long throughput times can be explained by the focus on controlling the final date, since using this metric there is no control on the start time of the production. It became worth to produce in advance some of the parts of a sub-stage, and let the remaining parts to finish when the final dates were close.

6.1.6 Summary

The diagnosis phase pointed out a number of improvement opportunities in the planning and control system of the company. It is worth emphasizing that the company had already some initiatives for implementing lean concepts and principles in all production units: the definition of batch sizes, through the establishment of the stages; the idea of engaging workers in *kaizen* projects; and the establishment of a Continuous Improvement Department.

The main method used for planning and control is mostly based on MRP core ideas. All information about the project are assumed to be known at the very beginning; even the set of machines that will be required in the manufacturing process are predicted in this phase. This is how the Planning Department allocate the available capacity for that project. As described by Bertrand and Muntslag (1993), an ETO system needs to deal with uncertainty in product specification and, accordingly, in the processes that will be needed.

A common problem seems to be the allocation of the capacity to a project soon after it is sold, which could not be moved even when projects were expedited. Due to this practice, the definition of the available capacity for new projects became ineffective. So the Planning Department used to develop calculation in parallel to the one in the ERP system in order to predict the end date of a new project.

The production planning and control system of the company have some elements from the Workload control, since there is a pool of jobs waiting to go to production between the end of the engineering process and the beginning of the production. As claimed by Kingsman (2000) this is a common practice in engineer-to-order companies. The production system of the company even defines mechanisms to confirm production. However, these mechanisms were not properly implemented, mainly because of the strategy of maximum utilization of capacity.

This type of system also promotes the use of top-down planning approach, in which master plans are difficult to change. This makes it difficult for the system to cope with the level of uncertainty that exist in its production system, and the structural complexity that results from a multi-project environment, creating a high level of work-in-progress, at the plant yard.

Problematic practices cannot be changed simply by establishing new rules. The mechanism to avoid sending incomplete stages to the site is an example. Although the rule was there, the main metric was still the amount of tons were sent per truck. That rule was circumvented very often. The main reason was the long lead times for the manufacturing plant in the delivery of complete sub-stages, associated with the fact that the Logistics Department should also achieve a tonnage goal. In summary, rules should be associated to the performance measurement system in order to become effective.

One important problem in the planning process was the lack of information from construction sites. The first step in this regard was to implement the Last Planner System in the construction sites in order to improve the control of this process. After this diagnosis, the company started an implementation program. The second step needed was to have systematic feedback from all sites to the Planning Department.

There was also lack of transparency in the different levels of the planning and control system. Even the Planning Department, responsible for compiling information about schedules, would hide some long-term information, afraid of delays or uncontrolled expeditions of projects. As a result, there is a formal long-term plan, but many planning decisions at different production units were made informally. For Laufer and Tucker (1987) this situation brings a wide range of consequences, as symptoms of ineffective planning: (a) rare contact between planners and top management, (b) lack of iteration in the planning process, and (c) large amount of data with spurious accuracy. Those authors also emphasize that when using this centralized approach there is a difficulty in maintaining consistency between decisions made at different planning levels – in this study there were not only different planning levels but also different production units.

In this regard, there was a lack of integration between all planning and control instances (design, manufacturing and site installation), and between them and the Planning Department. Despite the high level of uncertainty, the main source for planning the design, manufacturing and site assembly process was the project master schedule. The production was triggered by a plan made a long time in advance, making the production system predominantly pushed.

Although logistics main concern is transportation of components, the company regarded the logistics processes as value-adding. In fact, several investments had been made, such as new high capacity forklifts, and installation of shelves to store components in the yard. According to Koskela (1992) when a flow process is not understood as such there are two risks: not considering the non-value-adding processes, or considering every activity as a value-adding process. If the focus was on eliminating non value-adding activities the investment should be on reducing work-in-progress, rather than improving the efficiency of logistics processes.

6.2 THE IMPLEMENTATION PROCESS

The implementation process was initially focused on improving the existing planning and control system, by creating a planning and control process that integrated design, manufacturing and site assembly, in which the existing structural complexity and uncertainty were taken into account. The aim was to change the existing system from a management-as-planning to a management-as-organizing approach.

The three first steps of the implementation closed an important learning cycle, as discussed in 5.5.1. After the description of those phases, there is a discussion regarding the contributions to the final model through the analysis of the improvements in the planning and control system of Company A. Then, the fourth step is described, followed by its contributions to the final model.

6.2.1 First Step of the Implementation

Assuming that plans should be flexible, the idea was to understand the problems faced during the production and making the decisions of producing different projects in an integrated manner with the production units. This phase was focused on a short-term integrated planning and control instance from the whole system. It was carried out through a meeting, called adjustment meeting, which was not in the existing procedures of the company during the diagnosis phase. It was proposed in a Kaizen workshop after the research started, in order to avoid the traditional site meeting (described in the section 6.1.3). As it was new, it was an opportunity to enhance the integration in planning and controlling the production units. In the second workshop, the role of this planning meeting was discussed, as well as how the Last Planner System could be adapted for that planning level.

At the beginning of the implementation, it was not clear if this instance should be strategic or not, so the main concern was the development of mechanisms to confirm the need for production. These confirmations should have two main sources. One is the client demand for the component. Here, the client was considered the site assembly, which was strongly affected by uncertainty, either from the internal activities in the construction site, or from client decisions. This type of confirmation is addressed in the Workload Control Model. The second source of confirmations should come from the understanding of the internal production processes. In other words, the production carried out within the production unit should be used as a mean to develop future plans, as what happens in the LPS weekly cycles.

The Project Flow Coordinator of the Planning Department chaired the weekly meetings. The participants were mainly one representative from the Logistics Department, and one from the plant scheduling division of the Planning Department. At the beginning, there were no representatives from the site assembly process in the meetings. It was only after two months the manager of this department started to be invited. Nevertheless, it was not common to have his participation, as a manager he used to have a busy agenda. The researcher attended those meetings for the first four months of implementation.

During June 2012, there was some discussion about how this meeting should be carried out. In the **second workshop** (July 2nd), it was defined the procedures of this meeting, which would follow the idea of the commitment meeting (see section 4.3.5), from the Last Planner System. The meeting should start with a discussion about the main causes for not finishing some of the tasks planned in the previous week. There was a need to collect and analyse the causes for the non-completion of plans prior to the meeting, because of large number of tasks included in the plan (more than two hundred). In the final part of the meeting, the tasks for the following week should be discussed, and both plant scheduling representatives and logistics coordinators could commit themselves to deliver the components in the due date.

Still in the first week of July, there was the first attempt to carry out the meeting in the way it was proposed. The Planning Department made a strong effort to get different departments involved in the meeting. However, the results were not as expected. In week 27, the Logistics Department could only ship 11% of what was planned (Figure 6.15) and this was mainly due to the way this first meeting was conducted. The adherence metric was calculated using the number of sub-stages, within the plan, produced divided by the number of planned sub-stages for that period.

It is worth noting that the Logistics Department team was used to the procedure of always confirming the fabrication end date and the availability of space on the site. However, in the first meeting all the participants received a printed copy of the monthly target, signed by the Project Flow Coordinator and by the Planning Manager, who also participated in the meeting. Through the delivery of a printed copy of the monthly target, instead of just sending electronically, the Planning Department assumed it would be taken more seriously and the adherence would be higher. What was missed by the Planning Department was that the low adherence was not caused by people willingness to follow the plan. It was rather due to the amount of uncertainty that made it impossible to follow the initial plan, such as the accurate day that fabrication finishes, the conditions of the site, the possibility to loose components in the yard.

That document made the coordinators from the Logistics Department believe in the monthly target as if there were no need to make confirmations. Therefore, in the first week they schedule the trucks strictly following the monthly target, without even confirming if the components were already fabricated. It was only after the shipment started that they realized that sub-stages were not ready, or were not really able to be shipped because of site assembly constraints. At that moment, it was too late to change the truck orders, so most of the trucks stayed in the yard waiting for the fabrication to finish.

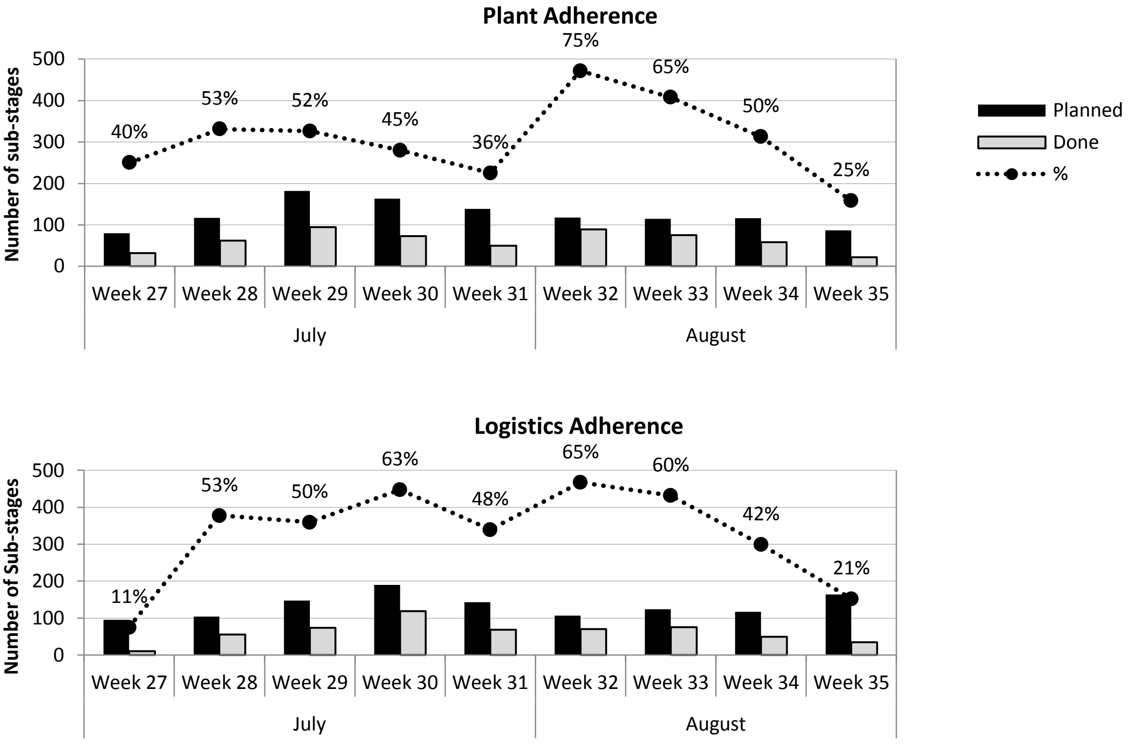


Figure 6.15: Weekly adherence to the monthly target by the plant and logistics[1]

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[1] The number of weeks in the figure refers to continuous weekly score, in relation to the 53 weeks of the year.

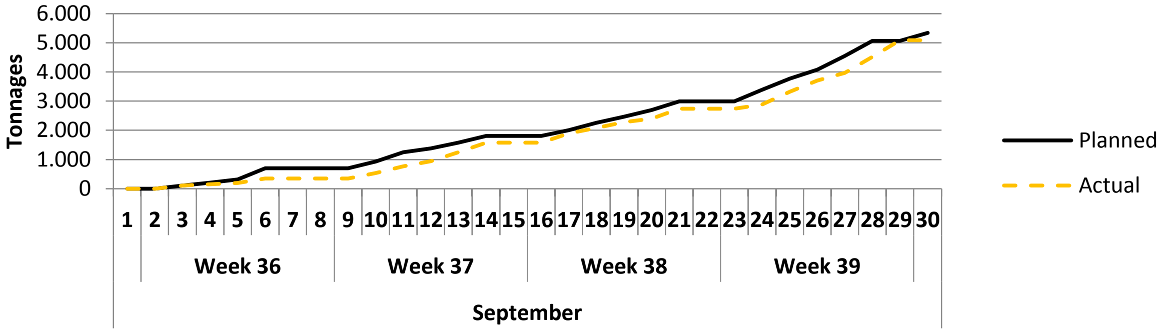
The lack of participation of representatives from the Site Assembly Department was partly compensated by the participation of logistics coordinators, since they could sometimes bring key information about the situation of construction sites. As explained before, this department needed to communicate with the sites that were about to start receiving material. Although there were opportunities for improving the plans according with the status of some sites, the chair of the meeting was not willing to make changes in the plans. When asked why he would not make those changes, he emphasized the importance of getting strict to the target developed by the Planning Department. According to him, there was no point of making a monthly target that could be changed; people would not take that seriously. This approach was hindering the possibility of participants to commit to the tasks, as they could not negotiate. It is worth emphasizing that his point of view was in accordance with the Planning Department as manager's approach, it was not a punctual opinion.

Another problem was the lack of transparency of the plans from the PUs, causing a huge concern in finding the new dates for finishing the sub-stages that were delayed. As the master schedule provided only planned and real delivery dates, there was no place to define and control the confirmed date, which were only known inside the PUs. There were no mechanisms for each production unit to share updated planning data with the others. This discussion looking for the new dates could take the whole afternoon. The whole meeting used to be 2 to 3 hours long.

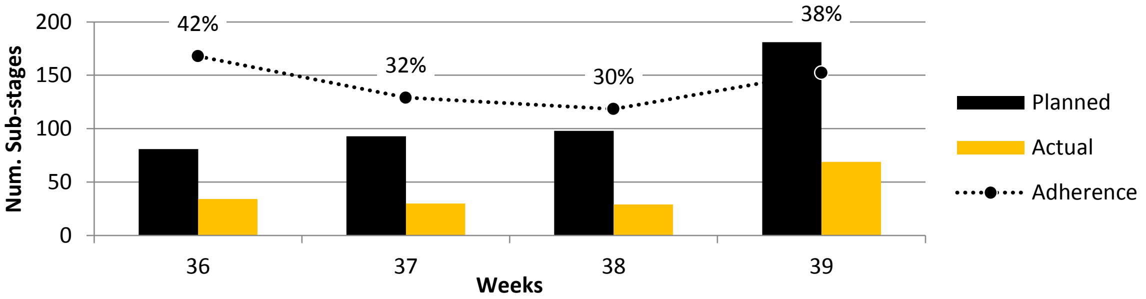
While the chair of the meeting tried to convince the participant to meet the long-term targets, the participants were concerned with gathering the confirmed dates from the upstream phase, i.e., the logistics coordinator asking the plant, the plant asking the design coordinator. The time spent on each part of the meeting used to vary a lot. As the meeting was held in the afternoon, when it took more than 3 hours the participants would ask to stop because their turn was ending. In general, most of the time of the meeting was related to the previous period. The problems for the following period used to be overlooked.

In the first attempt to collect the causes for the non-completion of the sub-stages (week 36), it was done during the meeting, the chair would ask "why?" for each non-completed sub-stage. At this opportunity, the time spent only in this task was about two hours, which turned the meeting unproductive. Although the focus was the monthly targets, Figure 6.15 reveals a low level of adherence to the target, even two months after the implementation started.

Figure 6.16 compares the adherence to the target in terms of sub-stages and tonnages. This latter refers to the metric production units were measured, without a linkage with the planned sub-stages. It is possible to see the amount of components that were planned and actually delivered, and the amount of tonnages produced in tons in relation to the amount predicted. Although 95% of the target in tonnages was met, only 58% of the planned sub-stages were fully delivered to the assembly sites. This disconnection means that the components that had been delivered were not the ones in the plan.



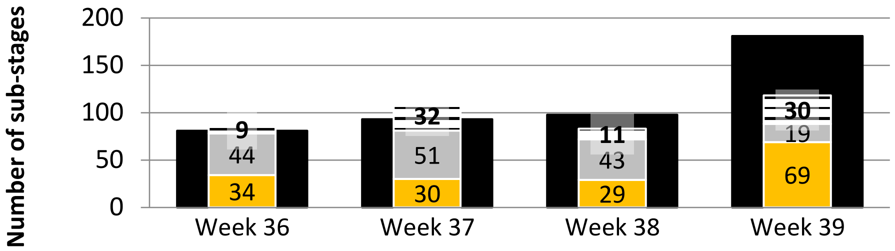
(a) Amount of material delivered on sites in terms of tonnages



(b) Amount of material delivered on sites, according to the monthly target, in terms of sub-stages

Figure 6.16: Comparison of the results in terms of tonnages and sub-stages

In order to understand how it was possible to achieve the tonnages with such a low adherence level, Figure 6.17 depicts the amount of products produced without being on the plan. There are some of the sub-stages that were not produced in the planned week, but they have been planned for the same month, which was not a critical problem. However, in this period, 25,7% of the sub-stages shipped were not in the monthly plan. It means that the requirements of the site were not considered when they were produced. It is not known if project managers discussed the situation of those construction sites.



	Week 36	Week 37	Week 38	Week 39
■ Planned	81	93	98	181
– Not Planned	9	32	11	30
■ Within the month	44	51	43	19
■ Within the week	34	30	29	69
Adherence %	42%	32%	30%	38%

Figure 6.17: Adherence to the target

At the **third workshop**, an assessment of the main problems faced in the meeting was made. One of the analyses can be seen in Figure 6.18, where it was given a grade to each meeting. This grade ranged from 0 to 10, and was established according to the extent to which each of a set of practices was tracked. Figure 6.18 also shows the criteria for assessing each practice. The final grade was an average of the grades of all practices.

During the first month, the meeting would just assess the previous week, and was not able to look further. In the following month, the causes started to be collected, but it was rarely collected before the meeting. In some cases, there was a problem of inconsistency between the data from the Planning Department and the data from the production units, regarding whether a sub-stage was finished or not.

In the discussions of the third workshop, one of the problems, raised by the plant scheduling coordinator, was that the meeting should be based on a well-established control mechanism in each production unit. The Last Planner System was still in the early stages of implementation in site assembly, and had just been implemented in 3 out of the 10 teams from the Design and Engineering Department. By contrast, there was already a large amount of information that could be gathered to improve this integrated instance of control.

	Grade				
Practices	**0**	**2,5**	**5**	**7,5**	**10**
Previous collection of production information	Not happened	Difficulty to find the information	Problems of consistency	Incomplete collection	Complete
Discussion of the previous week	Not happened	Just looked for new dates	Looked for the causes. In the meeting, but incomplete	Looked for the causes. In the meeting, complete	Looked for the causes before the meeting, and discussed the metric.
Overview of the following week	Not happened	-	Just for one dept.	-	For both depts.
Participation of shipping and plant departments.	Not happened	-	Just one of the dept.	-	Both departments participating

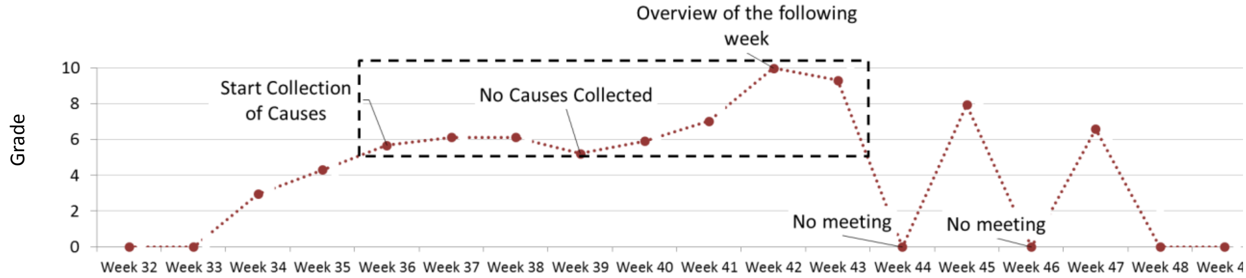


Figure 6.18: Assessment of the adjustment meeting

The assessment reveals that during the months of September and October (week 36 to week 43), the defined procedures for conducting the meeting were followed. In most weeks the causes for non-completion of the sub-stages were collected, as shown in Figure 6.19, contrasting the percentage of sub-stages produced with the causes for non-completion. During that period, the main cause for not sending a sub-stage was the problem of freight optimization, which means that the available material of the sub-stage was not enough to make a load, so it was waiting for more components from the same site to become available.

The second most frequent problem regards the lack of site conditions. As the site was not ready to receive, the load was waiting until it becomes ready. This problem raises a question on why a sub-stage not needed for a specific site was in the monthly or weekly plan. This was an important insight of the research process: the role of the project sequencing. If the decision to expedite a project does not rely in the construction site status, this most often tends to increase work-in-progress, i.e., the components will wait either on the yard or in the site before assembling the final building.

Some of the causes were not precise, such as logistics delay, or fabrication delay, which were adopted simply to find a department to blame. The development of the definition of the causes was one of the subjects of the third workshop. It was a challenge to change the idea of blaming a department instead of finding a source of the problem to be able to provide a solution.

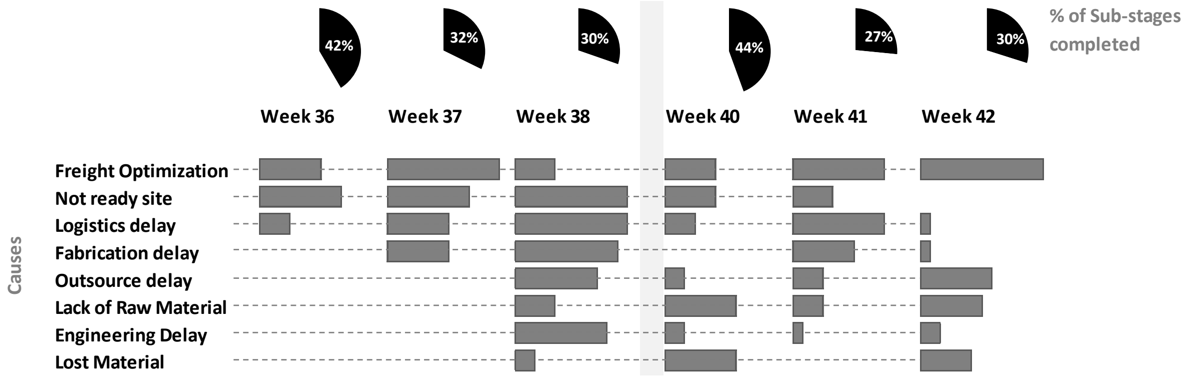


Figure 6.19: Causes for not adhering to the target

The assessment of the adjustment meeting was made to show the participants that the meeting was not achieving its goals. The idea of developing a collaborative decision-making environment and confirm production plans was not possible. There was a strong management-as-planning underlying assumption in the company procedures, but there was also a lack of precise information about the production process. This was the trigger to start the next step when the research turned its focus on the prioritization meeting and to the construction site needs.

The discussion regarding a need to change the company mindset sometimes seems to be fruitful. One example of that happened during a planning meeting from the manufacturing plant, the plant scheduling coordinator was always against idleness in the plant, and was not used to analyse site situation before producing items. However, after the third workshop, during that meeting, this coordinator was discussing if the construction site was able to receive a sub-stage. When the head of shipping department suggested him to produce the components anyway, he answered: *“Why shall I produce something that is not going to the construction site?”* This attitude was a change in his approach.

The adjustment meeting was followed up until the end of the year, when the meeting was suppressed because of internal problems in the end of the year. By contrast, after three months of implementation there was a clear improvement in the short-term integrated planning and control instance, as shown in Figure 6.18. It started to have a systematic collection of production information, and a previous data collection on the causes, and logistics and plant scheduling team were becoming aware of the need of confirmations and of understanding site conditions. In March 2013, the meetings started to be carried out again, making use of some tools discussed in the third step of the implementation process.

6.2.2 Second Step of the Implementation

The action taken in this phase concerned, first, the attempt to develop the idea of confirming the project needs and, second, the change of tools and criteria to assess the projects. The need of making confirmations was a matter of discussion in all workshops. The development of the tools were settled in two meetings with the Project Flow assistant, a representative from the Continuous Improvement Department, the Project Flow coordinator (in the second meeting) and the researcher.

During this phase of the implementation that the LPS implementation program in site assembly started. This program aimed to increase the reliability of the site assembly processes, and provided systematic feedback to upstream processes. After site managers started to use the Last Planner System, the communication between the sites and the Planning Department improved. In one project, the site manager started to request changes in the master schedule because he had improved the productivity rate, and was willing to receive the components earlier. The understanding of the actual capacity is an important consequence of the LPS use. The LPS also improved the communication between site and project managers, these latter could get support for their opinions from the reports of site managers.

There was an initial attempt to start carrying out the prioritization meeting twice a month, but it was unfeasible, because of the geographic distance each project manager would need to travel. Besides, the Planning Department did not support the idea of collecting the information electronically, due to concerns with the lack of reliability. Aggregate information from all construction sites should be brought in order to provide an overview of changes in the demand from construction sites. This effort involved the Planning Department and project managers.

As mentioned before, the general comments project managers used to give in the old version of the meeting were not systematically considered when planning the plant. Another problem was that the number of projects that could be expedited was high and, in most of the cases, not supported by reliable from the sites. This means that there was a large chance that products expedited would have to wait, even allowed to be produced earlier. For that reason, the Planning Department decided to collect the information shown in Figure 6.20 in order to make a more accurate and systematic assessment.

The project managers started to give information about the number of crews, the availability of space on the site, the situation of the construction schedule, as well as the situation of design approval. The latter refers not only to the projects that had not started yet, but also to large projects that had different buildings, in which design was approved in stages.

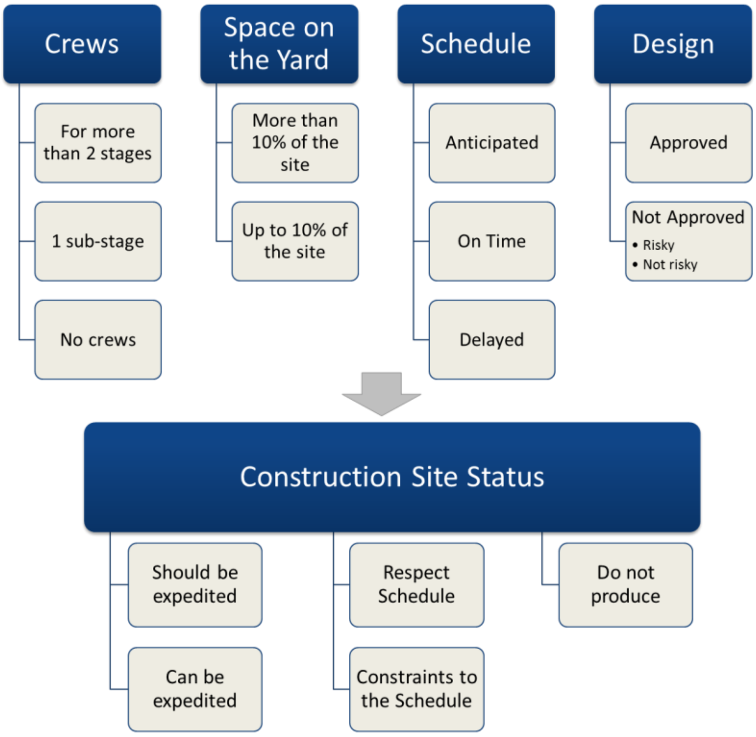


Figure 6.20: Systematization of the information from construction sites

Using those answers, the project managers would define the final status of the construction site. With the aim of providing more useful information, compared to a yes-no answer, the description of the status of construction sites was improved, as shown in Figure 6.21. Regarding the projects that could be expedited, it included a should-can differentiation. Project managers needed to differentiate the ones in which site assembly could be also expedited (should) from the ones that only have space available to store components ahead of the schedule (can). This differentiation was necessary because only the former one really represents a benefit for the company, since the final building could be delivered in advance.

The projects that could not be expedited were divided into three categories. First, the ones that should respect schedule, i.e., no critical constraints for the site assembly, but with limited resources in terms of space and workforce. This category corresponded to the projects previously labelled as “not able to be expedited”. Second, projects that had schedule constraints and require special attention, since the assembly process is being affected by some issue on site, such as delays in previous tasks. These projects are the ones that should have special confirmation routines, and their status should be carefully analysed. Finally, the third category refers to the projects that should not be produced by any unit because of contractual or client issues.

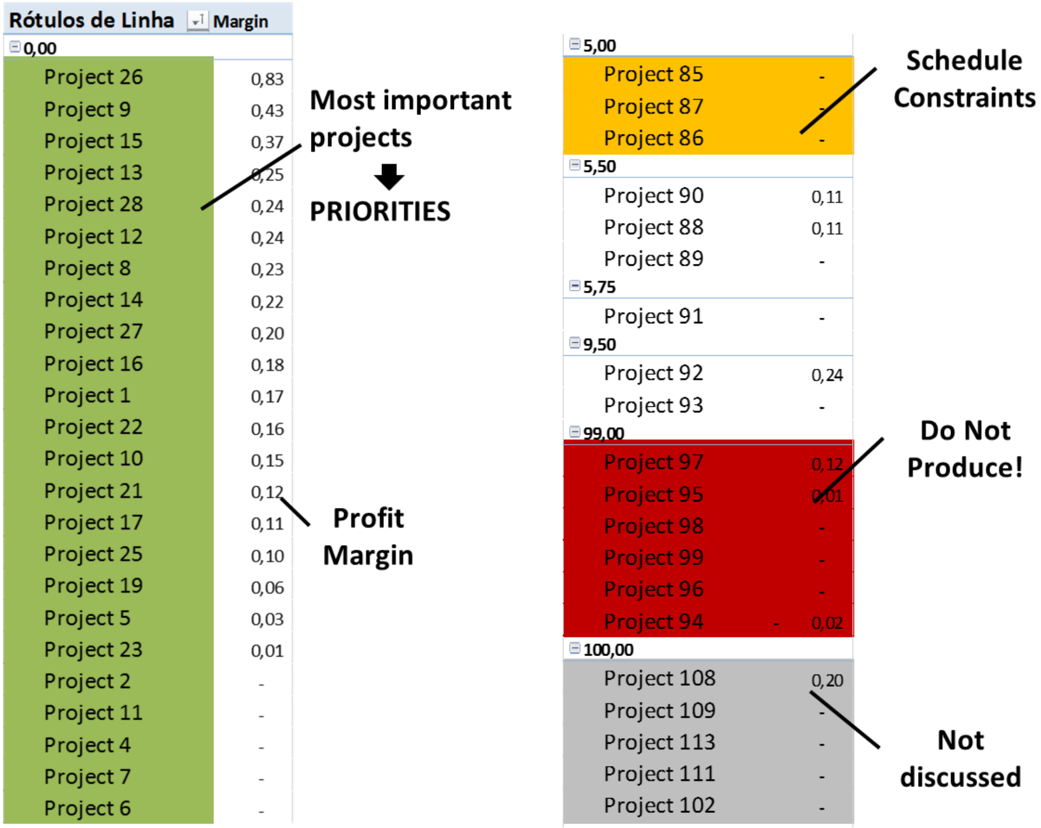
Status	**Meaning**
Should be anticipated	Construction site is full of resources and is able to receive and to assemble the components before the predetermined dates.
Can be anticipated	There were available resources, such as teams and yard to store material, but the due dates of the site assembly are not going to be anticipated.
Respect schedule	The site assembly is going to respect the due dates and has no room to store material produced in advance.
Schedule Constraints	There are some specific problems in the site for the production of some of the stages. In this case, there is a need to verify the situation before shipping.
Do not produce	There are some contract issues with the client and the materials should not be produced

Figure 6.21: Defining construction site status

The Planning Department was willing to use an additional criterion to decide between the projects most suitable to be expedited. In a discussion with the Site Assembly Department managers, the decision was made to consider the profit margin in this decision. In the first meeting in which these criteria were applied, the most suitable projects decreased from 40 to 24 by using the Should-Can differentiation. The profit margin was then used to prioritize those 24 projects, as shown in Figure 6.22.

This categorization changed the source for defining the monthly targets. There was still a need to make the data from this meeting to give a feedback to the short-term adjustment meeting. This was one of the aims for the implementation of visual tools, in the third step of implementation. The adjustment meeting would use only the information directly from the monthly target. Therefore, it was important to make sure that the monthly targets were taking into account the information from the prioritization.

The **fourth workshop** was concerned with how to develop a medium-term integrated planning and control instance. In this level, the monthly targets are defined and could be integrated through the use of updated information from each other. One important decision taken in this workshop was that there was no need for another meeting, as it was the case of the adjustment one in the short-term level. The managers acknowledged the role of the prioritization meeting for the development of this medium-term integrated level. However, that meeting was focused on the situation of the sites, and this planning level should take into account all the production phases. The integration should be achieved through the availability and transparency in-between plans.



Rótulos de Linha	Margin
⊟ 0,00	
Project 26	0,83
Project 9	0,43
Project 15	0,37
Project 13	0,25
Project 28	0,24
Project 12	0,24
Project 8	0,23
Project 14	0,22
Project 27	0,20
Project 16	0,18
Project 1	0,17
Project 22	0,16
Project 10	0,15
Project 21	0,12
Project 17	0,11
Project 25	0,10
Project 19	0,06
Project 5	0,03
Project 23	0,01
Project 2	-
Project 11	-
Project 4	-
Project 7	-
Project 6	-
⊟ 5,00	
Project 85	-
Project 87	-
Project 86	-
⊟ 5,50	
Project 90	0,11
Project 88	0,11
Project 89	-
⊟ 5,75	
Project 91	-
⊟ 9,50	
Project 92	0,24
Project 93	-
⊟ 99,00	
Project 97	0,12
Project 95	0,01
Project 98	-
Project 99	-
Project 96	-
Project 94	- 0,02
⊟ 100,00	
Project 108	0,20
Project 109	-
Project 113	-
Project 111	-
Project 102	-

Most important projects

PRIORITIES

Profit Margin

Schedule Constraints

Do Not Produce!

Not discussed

Figure 6.22: Overview of the result of projects assessment in the prioritization meeting

The implementation of the new criteria for the prioritization meeting was quite successful, since it has been used for a year with some adaptations: the “schedule constraints” category was suppressed at the beginning of the implementation and soon the “can be expedited” category was too. The former was due to the need of collecting extra information for those projects, regarding which were those constraints. The latter was defined as a matter of differentiating the projects able to be expedited, but it was actually a countermeasure since it was not related to the real capacity of the site assembly process to be expedited as well. Therefore, after the first months, the Planning Department found this category useless. In order to share the most important information, the Planning Department developed some posters to inform about the prioritization results, as shown in Figure 6.23.

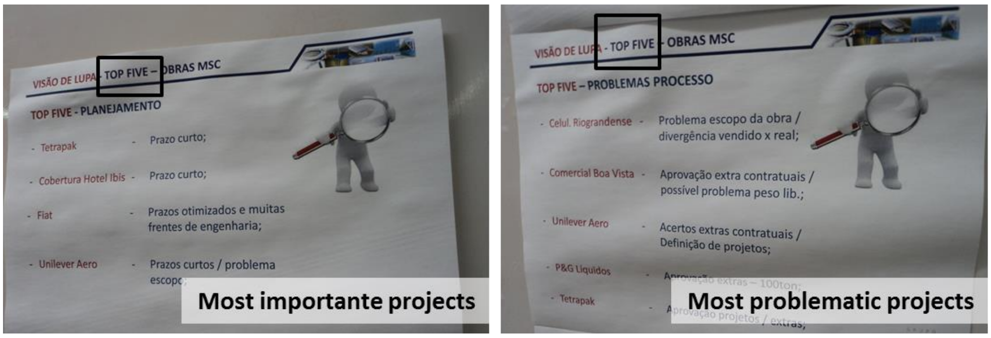


Figure 6.23: Posters to inform about the prioritization results

The fourth workshop represented an important point in the learning cycles of this investigation. The presence of managers and coordinators from the most important departments: planning, design, plant, logistics, and site assembly, together with the director of this business unit, turned it possible to make important decisions over how the information previously collected should be used and what should be analysed in the next phase of the research.

6.2.3 Third Step of the Implementation

This phase started with the decision by a company director that each production unit should devise a visual tool to support production planning and control. The visual device regarding the integration of the production from the compilation of the production units was developed by the researcher with the collaboration of representatives from the Planning Department, and from the Continuous Improvement Department.

The first version of a board for integrating information from all construction projects was developed during January 2013. In February, that version was presented in a meeting, involving the company director; the managers from the Planning, Site Assembly, Design and Engineering, representatives from the Continuous Improvement Department; the project flow coordinator, and the plant scheduling coordinator. This group will be called as company team, since they provided several contributions to the development of the board in further meetings.

The proposal was to use the adjustment planning and control meeting as a means to update the board and discuss about the changes and problems in the production units. In fact, the adjustment meeting had been misled in the final months of 2012 (c.f. section 6.2.1), and only came back to the routine in March 2013. The final version of the board contained four important pieces of information about each production phase, as shown in Figure 6.24:

- **urgent sub-stages:** including batches that are late or that should be produced earlier than scheduled;
- **monthly target:** established by the Planning Department for each month;
- **can be produced**: consisting of a backlog of products based on the position given by project managers about the construction site status; and
- **cannot produce:** regardless the master schedule.

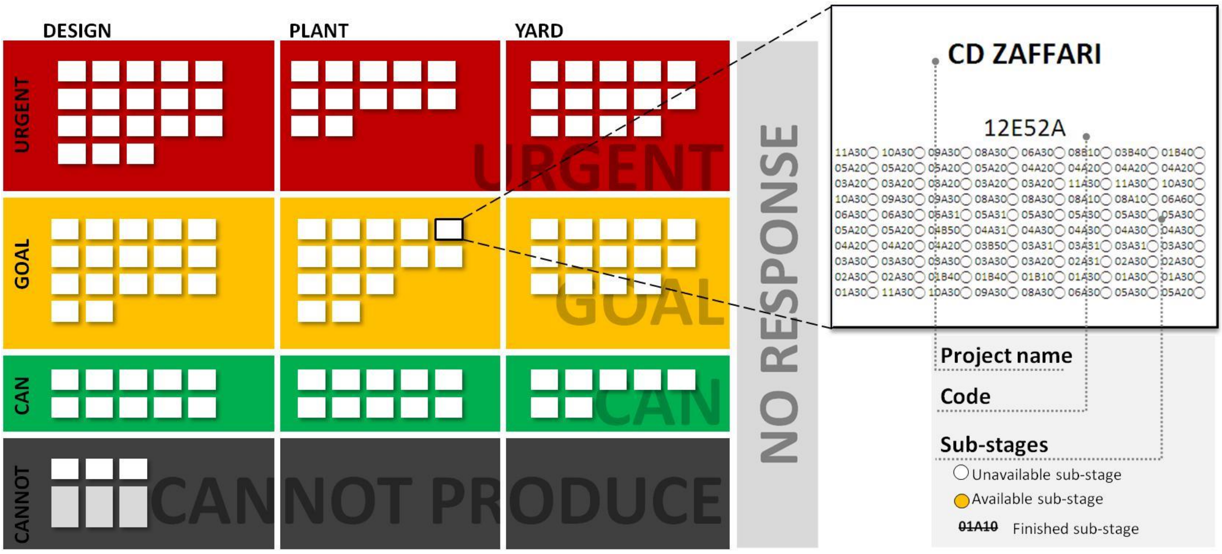


Figure 6.24: Schematic representation of the integrated planning board

Each (printed) card on the board refers to a set of sub-stages of a project. Weekly the representatives from each unit should mark if the sub-stage was available or already done. There was a group of projects classified as “No response” which refers to the components already produced by the plant but had not been properly analysed, as discussed later.

The criteria just described for each area of the board changed along the development of this visual device, mainly from January to March 2013. Figure 6.25 illustrates the different versions of the board. In the first version, the “no response” category would appear for every production unit. The urgent lane revealed only the projects with a special type of sub-stage called “R”, which stands for rework. The researcher understood that every production unit should stop the common flow of work to produce this type of sub-stage, since it was only created when part of the production process has stopped. There were also an extra classification called “In delay” which refers to what should have been produced in the previous month but were not. Another peculiarity of the first version was that the unit was project, so each white square contained only the name of the project to be produced in each lane and unit.

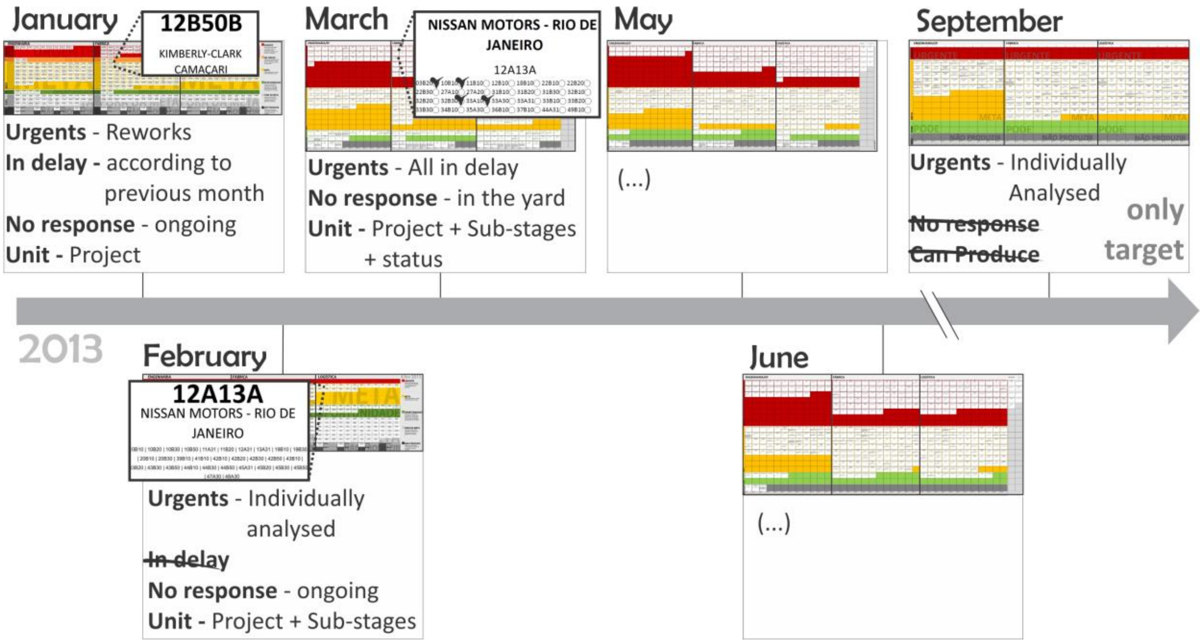


Figure 6.25: Evolution of the board in monthly versions

The company team decided to have the description of the sub-stages in the cards, since the same project could appear in different lanes referring to different set of sub-stages. Then, each card started to have the name of the project and the sub-stages that should be produced. Because of the large number of sub-stages per project, it was not possible to have one card for each sub-stage. The criteria for the urgent lane were also changed. According to the company team, the “R” sub-stages were too dynamic to appear in a board updated weekly. In fact, they argued that this type of product should not appear in the board, since everybody knows its importance.

In March, the decision was made to put all the sub-stages in delay in the urgent lane, including batches from both master schedule and projects expedited in previous planning cycles. The result of this criterion is illustrated in the example of Figure 6.26: a larger number of urgent projects than projects in the target. The amount of projects in the board was becoming unbearable.

At this moment, the urgent lane was revealing what the Planning Department understood as delayed, but they were actually not, considering as delayed components that the construction sites were willing to receive for a long time. The coordinators of the logistics and from the plant scheduling argued that most of those projects were not a priority either because their schedules have changed or because the site was not able to receive anymore. The discussion over those projects also revealed some problems in updating the ERP system, which was still showing some finished sub-stages as incomplete. This kind of problem happened because of failures in the existing reporting system. It was at this moment that the researcher realized that the information about the monthly targets was not reliable, and that there were flaws in the control tools used by the Planning Department.

The targets were monthly defined including as much products as each production unit was able to produce. Regarding the target for the plant, there was even an analysis on the use of the production lines by the selected products to avoid idleness. By contrast, there was a large number of sub-stages, which the Planning Department were assuming the PUs should be producing, namely the ones in the new version of the urgent lane. Those projects were not considered in the evaluation of available capacity. It means that there was a strong effort on defining the targets, carried out monthly by the Planning Department that was useless for the production units planning and control system.

As long as the participants of the adjustment meeting started to have a closer interaction with the board, they started to question why a sub-stage within the schedule would appear in the urgent lane and not in the target lane. It became clear that the aim of the Planning Department when defining the monthly target was not to assign the real amount of work required to the available capacity. It was mostly concerned with doing pressure to achieve the amount of tonnages that were defined as targets in the strategic planning of the company.

It is worth remarking that the main information provided in the ERP system of the company, and that could be easily checked by anyone from any department, was the master schedule. The information from the monthly target was sent to coordinators and managers of the production units, and was available in the company internal network. It was already hard to manage both documents (targets and master schedule), comparing also with previous targets was unfeasible for the production units. The amount of projects that stayed on the urgent lanes for months revealed the flaws of this planning development process.

The first versions would also reveal the projects under production with “no response” either from the project managers, or from the Planning Department. Projects produced out of the monthly targets, as discussed in Figure 6.16. The company team decided to see projects in this category only for the components already in the yard. This information would be useful for the Logistics Department to decide what to do with those items.

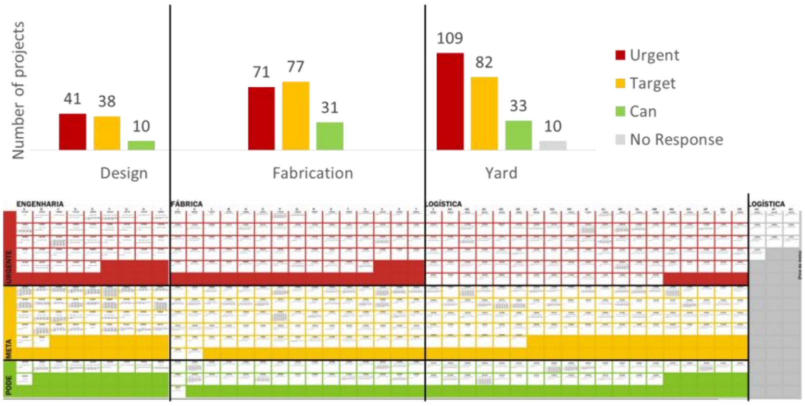


Figure 6.26: Amount of projects in each lane, version developed in the end of February 2013

Regarding the construction status defined in the prioritization meeting, the projects signed as "should be produced" and the ones in the master schedule with no constraint for production would form the monthly target, being placed in the target lane. The "can produce" lane was filled with the projects signed in the prioritization meeting as "can be produced", which were not scheduled for that month. Therefore, each production unit could easily understand what to produce if there is any problem in terms of following the monthly target, working as a backlog for production. The information of the projects that cannot be produced was also released at the prioritization meeting. However, the participants realized that during the project tender stage, this information should be provided by the design coordinator, since the hand-off for the project manager has not happen yet. Figure 6.27 illustrates the source of information for updating the board.

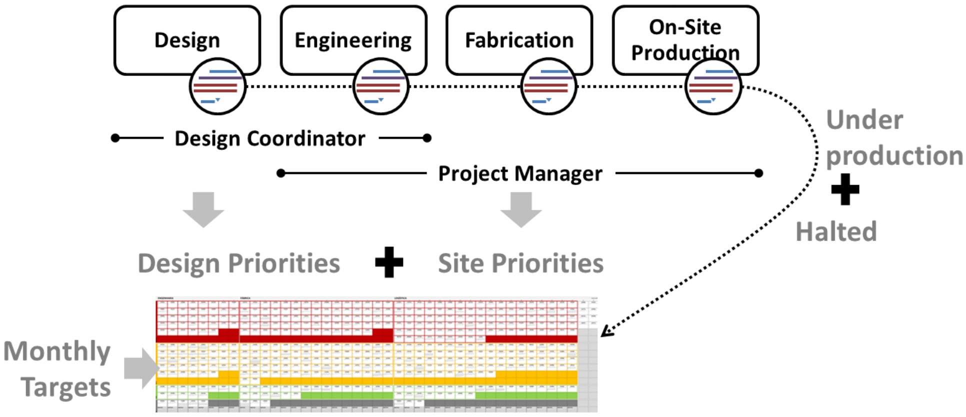
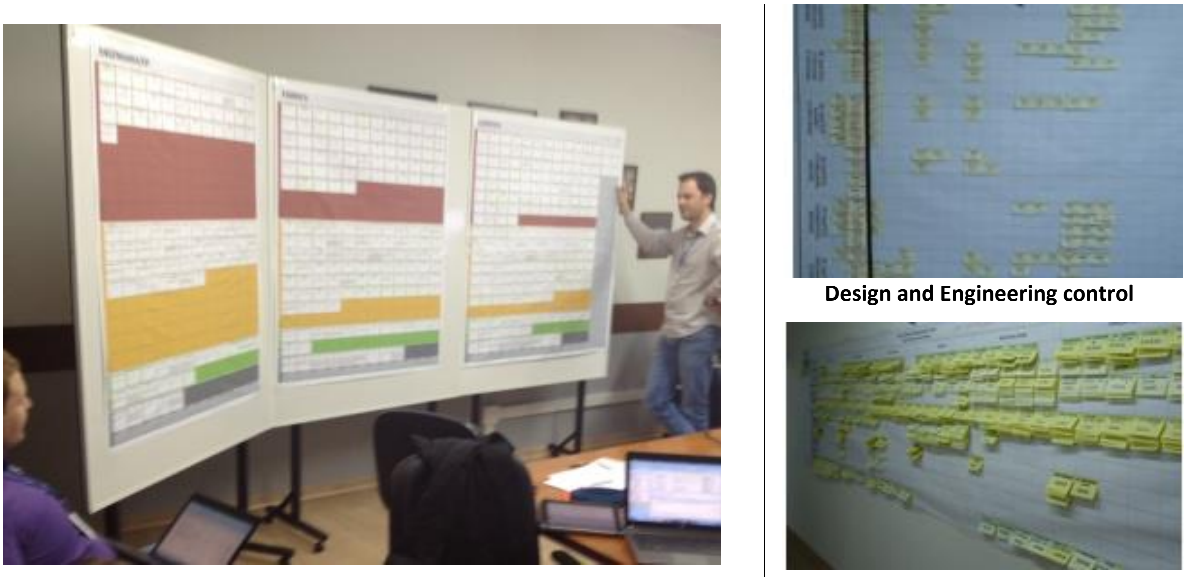


Figure 6.27: Sources for the development of the board

As the board displayed a large amount of information, the meetings should be focused in a set of them. The decision on where to focus was made by the Site Assembly Department, represented by the managers, who selected the most critical construction sites, making all the production units to be aware of the main problems, or opportunities. This became an important source for look-ahead planning at each department, making available information from construction sites the upstream processes.

Regarding the adaptations of the adjustment meeting in relation to the first step, there were some benefits in avoiding some operational discussion; it became a tactical level of planning. The board was updated once a month according to monthly targets and prioritization meeting, and weekly with information from the short-term planning from each production unit. Figure 6.28 shows a photo of an adjustment meeting using the board, and also some examples of the boards developed in the production units.



Design and Engineering control

Integrated planning board

Plant control

Figure 6.28: Visual management boards and the integrated instance

The board developed by the Plant Department was on testing, and ended up not being implemented because of the amount of sub-stages that used to be carried out concurrently in the production lines. By contrast, the Design and Engineer Department have developed, in partnership with the Planning Department a method to integrate the information from the short-term control in each of the design teams. That department improved an existing meeting to make it possible to discuss with the representative of all projects under production in this department that had a close relationship with the client and was also aware of the need to avoid overloading their teams. The relation between those boards is illustrated in Figure 6.29.

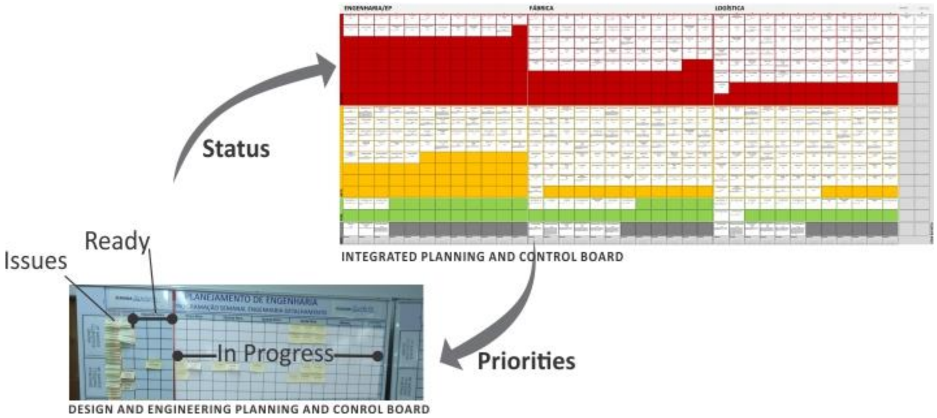


Figure 6.29: Relation between the Integrated Planning and Control board and the Design and Engineering Planning and Control board

During March and April 2013, the researcher attended the weekly meetings for analysing the use of the board, and to give some support in information processing. From April to August 2013, the meetings continue to happen without the participation of the researcher. In August the company realized that the adherence to the target was still low, so a representative from the Continuous Improvement Department asked the researcher to help in the implementation of some changes.

In a meeting involving representatives of the Continuous improvement Department, the Project Flow coordinator, one of his analysts, and the researcher, the decision was made to change the criteria for the projects placed in the “urgent” and the “can produce” lanes. The idea was that the board would start the month only with the information from the target. In the course of the month, the sub-stages that were in delay should go to the “urgent” lane, so that this lane would only report the most important projects for the production units. However, it would only make sense with a revision of the way monthly targets were defined. In this regard, the Planning Department agreed with considering all the available projects for production (even the ones that had already been assigned in a previous month) in the target definition.

Regarding the “can produce” lane, the main change was to produce up-to-date information about the designs that had been developed. Sometimes design coordinators face some problems in the design process, due to delays in the decisions that should be made by the client, and decide to change the order of design batches so that the monthly target in tons is met. Therefore, it would be useful for the plant, if the project manager could inform the status of those batches, in order to know if it should or should not be produced. However, this idea was not implemented, because of the work required before the meeting was considered to be too time consuming.

The adherence of the shipment process to the monthly target can be seen in Figure 6.30, in terms of number of complete sub-stages shipped in relation to the planned ones, in a period of one year. The dashed line represents the period when the visual tools were developed, and the continuous line identifies the period when those tools were used. Although the average level is still low (57,08% in this period), it is possible to observe an improvement since the beginning of the implementation.

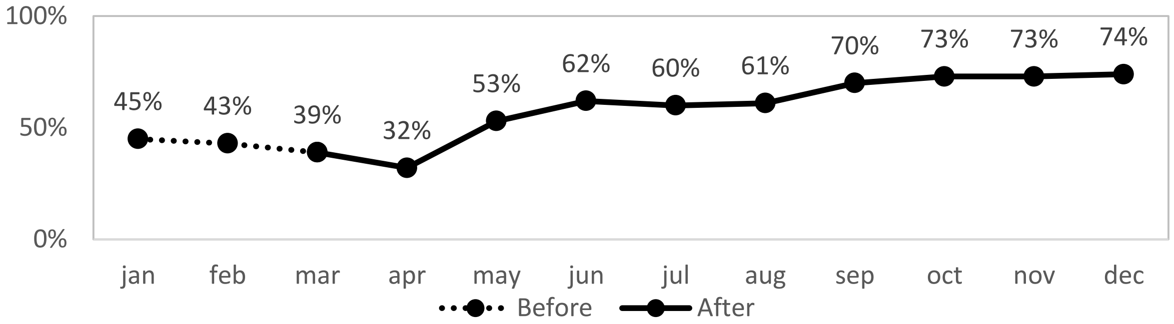


Figure 6.30: Adherence to the monthly target

The periodicity of the monthly target definition was also discussed with the Planning Department. The system would probably benefit if the monthly target was developed as a rolling plan, in which the horizon from the previous overlaps with the current. The Project Flow coordinator and his analysts were not willing to increase the frequency of targets definition because of the amount of work it would generate. Although this idea could not be put in practice, this was one of the topics of the **fifth workshop** in which the coordinators from the Design and Engineering production unit, as well as the plant scheduling coordinator claimed for the importance of that practice.

Another evidence of the impact of the study was in an effort taken in 2013 to decrease the amount of WIP in the plant yard. Figure 6.31 shows the way control was carried out, discriminating the situation of the projects, namely ready to be shipped, with some constraints, and the ones halted by client. Each of those groups is divided into complete or incomplete sub-stages.

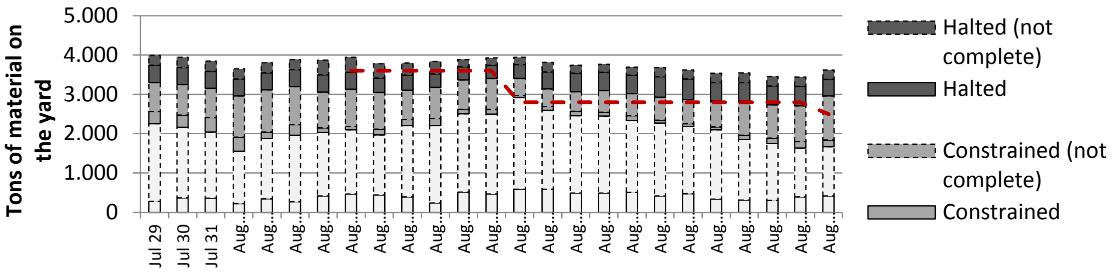


Figure 6.31: Amount of components in the yard

6.2.4 Contributions to the Model Development

The focus of the first version of the model was to devise and implement a level of integrated multi-project planning that could establish a formal and systematic connection between different production units. This version was first discussed with Company A in the **fourth workshop**. During the fifth workshop, more than the model, the concepts underlying it were also discussed with the participants, such as the core requirements discussed in section 4.2, the importance of limiting the amount of WIP, and how those concepts could be related to the planning and control system. Figure 6.32 shows the first version of the model, which makes explicit the different hierarchical planning levels, from the Last Planner short-term planning to the top planning level, which is concerned with the company as a whole. Each level encompasses its own control mechanisms and performance measurements, as described below.

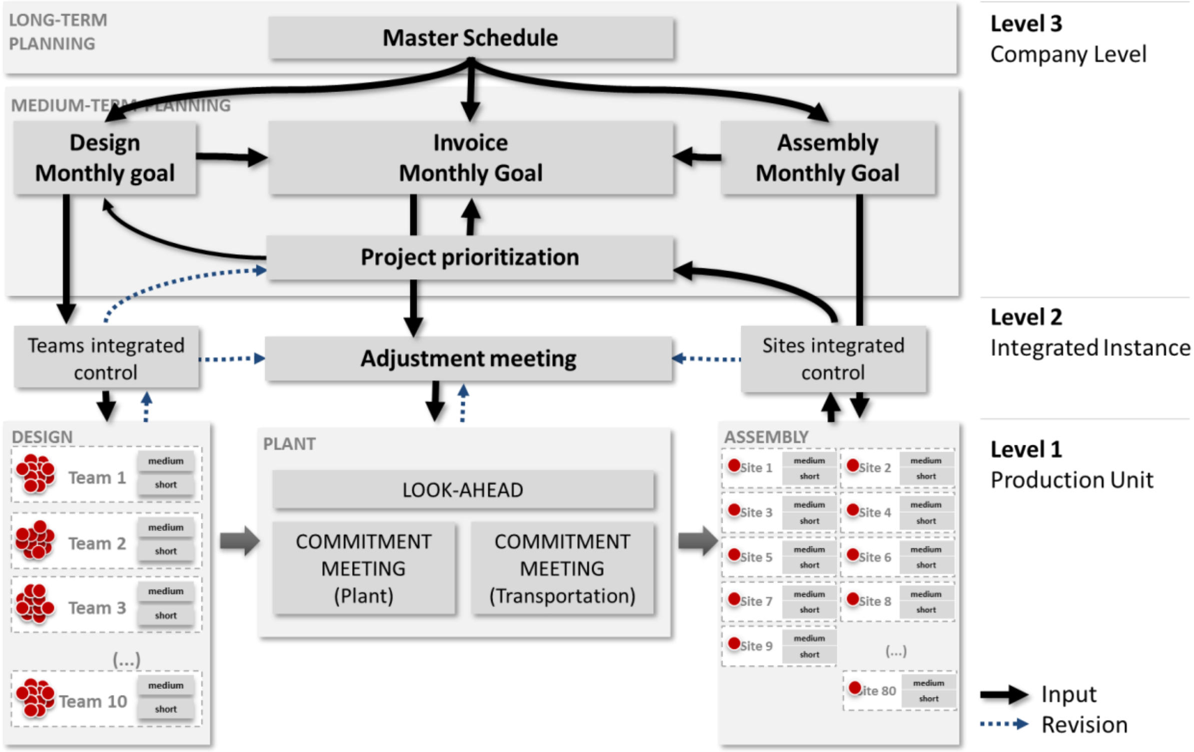


Figure 6.32: First version of the model

6.2.4.1 Level one: Production Unit Level

The adoption of the LPS was an important mean to decentralize decision-making from the Planning Department and to implement a more collaborative type of planning and control system both in the design process and in site assembly. The LPS is also an effective method for the production unit control, the directives from the operational level plans should come from a tactical level, namely the integrated instance level, where the project flow is controlled, as discussed in the second level.

The system was adopted in each production unit based on delivery batches, within the control units shown in Figure 6.2. The company was engaged in implementation programs of LPS both in the design (WESZ; FORMOSO; TZORTZOPOULOS, 2013), and site assembly. In both cases the degree of implementation of LPS was relatively high at the end 2013: 77,8% of the design teams, and 68% of the construction sites. Regarding the manufacturing plant, a planning and control model that adopted some LPS tools had been used for two years.

Therefore, all three production had a metric similar to the Percent Plan Complete (PPC) for each team, flow shop, or site, and also the causes for the non-completion of work packages. The teams from the Design and Engineering Department, as well as the site managers from the construction sites have also been engaged in making a systematic removal of constraints, by having look-ahead planning, although the implementation at this level of planning has not been as successful as at the operational level. At the Design and Engineering Department the planning horizon has been one month, updated monthly. The reason for this horizon is related to a strategic practice from the planning department to define the monthly targets, as discussed before.

In the site assembly process, the planning horizon depends on the schedule of the project. An assembly process up to 3 months long should have just one constraint analysis, which is part of long-term planning. Between 3 and 6 months, the horizon of medium-term planning should be 2 months, updated monthly. Lastly, projects longer than 6 months should have a horizon of 3 months, also updated monthly.

Although almost every production unit have implemented LPS, some of the practices are not consolidated, such as the systematic removal of constraints. After 3 months of the implementation process, the design and engineering teams reached 52,4% of implementation of this practice, while in the assembly process only 13% of the construction sites have been able to implement that.

For these reasons, the main metrics of the medium-term, such as the constraint removal index had not been effectively implemented. Nevertheless, the fact that some of the design teams and site managers have already been engaged in systematically removing constraints has contributed to improve the effectiveness of the whole planning and control system.

6.2.4.2 Level two: Integrated instance

The first step to provide an integrated planning and control system was the development of control systems concerned with the engineering design and assembly production units as a whole; similar to what had already been implemented in the manufacturing plant, as shown in Figure 6.33.

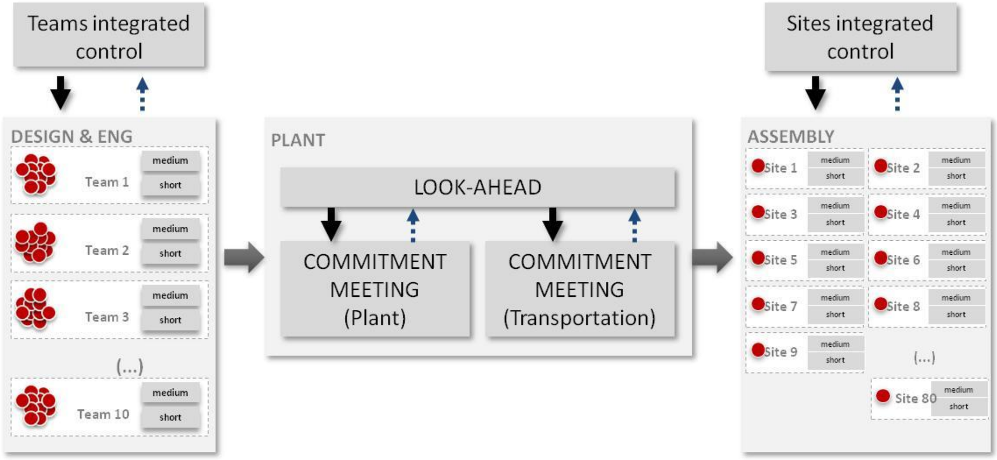


Figure 6.33: Integrating different units of control

At the Design and Engineering Department, the control became consolidated through a management board, which compiles information from different teams. This board was updated in a weekly meeting with all the design coordinators. The board summarizes the production of each team for the following two weeks, using one post-it for each sub-stage to be delivered. If a coordinator signals that his/hers team is overloaded, it is possible to share the production with an idle team. The most important benefit of using this approach was sharing existing problems among design teams, and balances the load between them.

With the dashboards, it was possible to compare this level of planning targets and actual production. This adherence to the target metric, in terms of sub-stages was the basis of this level. It was important to avoid the focus of control tools only based in the master schedule, since it hinders the possibility to make confirmations along the production process.

6.2.4.3 Level Three: Company level

At the level of the company, there is a need to integrate the information from different production units. For geographical reasons, the most critical source of information are the construction sites. In order to consider this information systematically, a prioritization meeting was carried out with all project managers, who are able to provide information about the construction site status, as explained in the section 6.2.2.

The importance of this level of control is to understand the project flow as a whole providing important guidelines for the development of plans through the production units. This was an important change in the planning approach adopted by the company, since at this level it is critical to provide reliable information regarding the projects priorities, rather than simply follow a long-term plan.

6.2.5 Fourth Step of the Implementation

This study was triggered by the demands from an important client of the company. This client had already contracted Company A for some previous projects, in which there were problems regarding material handling, such as large inventories of components on site, material losses, and even stolen materials. For those reasons, Company A was willing to improve logistics processes in order to improve the reliability of delivery, especially in terms of sequencing for the site assembly. This project is called project X.

At the beginning of this implementation phase, a detailed analysis was made of the logistics operations at the plant yard, complementing an analysis of the Logistics Department that was made at the beginning of the empirical study in Company A. In the diagnosis of this phase, two chrono-analyses on two different kinds of loads were carried out, to improve the understanding about the loading process. Through this phase of the implementation, it was possible to develop some loading plans and discuss how some decisions were taken in the Logistics Department.

In March 2014, the company yard was handling almost 4 thousand tons of material, from which 1.602 tonnages were ready sub-stages waiting for being shipped. The main criteria for organizing the components was the type of product, making the materials of one project spread along the yard. Here it is used the term main criteria, because there were also batches of components organized by project, which were organized in a steel structure called skid, a rectangular platform that fits inside the truck. Figure 6.34 shows an overview of the yard, indicating areas organized by products and by project.

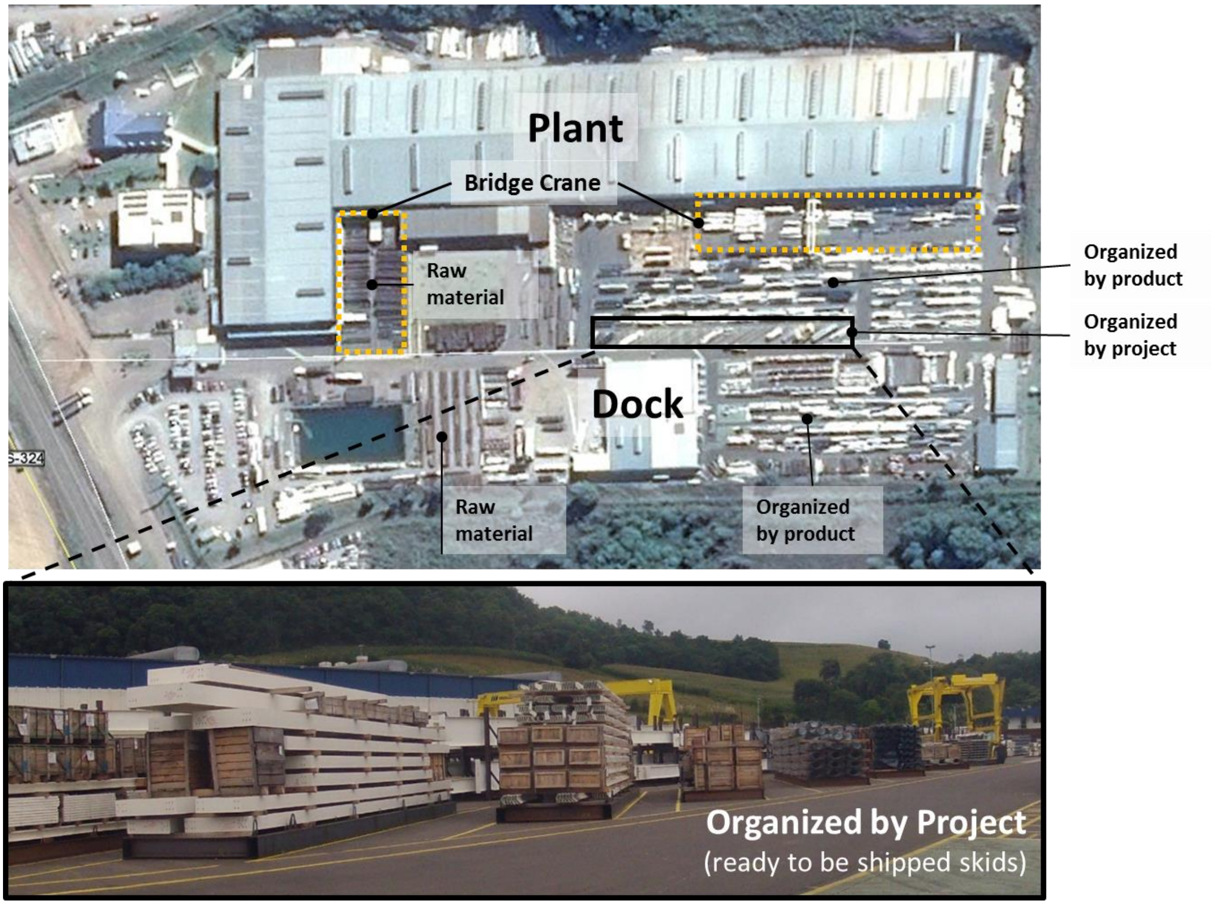


Figure 6.34: Organization of the yard

When the plant finishes the production of a batch of components, these are organized in trestles, which are then transported to the yard, according to product type. Each trestle should contain the same type of product of the same project. The decision for organizing the components by projects was a strategy for optimizing the storage space. The projects that were produced for exporting or the ones that for some reason had to wait on the yard would be then organized in skids. The loading of the skid can be made either in the docks, like the trucks or in the zone of the yard where there is a bridge crane.

Figure 6.35 reveals how the flow of material in the yard is. Starting from the plant, the components are organized in trestles and transported using forklifts to the yard. Then, it can be transferred to a skid, in the bridge cranes areas, or, the trestles can be transported to the docks for the truck loading. In some cases, the skids can also be loaded in the dock. The ready skids are transferred to the truck using a special type of crane specific for transporting this kind of load.

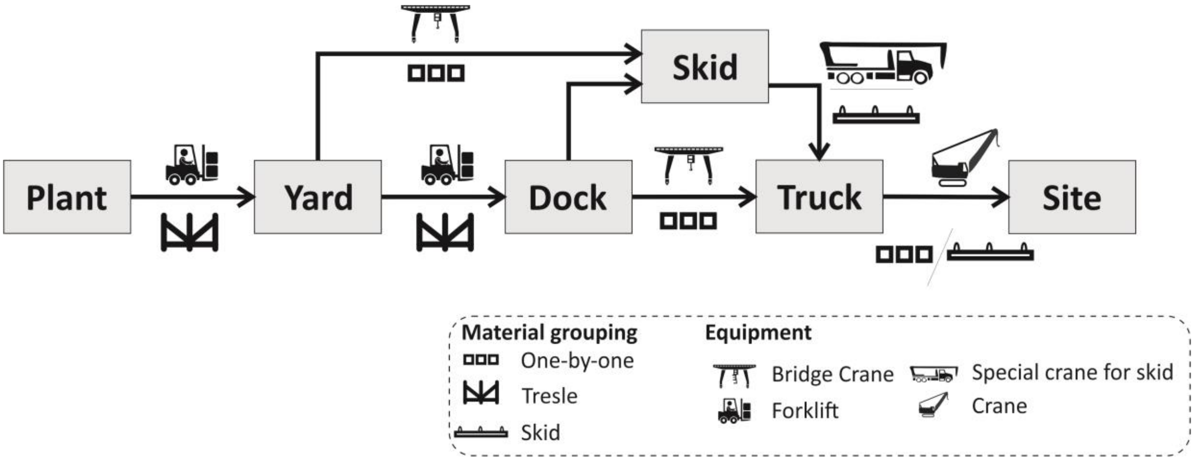


Figure 6.35: Flow of material in the yard

Figure 6.36 shows the dimensions of the trestle and the skid, and the amount of material equipment are capable to carry. It is worth noting that the batching of the sub-stage is not the same of the truckload, as discussed in Figure 6.2, and that different types of products form one sub-stage. For that reason, organizing one load using the trestles requires transportation from different parts of the yard. Due to the large amount of inventory, and the gathering of components form different parts of the yard, the shipping process could take several hours, except when skids were used.

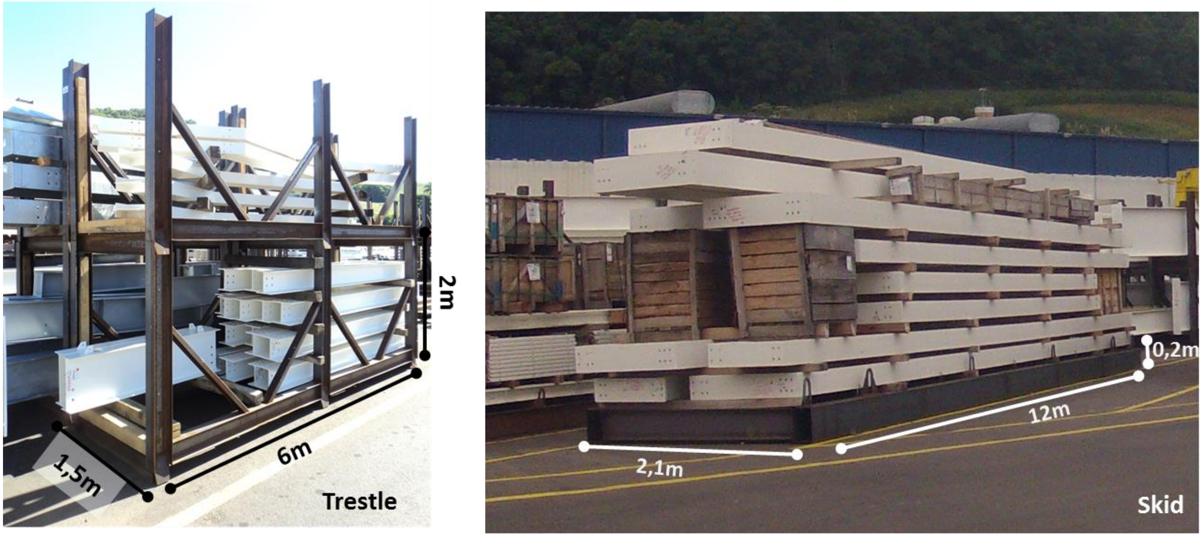


Figure 6.36: Equipment used to organize the yard

Figure 6.37 presents a histogram of shipping time, considering data from all shipping operations from 2012 and 2013. The shipping time was obtained from the register of the truck plate when getting into the plant facility until the moment it leaves. The median of this process during the analysed period was 32 hours and 39 minutes. This means that 50% of the trucks would wait more than one day to be loaded.

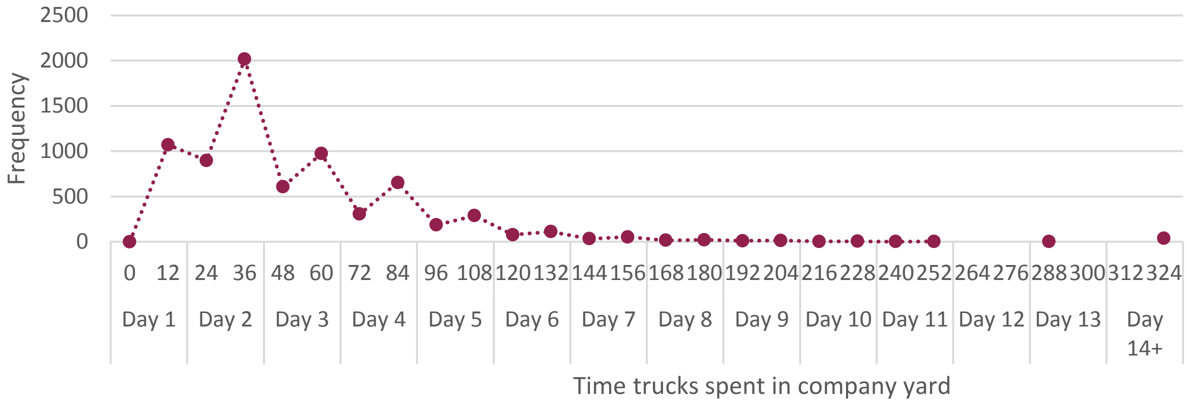


Figure 6.37: Histogram of the time spent for shipping in 2012-2013

Figure 6.38 shows the median in each month. The peak from December 2013 refers to the implementation of a new ERP software in the company. The periods got longer because of unexpected bureaucratic problems in issuing the invoices.

Figure 6.38: Median of the shipping time in each month

Another important problem faced by the Logistics Department, caused by the lack of integration between plant and site assembly, was the need to pay extra daily rates for the truck drivers. When contracting a freight, the daily rates for the normal trip are already included. The extras can occur when there is a bureaucratic issue related to the production of the invoice; a delay in finishing a component by the plant; a problem in the shipping process, such as time spent looking for a given component; or a problem on the site that hinders the unloading process, such as rain, or lack of space.

Figure 6.39 presents the monthly expenses with those problems in 2013, divided into the following categories: invoice, plant, shipping and on-site. The goal for this kind of metric should be zero. In 2013, the company spent R$ 241,389 in daily rates only because of shipping problems - this amount refers to 30% of the total spent in daily rates.

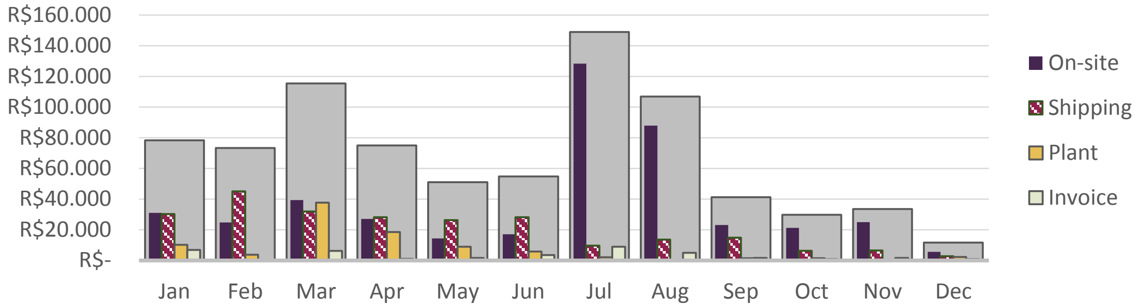


Figure 6.39: Daily rates for the truck drivers in 2013

In order to better understand the shipping process, there was a need to deeply understand how this process was undertaken, looking at the operational and strategic decision-making. For this reason, two chrono-analysis were carried out. First, the times for loading a skid considering that all the components were available. Second, the times for loading a truck in a real situation where the components are not available. During these analyses, it was possible to observe the role of the forklift operator in defining which products from one sub-stage would go in the truck and which would be left to the next load.

When the amount of material of one sub-stage is larger than one truck, the logistics coordinator (responsible for the processes mentioned on section 6.1.4) delivers a list of all the available material for the team in charge of loading. The dock operator selects the heaviest components and asks the forklift operator to bring them. When there is some component that the operator cannot find, the dock operator analyses if it is possible to make a complete shipment without it. Therefore, the final decision on what is going to the site relied on yard issues and not on the site needs. This was especially critical for the delivery system required by project X.

6.2.5.1 Chrono-analysis of ready-to-ship items

The main goal of chrono-analysis was to have a baseline of the shipping process, without the uncertainties regarding the plant production and the time spent looking for components in the yard. Therefore, it was possible to understand the operations carried out at the dock, the problems faced by the operator, and ultimately how the loading process carried out in the dock impacted the efficiency of the different processes in the yard.

The layout of the dock is shown in Figure 6.40. There were four bays with independent crane bridges to load the trucks. The workers had to constantly move from the dock to the loading bay during the shipping process. One year before this analysis, the dock use to have only two crane-bridges, as the installation of four bridge cranes was a recent investment of the logistic department, which is discussed later in this chapter.

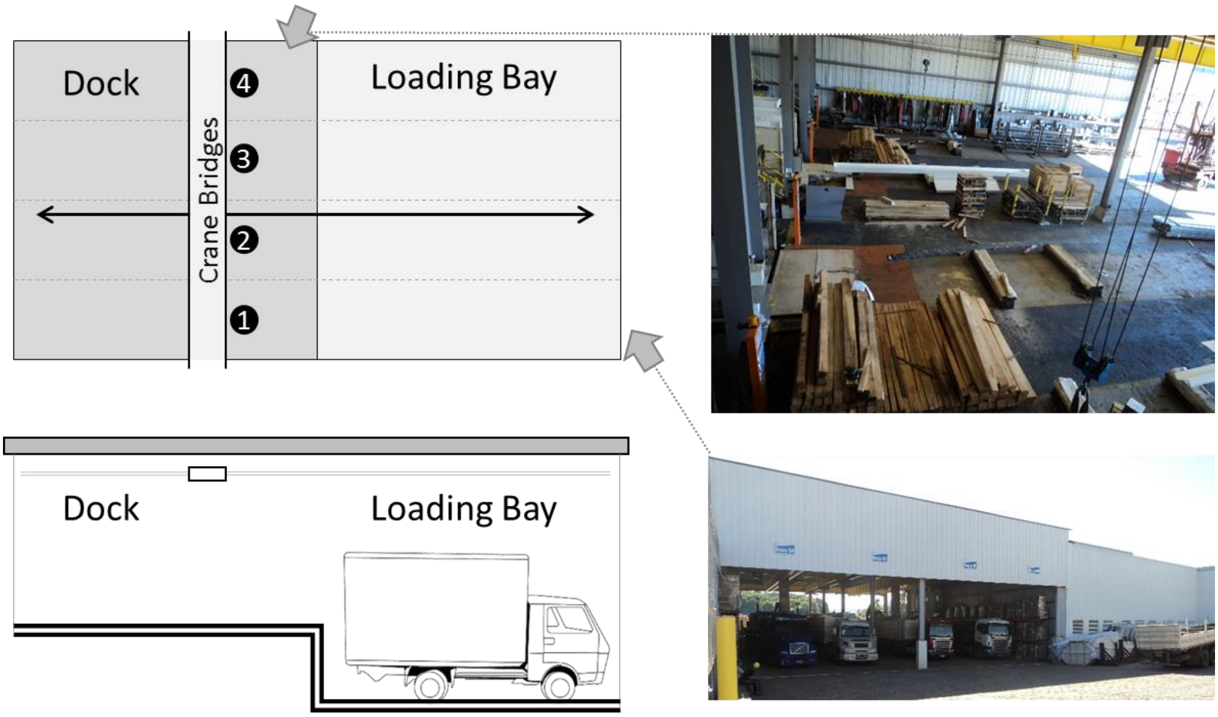


Figure 6.40: Dock layout

For the chrono-analysis, an already packed skid from a project halted by the client was chosen to be transferred to a new skid. The logistics manager decided to use this load only for the sake of this analysis, which means that the load was not going to the site. However, this might represent a bias in the analysis, as the operators involved might not be as careful as usual.

Figure 6.41 presents a summary of the chrono-analysis data. The measurement exercise lasted for 8 hours (from 10h32min to 18h36min). However, 64% of this total time refers to stops such as intervals, meetings, and even medical assistance. During the standard meeting to make the turnover, the team celebrated one year without accidents, increasing the time of the common meeting. Therefore, the productive time analysed was actually 2h 53min. The activities realized by the operators were classified as:

- **Component displacement:** the movement of the hoisted component from one side to the other of the dock. (19% of the total productive time).

- **Adjusting handle place:** the act of hanging the component in the crane bridge using a fabric handle. (27% of the total productive time).
- **Operator displacement:** Time spent by the operator moving from the dock area to the loading bay area, while the process is stopped. (18% of the total productive time).
- **Balancing component:** Time spent to equilibrate the component in the one-point-handle. (11% of the total productive time).
- **Wood work:** Time spent measuring and cutting wood to separate the layers of components. (19% of the total productive time).
- **Analysing the work:** Time spent analysing where components should be placed. (6% of the total productive time).
- **Stops:** Moments with no work, i.e., intervals, rests, meetings. (64% of the total time).

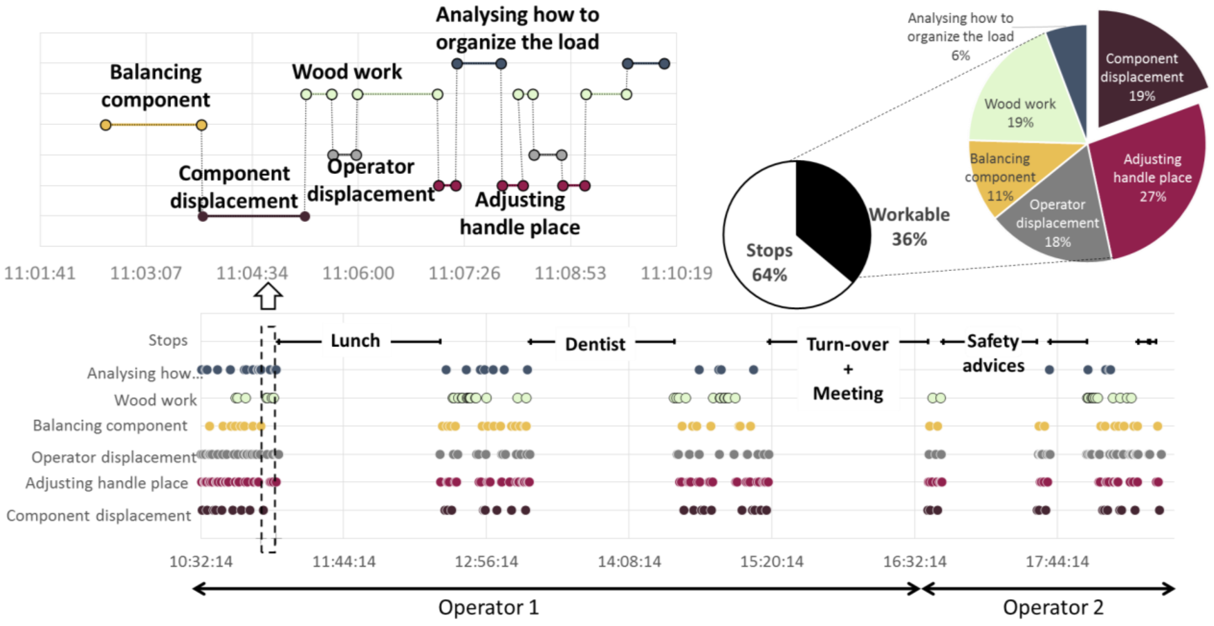


Figure 6.41: Chrono-analysis of the ready-to-ship material

Some differences were observed between operators. Although the first one had to spend some time reorganizing the material to be loaded in the new skid, he could only move six components to the final position, while the second one moved 20 components. The second operator was able to place the handle in a more efficient way than the first one. This activity was the most significant one in the workable time (not considering the stops and meetings). These differences reveal a lack of work standards to perform the loading process.

The time required for bringing materials to the dock was also measured. Six forklifts travels were measured, bringing different types of materials from different parts of the yard, using the same assumption of avoiding the uncertainties of not finding materials. The total time of the six travels was 18 minutes, when the forklifts could bring 10 different components to the dock. The average per component was 1min48s. In loading the skid during the 2h53min of productive time, 26 components were moved, an average of 6min41s per component.

Therefore, without considering logistics problems, this analysis reveals that the process of taking components from the yard and into the dock was much faster than the loading process. This means that as long as the forklift operators know where the components are, the organization according to the product type would not affect the work in the dock. Although this organization generates an increase in transportation time, the bottleneck was the operation of moving and organizing the components inside the truck.

It is worth noting that the total time of the loading was much lower than the median durations observed in the shipping operations from 2012 and 2013, even with the long stoppages. This difference shows how the problem of losing components in the yard, waiting production to finish, and even registering the shipped items affect the total shipping time. Even without looking at those issues, this analysis reveals that the decision on how to organize the components is a solely responsibility of the bridge crane operator.

6.2.5.2 Chrono-analysis of not ready-to-ship items

The chrono-analysis of not ready-to-ship items was a common loading process, since it was actually going to the construction site. The type of load chosen was critical, it was called a closing load, referring to the remaining material of different sub-stages that were left behind. As mentioned in section 6.1.1, the company had the policy of not shipping materials from sub-stages that were not fully produced. However, after been produced, the Logistics Department could choose to ship only part of the sub-stage because of limitations in truck capacity. This practice was hindering the Logistics Department to see the problem of material losses. In the first loads of a given sub-stage the decision of what should go and what should wait ended up relying on the (heavier) components the operator could easily find in the yard. It is also worth remarking that the client pays the higher portion of the project cost when the materials are shipped to the site.

Therefore, while the first loads were usually shipped faster, there was a trend of increasing problems in the loading operations towards the end of the batch, such as difficulty to find the materials, and type of products available. For those reasons, loads took around 8 days to be shipped. Measurements were carried out only in the first day, from 10h49min in the morning until 19h21min in the afternoon. During this period, 13.775,09 tons of materials were loaded, representing 78% of the total load shipped on that truck. After that day, the truck remained in the dock and was fulfilled whenever a lost component was found. Figure 6.42 shows the amount of material loaded in the truck on each day, starting from the day of the analysis until the departure day.

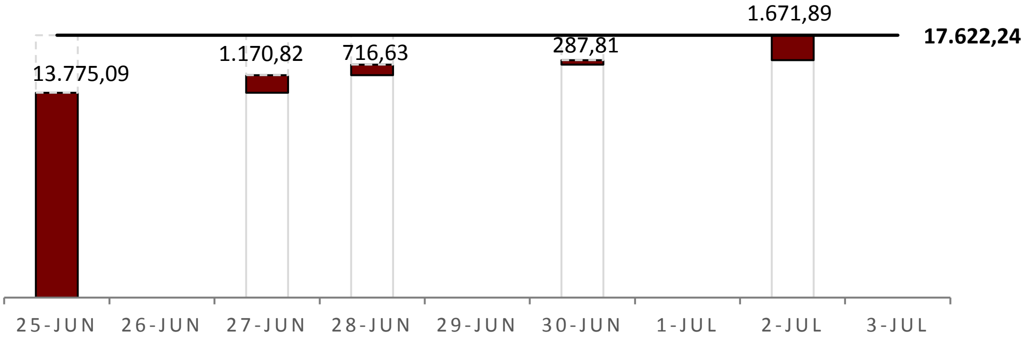


Figure 6.42: Amount of material loaded per day

Figure 6.43 shows the results of the chrono-analysis of the shipping process in a real situation. There was less stops regarding intervals and turnover than the first analysis. However, there was a new type non value-adding time: waiting for materials. It is worth noting that when the operator is waiting, it does not mean that there is no component in the dock to be shipped. The operator receives a sheet with the type and size of the components that should go in the truck, so he can decide not to continue the loading because a large component is missing. During the period of analysis this situation happened, i.e., the dock was never empty. After finishing the 13.775,09 tons, the components that were missing were the smaller ones, namely some boxes of bolts, standard steel components, and smaller structural components.

As this measurement was made on a not ready-to-ship chrono-analysis, there were some different activities, compared to the ones observed in the first analysis, as follows:

- **Registering:** the time required for registering the component as a shipped item in the company ERP system. The operators used a bar code reader and a printed sheet to make this task. Both of them were carried out, so that they were able to check the information in the system when facing some problems in matching the real load with the information registered in the system.

- **Reorganizing components:** refers to the time spent in mannualy organize the components in the truck, after hoisting the material using the bridge crane.
- **Waiting for materials:** as explained before, when the operator is hindered from continuing the loading because a specific component is missing.

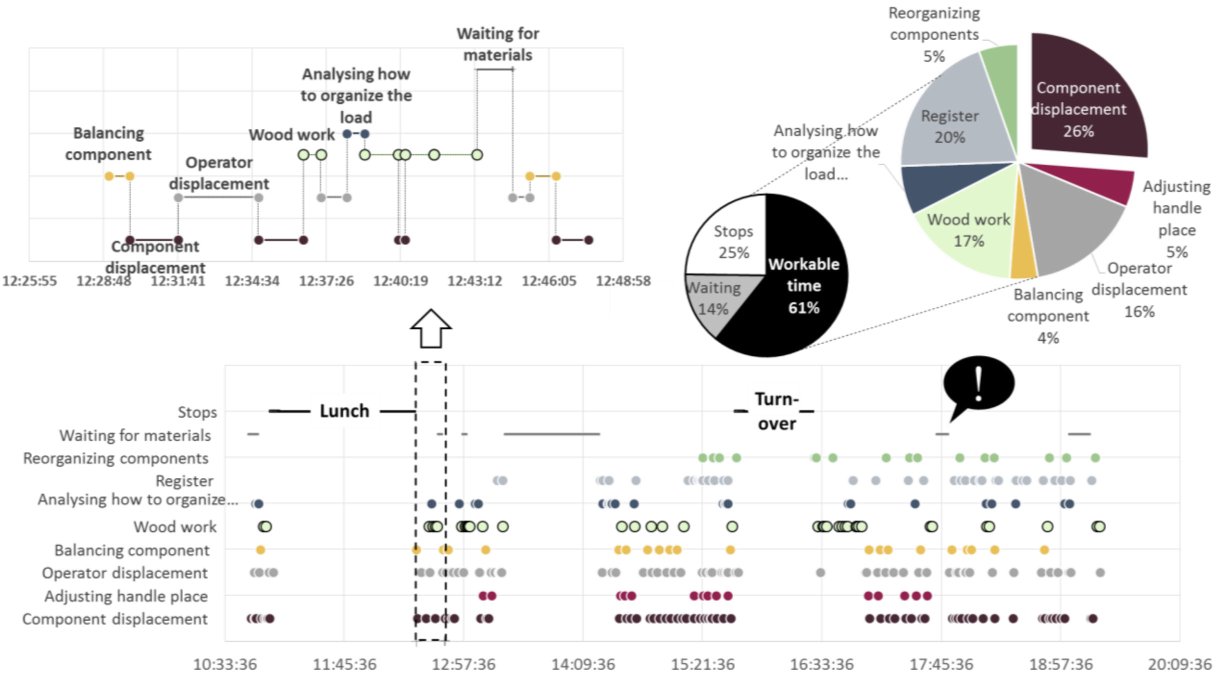


Figure 6.43: Chrono-analysis of not ready-to-ship items

The problem of organizing the yard by product was that the sequence of staging is defined according to plant delivery instead of shipping requirements. Figure 6.44 illustrates a problem in taking a beam from a trestle in the bottom of a pile and surrounded by different products and boxes. The beam had to be pulled using the forklift, to avoid moving all the materials around that trestle. This happened in the moment marked with an exclamation point in Figure 6.43. Although the time of waiting is not expressive, the team responsible for transporting the materials from the yard to the docks spent the whole day trying to figure out how to take that beam out.

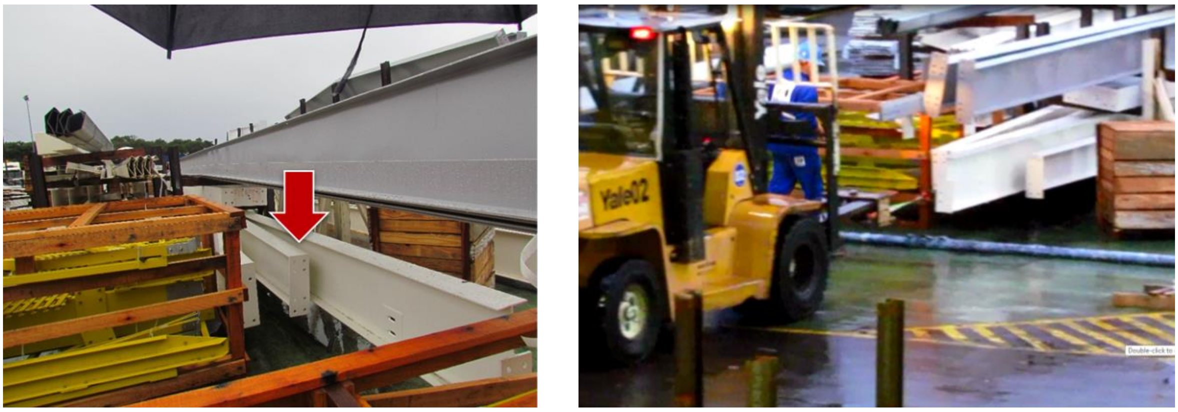


Figure 6.44: Difficulty in taking a component

Figure 6.44 also shows that different products were together in the same area. If the criterion of organizing the yard was product type, this should not happen. However, the amount of material accumulated made it difficult to use the same criteria consistently. The storage of the same type of component in different places was one of the main reasons for not finding the parts to be shipped.

6.2.5.3 Discussion

The analysis of the plant yard and the measurement of loading operations revealed some insights on the way the shipping process was carried out. The company managers were willing to see the results of both chrono-analyses, so that they could make operational investments to improve shipping productivity. The investments of the Logistics Department used to be a typical case of considering flow processes as transformation processes and, therefore, investing in machinery instead of analysing how to eliminate non-value adding activities. Some examples of this kind of investment were the installation of shelves to be able to store more standard products; the increase in the number of bridge cranes in the dock and in the yard; and the development of a system to better address where the components were located.

The productivity of the shipping process in the docks was low. However, the problems identified in the measurement of full loading operations revealed that the focus of investment should be in reducing the amount stored in the yard, and rethinking its organization. It was clear that the investment related to the development of addressing systems and on the bridge cranes did not seem to be effective, since the cranes were often idle, especially in the final days of loading a batch. Moreover, in a busy day this truck would be taken away from the dock to open space for new loads.

The investment on the shelves was a countermeasure to deal with the large amount of components that need to be stored. However, it is worth noting that most of the boxes in the shelves were storing standardized components, which raises a question on why having standard components stored for specific projects. The uncertainty of project situation increases the probability of storage time. The adaptation period for the new ERP system in the beginning of 2014 worsened the situation of the logistics. In the first months, there was no report on the amount of material in the yard and the system developed for addressing the components was not working anymore.

During the period of observation of shipment procedures, it was possible to understand the decision-making process for organizing the loads.

The idea of planning the loads was to define a plan showing which components should be shipped and how it should be organized. The former was a mechanism to deal with the amount of material in the yard, not a mean to avoid it. The latter was a mechanism to make a deeper analysis on the way materials were shipped. This was seen as an opportunity to improve the communication of the yard with the construction site, which could ultimately be attached to the plant and even to the design. For those reasons, the loading plans became the focus of the implementation phase of this empiric case.

6.2.5.4 Planning Loads

The first step for planning loading operations was to define the assembly sequence. The project manager set with the client the sequence shown in Figure 6.45, and this was discussed in the Logistics Department. The logistics team claimed that this was the sequence that the plant should deliver, and also the sequence for producing detail design batches.

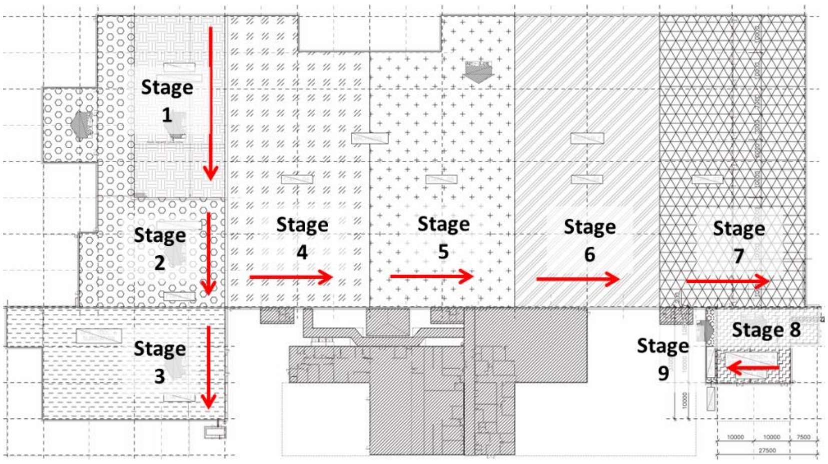


Figure 6.45: Construction sequence

For this reason, a meeting was carried out with the project design team, the plant coordinator (responsible for planning and controlling the plant production), the project managers (there were two in this case), and the logistics team (manager, and the leaders responsible for the shipping process). The goal was to make the different production units to work together to make the loading plans possible. The ideal loading plan discussed with the client was to organize the load so that it could be installed directly from the skid, in a last-in-first-out fashion, as illustrated in Figure 6.46.

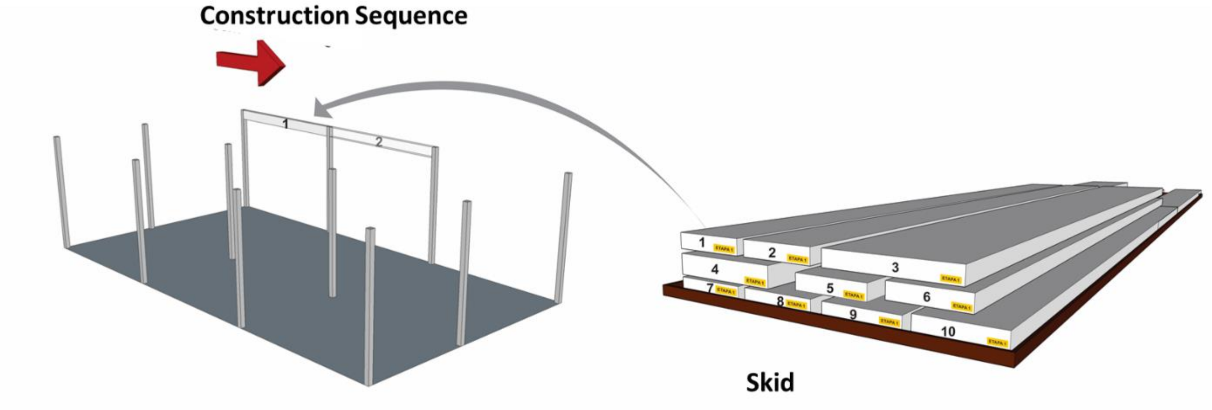


Figure 6.46: Ideal of the loading plans

During that meeting, the logistics department representatives claimed that the ideal was not feasible because of constraints of the truck, such as the need to place the heavier components in the bottom to avoid toppling. It was only after the development of the first plan that the research team realized that the ideal alternative was unfeasible. An important characteristic of the product was left out of this conception: the structural beams come in small sections that have to be bolted before the erection. Therefore, there was a need to place and assemble the components on the ground beforehand. Anyhow, at that moment the teams agreed that the closer the loads get to the construction sequence the better, considering the truck constraints. As a pilot case, the loading plans were developed only for the structural components.

Previously to this study, the Logistics Department used to receive a list of the components to be produced from the design team. In this project, they would like to receive this list and also the assembly sequence. For some technical reasons, the design team was not able to provide that, since the lists were developed automatically. They, in turn, proposed they could include an arrow showing the construction sequence in each of their drawings, as shown in Figure 6.47.

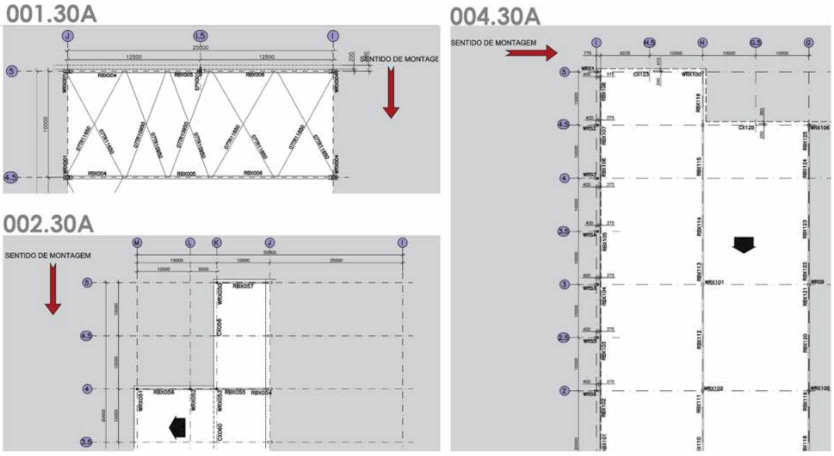


Figure 6.47: Integration with the design process

However, the marks in the drawings were not enough for the logistics to define specifically what should go in each truck. The research team provided some support for filling this gap. Figure 6.48 shows the process of developing the loading plans. First, each structural component was separated from the design drawings and organized according to the assembly sequence. Then, the loading plans were developed using plan views showing the position of the elements on each layer of the truck. In parallel with the drawings, a spreadsheet was fulfilled showing the main characteristics of the components (name, site axis, size, place in the truck, and weight). The spreadsheets were important both for the Logistics Department for planning the loads and for the development process to ensure that each layer was less heavy than the bellow one.

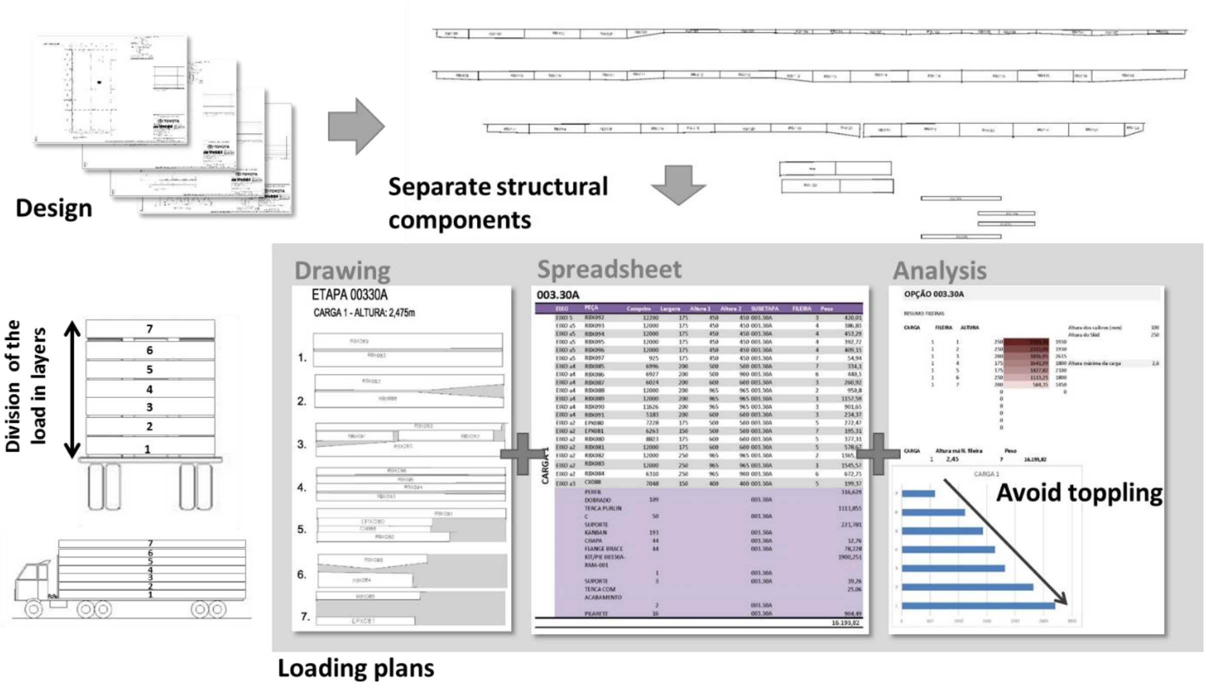


Figure 6.48: Development of the loading plans

An important lesson learned from the first loading plan, was that it was not enough to check the weight in each layer, it was also important to balance the weight horizontally. Figure 6.49 shows the problem faced by the logistics team in carrying out the first loading plan. Two boxes of sheet metal Z-section components were in the same layer as a much lighter beam. The boxes were piled in the first two layers of the truck. The logistics team realized that this would cause an unbalance in the truck, so they changed the position of one heavy box.

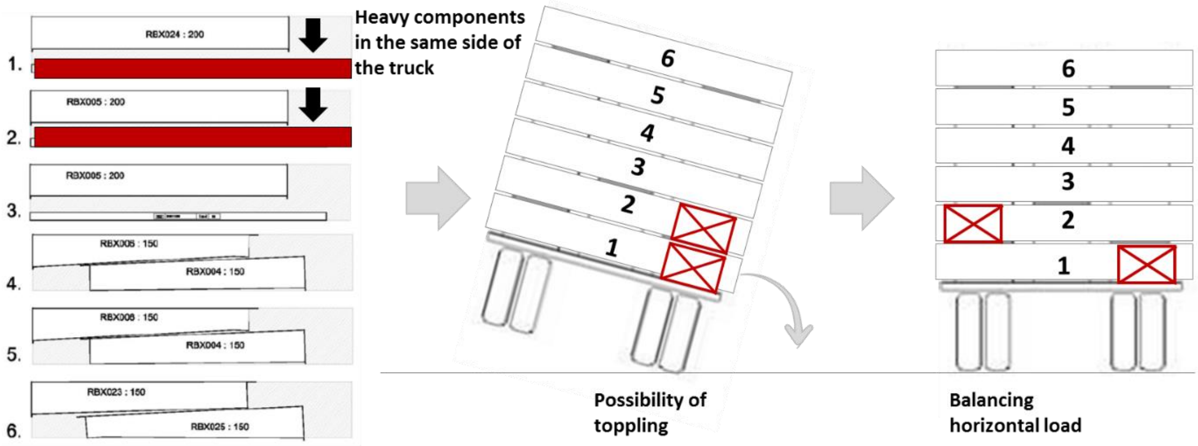


Figure 6.49: Lessons learned from the first loading plan

The loading plans were proposed by the research team and discussed with the logistics team. Loading plans were devised for the structural sub-stage from stage 1 to 8. The researcher had to go to company once a week to monitor the execution of the loading plans. The logistics team implemented the plans and provided feedback for the development of the remaining ones. The components in the plan were analysed one by one from the list of material from the design. In the first two plans, one component was left behind. In one of these cases, this component refers to a bollard, a small pillar that helps in the connection of the columns with the beams. When the size of these components was less the one meter, it was included in a box. The boxes were not detailed in the loading plans due to the lack of size predictability. However, when it was larger than that, it was organized in the same manner as the other structural components and should appear in the loading plan.

The three first months of shipping were monitored; Figure 6.50 shows the content of the first 22 truckloads sent to the construction site. The loads highlighted with a dashed line are the structural sub-stages, which means they follow a loading plan. It is more critical to have a mixed load in those cases. Only the first two loads with a loading plan mixed different sub-stages. The operators were still used to the practice of freight optimization, which was not the main criteria used in the loading plans. In other words, when there was room for more components in the loads, those operators sometimes completed with components from other sub-stages.

It was important to ensure that this practice should be avoided, at least for this project, since the mixed loads directly affected the site logistics management. This was an issue discussed in the **sixth workshop**. The importance of adhering to the plans were emphasized, making clear that the company director and logistics manager had agreed to increase the number of freights in order to facilitate the organization of the site. The workshop happened after the eleventh load was delivered in the site. Figure 6.50 indicates that after the eleventh week there was no more mixing of sub-stages.

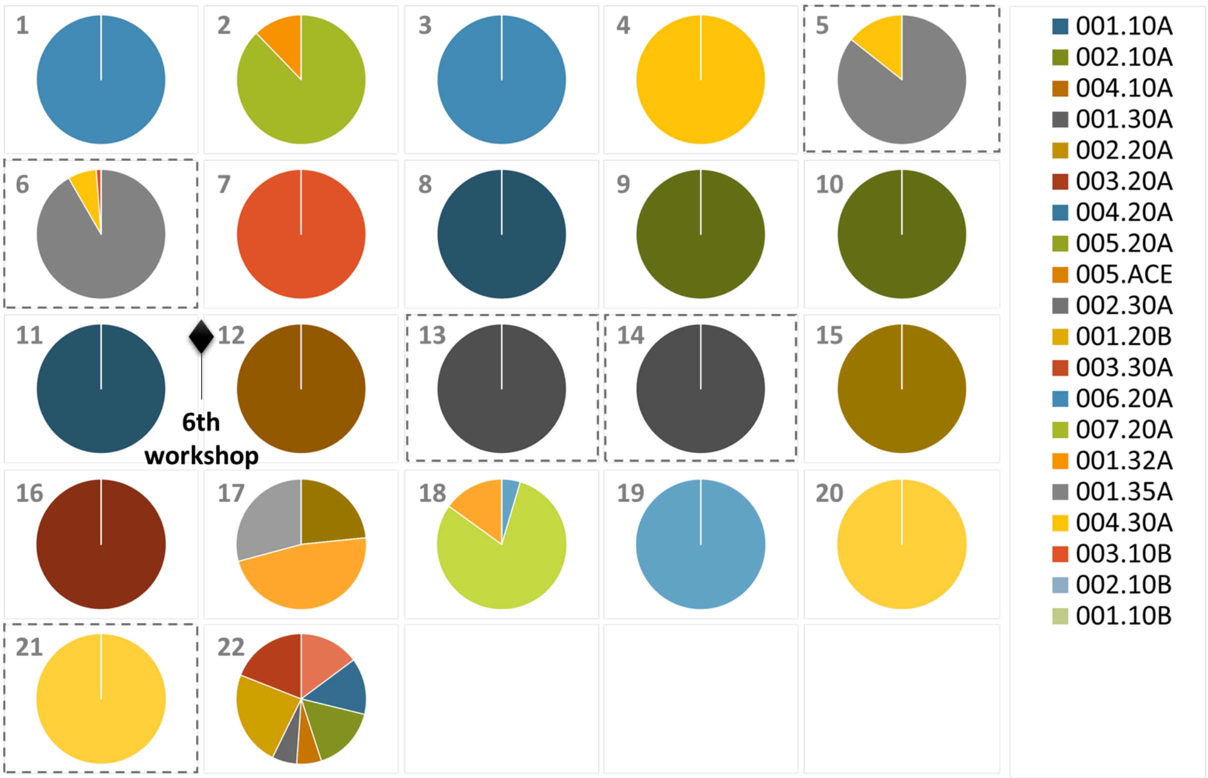


Figure 6.50: How mixed were the loads

The intended benefit of the loading plan was to help the site manager, and the research team analysing the site layout, to better plan the staging, assembly and erection operations in the field, by receiving in anticipation how the components would be organized in the loads. Besides, it was also possible to improve the material management process.

The analysis of the loads sent to the site required the use of control tools for material management, which revealed a mismatch between the list of materials sent to fabrication and the list sent in the truck. The former was based on the design weights and quantities, while the latter in the actual data. This mismatch could make it difficult for the site manager to know whether all the necessary components to start a sub-stage were available. Therefore, the research team, together with the site team, developed a list crossing the information from the list of materials sent to fabrication and the list sent in the truck, highlighting the items that seemed to be missing, so that it was possible to check with the Logistics Department if the sub-stage was complete or not.

6.2.6 Contribution from the fourth step to the final model

The main contribution for the final model was the possibility of using the knowledge from the logistics processes as the integrated instance responsible for taking feedback from the construction site in a short-term, as illustrated in Figure 6.51. This instance was performed by the adjustment meeting, managed by the Planning Department. It is worth noting that it was relatively easy to put this role in the Logistics Department when only one project is analysed.

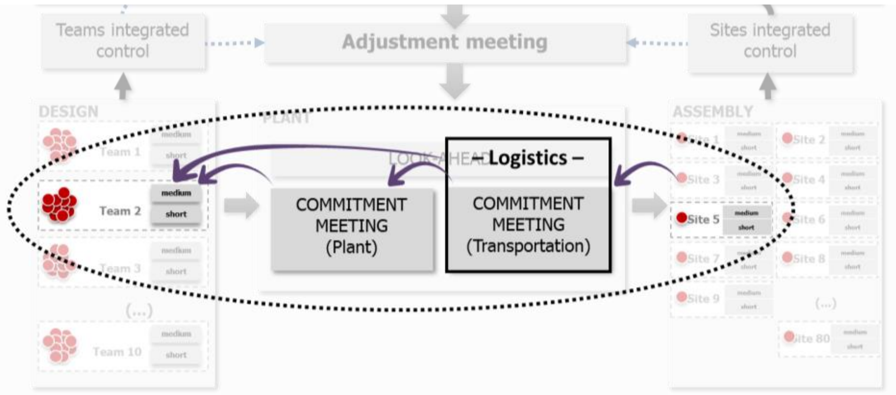


Figure 6.51: Contributions of the embedded case to the final model

In this analysis, the logistics team provided the constraints for the loading process through the analysis of the components design. Here, the task of producing the loading plans was carried out by the research team, but it revealed a connection between design and logistics. As a special project, the logistics confirmed each load with the site manager, making them aware of the site needs. This information was used to communicate with the plant regarding the short-term priorities for components.

The complexity inherited in a multiple projects environment contributes to the functional specialization of each department, making the logistics to focus on ready products, and not to pro-active work on the components required by the construction sites. However, the Logistics Department is situated in the interface between the end of fabrication and all the on-site productions. For this reason, it is able to gather an up-to-date information from the sites, and have to be aware of the transportation constraints and fabrication completion dates. However, excepted by the elaboration of the loading plans, even in this study there was a lack of formal procedures for making this communication.

For this reason, the Logistics Department should assume a more strategic role for the integration of the on-site activities and fabrication of components, but this would require data collection to become more systematic, and aided by information technology systems. As discussed before, logistics was still seen as a transformation process so the improvement focus tends to be on transportation efficiency. The company had not realized the contribution it could make in the management of the production system as a whole.

6.3 DISCUSSION

The type of problem analysed in this research was a typical wicked problem. During the diagnosis phase, it was not possible to thoroughly understand the planning and control system problems faced by the company. Part of those problems was realized during the implementation phase. The stumbling blocks described by Wiendahl, Von Cieminski, and Wiendahl (2005) played an important role in this understanding. The idea they highlighted regarding inconsistencies between logistic objectives was an important insight for understanding the problem of a production unit being measured by volume, while the Planning Department was charging for schedule reliability.

The realization of the problems in the definition of the targets was also part of this iterative process between diagnosis and solution development. The beginning of the implementation was based in the short-term, trying to change the mindset from producing more volume to adhere to the schedule. At this point, the research was assuming that the development of the plans was ensuring the best possible flow for the projects. The idea of having flexible plans was to deal with the uncertainty during the production. However, there was a need to reassess the validity of the plans. The problem was that the decision for starting the production was based on the need to keep the production pace and not to finish the products. Here, product refers to the final building, delivered to the client. The Planning Department was not making an assessment of the project flow through the production units.

In a project domain, the production sequence can be changed but it is less common to have an activity that will not be needed anymore, the study of the production sequence is related to the efficiency of the production and use of resources, for example. On the other hand, in a multiple project environment, the decision over the sequence of projects is crucial to define how the shared resources will be used, and will strongly affect the production flow in each site. In this environment, it is possible to have components that will not be needed for a long period.

In this multiple project environment, where the utilization of capacity is so important, there is no assessment over the misuse of this capacity, regarding how much labour, time and material were spent in components that will turn into scrap. Even more important, how much the company lost, in terms of reliability with the client, by not having its capacity available for delivering what was required by the construction sites. This point is highlighted by Ballard and Arbulu (2004) arguing that fabricators should sell the use of fabrication capacity instead of the products itself, to avoid this emphasis in utilization of capacity causing huge amount of inventory.

Therefore, the planning and control system can never lose the track over the project flow control. As highlighted by Bertrand and Muntslag (1993), the project flow control enables the coordination of the logistic chain, and is responsible for developing directives for the production units. In this ETO environment, those directives are fundamental to support the different confirmation instances, highlighted by different authors (KINGSMAN, 2000; LAND; GAALMAN, 1998; LITTLE *et al.*, 2000). Here, carried out in the medium and short-term levels.

The Last Planner System is also concerned with this differentiation (BALLARD, 2000). Although there is a need to abstract the strategic level of the system to this multiple-project environment, the definitions of what Ballard called workflow level, will guide the production units. This means that if the first is neglected, a high level of commitment to the plans in the short-term will not reflect that the right things have been done. In Company A, LPS was an important source of confirmation and learning in the production unit level.

The process of developing and understanding Company A production planning and control system revealed the importance of three of the requirements presented in section 4.2. At first, it was noted the need of dealing with uncertainty and providing the confirmations mechanisms, as described in the second requirement. However, this was only possible through the proper analysis of the project flow, highlighting the importance of the third requirement as just discussed. Last, the third important requirement to be considered in this system is the interface between sales and production, which have been constantly neglected by the company managers who were imposing a production higher than what have been sold. This was one of the causes for the excess in anticipations.

7 EMPIRICAL STUDIES ABROAD

This chapter is dedicated for the studies carried out in the USA. Section 7.1 refers to the study on Company B; Section 7.2 to the study on Company C.

7.1 EMPIRICAL STUDY ON COMPANY B

The study on Company B is described in 4 sections. Section 7.1.1 describes the project planning and control system and processes related specifically to Company B. Section 7.1.3 concerns the analysis and implementations carried out in this study. Section 7.1.4 discusses the findings. Last, section 7.1.5 describes the contributions of this study for the final model.

7.1.1 Project Planning and Control System of Company B

The project investigated consisted of the construction of a building of almost 300.000 m²of gross floor area, being located in a construction site of almost 780.000 m², and costing around 5 billion dollars. The project involves numerous industrialized technologies, not only to improve efficiency and reduce the lead-time, but also to be able to fulfil design requirements.

The building was divided into nine similar zones. The project started in one of them, which was a restaurant (named Zone Z). The construction of that zone was conducted by different subcontractors, while the remaining eight zones were under the scope of Company B; this company was a design-build subcontractor to the general contractor (GC). Most of the components used to build each zone were highly industrialized, but the interface between zones involved several traditional construction technologies, such as casting on-site concrete. The scope of Company B included all the HVAC and piping systems, including the ductworks, risers, Air Handling Units (AHU), ventilation equipment, and radiant floors.

The production strategy for the construction process started in Zone Z followed by two big phases of four zones each, involving only industrialized components. In each phase two crews were used to attack the two sides of the building concurrently. In between those two phases, there was a period of 14 weeks for carrying out traditional construction. All subcontractors had to follow that sequence. Figure 7.1 provides a schematic overview of the strategy. For confidentiality reasons, this illustration does not reflect the real shape of the building.

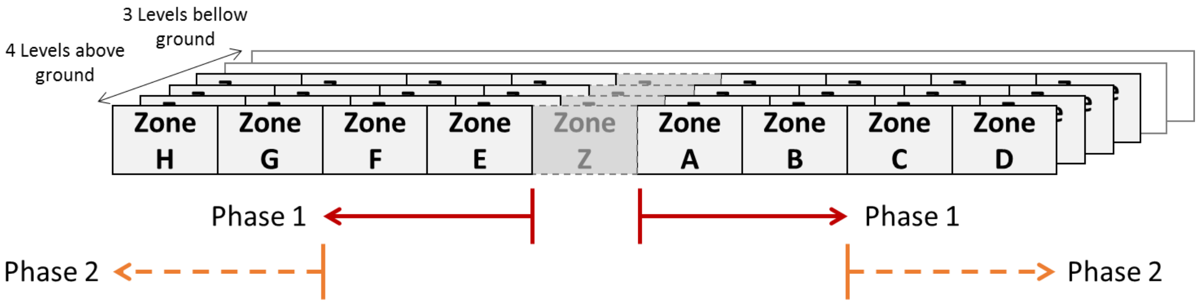


Figure 7.1: Schema of the Production Strategy

Due to the fast pace of the project and the number and size of components to be delivered, the GC required all subcontractors to use a just-in-time installation process. The construction site afforded little space for inventory and each subcontractor had to deal with space and resource constraints regarding the use of equipment, such as cranes. For safety and time reasons, most of the activities scheduled had to be carried out off-site.

In the beginning of the project, the GC developed the first schedule for the whole project that need refinement during the construction phase, since few subcontractors had yet been defined and the detailed design was unfinished. The GC differentiated subcontractors by role. Some subcontractors were responsible for critical-path activities, which means their scope would release areas for other subcontractors to work on. Their hand-offs would dictate the pace of the other trades. Any delay or anticipation would mean a shorter or longer cycle time for the remaining activities. This was the case of precast concrete, shotcrete, and steel structure. Because these subcontractors had a different role in the production planning and control system of the project, they will be called the “**main**” subcontractors.

In this research work, the interval of time constrained by the activities of those main subcontractors has been called as a “**window of opportunity**”. This was the main source of data for the HVAC subcontractor to plan its work and define a production sequence. This window could fluctuate in time, and sometime be compressed or extended, as shown in the different versions of the GC schedule (Figure 7.2). In each version of the schedule, the window starts when the concrete casting of the topping slab is completed and finishes when the steel structure of the roof starts. This is the period when most of the HVAC equipment need to me installed. The release for starting the work was delayed two months, and the window was extended. The need for working with a flexible plan within this window of opportunity strongly influenced the implementation process, as described in the following section.

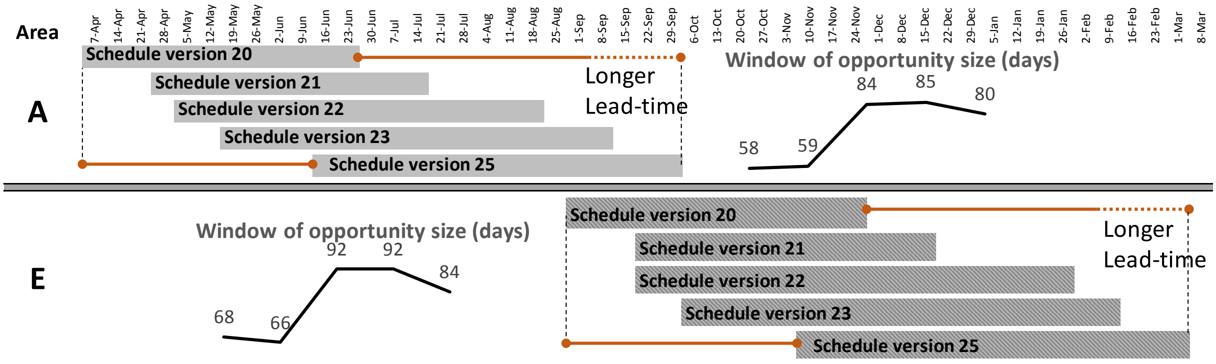


Figure 7.2: Changes in the window of opportunity for a given activity

The long-term schedule used a high level of detail. Counting from the beginning of the project 25 versions of the main schedule were released in 30 months. Each version contained information from the construction site and from the design coordination process, still going on at that time, showing the main milestones for design submittals[1] of each subcontractor, using a high level of detail. Figure 7.3 reveals that in five months' time the final date of the construction project was delayed by five months as well, due to numerous unexpected situations, such as finding a water table (which was not in the soil analysis) and the amount of rains. Making the GC not able to overcome the delays.

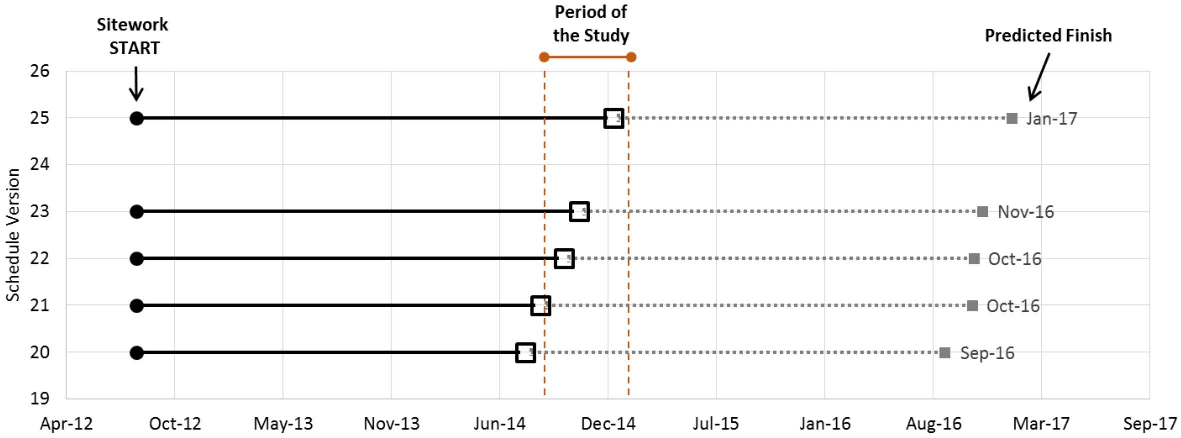


Figure 7.3: Schedules review on the final date

The planning and control system adopted by the GC was based on the Last Planner System for managing medium and short-term planning in the construction site and in the design

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[1] The submittals were all the data required (shop drawings, material quantities, product data) for the GC to verify if the products to be installed are according to the requirements of the project.

process. It is worth noting that the production in the field was carried out concurrently to detail design.

The planning and control meetings involved the superintendents[1] of all subcontractors, based on the assumption that plans need to be flexible, so as to be able to deal with the uncertainty and the structural complexity of the project, i.e., some subcontractors needed to adapt to the window of opportunity between the main subcontractors.

Figure 7.4 illustrates the relationship between the design, fabrication, and site installation processes. The field coordination starts with a “CAN” directive that summarizes a series of planning processes such as the long-term scheduling, collaborative planning sessions, look-ahead planning, and logistics meetings. The process that defines the activities that can be produced is based on a make-ready process in which the constraints for starting the activities are identified and removed.

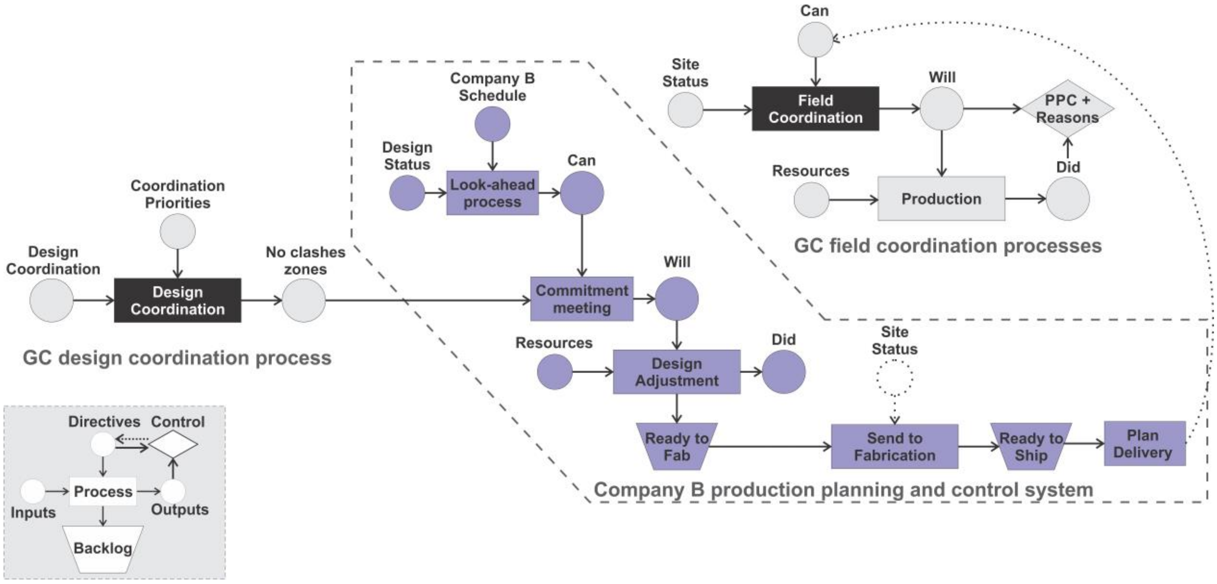

Figure 7.4: Project Planning and Control System

The design and field coordination occur in a weekly basis. The design coordination process uses the schedule of each subcontractor using the start prefabrication date to establish priorities. Therefore, systems that needed to be fabricated earlier were coordinated earlier. Due to the large size of the building, it was not possible to discuss all systems in a single meeting. For that reason, five different two-hour long weekly meetings were held, one for each specific part of the building. The GC used to specify the specific subject of the meeting

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[1] The superintendents are responsible for the on-site production of a specific set of activities, being in charge of a team of workers. In the case of Company B, the superintendents were also responsible for controlling the fabrication of the components required for those activities.

to the subcontractors in advance, so that they could analyse who should participate. The regular frequency of the meeting enabled regular contact between different designers, helping to solve small problems (REINERTSEN, 2009).

Regarding the construction processes five different weekly meetings were held. On Mondays and Fridays, a commitment meeting, which were concerned with the activities of the following week. Due to the large number of superintendents involved in the construction, the GC broke down each meeting into two, in order to discuss with a small number of subcontractors.

The division was based on the amount of interdependencies between the subcontractors. In other words, the group of subcontractors with a high number of interdependencies would be together in the meeting. Sometimes one sub needed to participate in more than one meeting, such as the cast-in-place concrete or the structural steel, because of the high level of interfaces they had with other trades. On Tuesdays, a special planning section was carried out, looking at a milestone three months ahead, and the trades developed a backward plan from that milestone. On Thursdays, a half-an-hour meeting was held to analyse if there were any special constraint in the activities of the next day meeting. All subcontractors participated in this meeting.

Besides the production meetings, a weekly logistic meeting was held, with all subcontractors to analyse the interaction between cranes, trucks and storage areas. Even so, every time a subcontractor needs to enter in the construction site with a truck or crane, they need to request a permission from a logistic web-based portal, where the GC manages the site on a daily basis.

7.1.2 Production Planning and Control System of Company B

Figure 7.5 represents schematically the activities carried out by Company B and the interactions with the GC designers, the mechanical engineer, the ductworks’ fabricators, and the GC site managers. The figure highlights the process of ductwork production. The overall design of the ductworks was given by the GC, and Company B designers were responsible for highlighting problems regarding the development of the shop drawings.

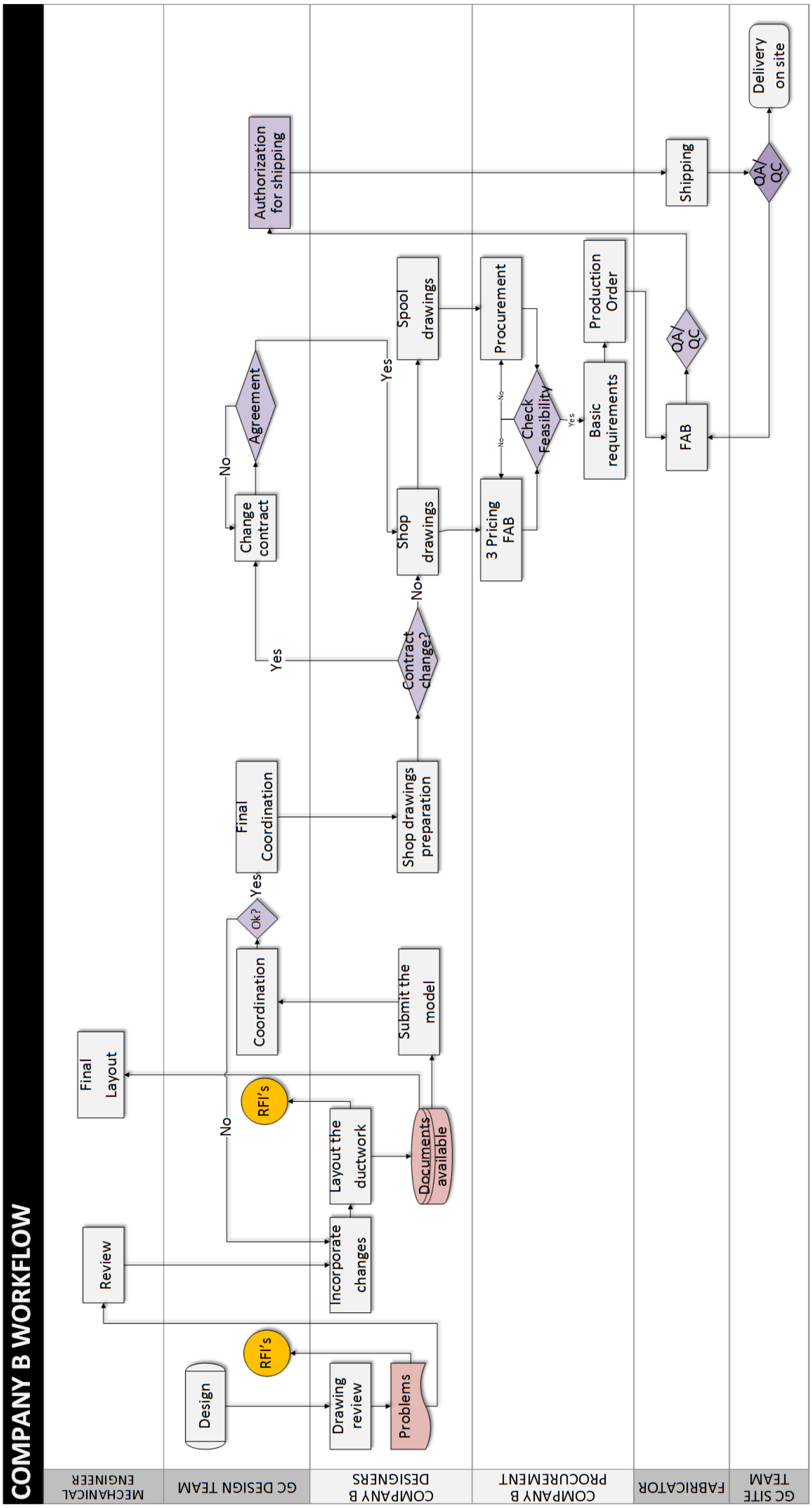
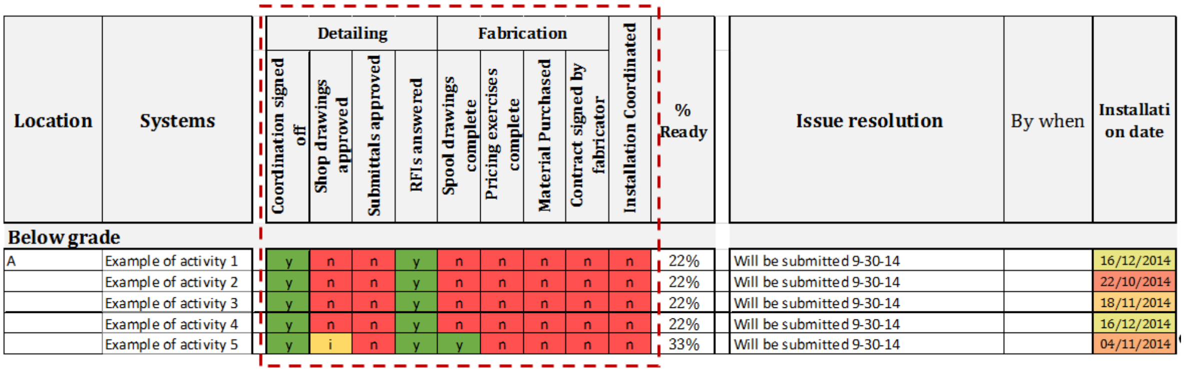


Figure 7.5: Main workflow of Company B

After some review cycles, the GC would coordinate the mechanical drawings with the other design disciplines of the project. When design was approved, the procurement department was responsible for requesting pricing from the fabricators and procure the materials. After selecting the fabricator, Company B would establish the basic requirements for fabrication and generate the production order. After fabrication, the products are checked against quality requirements by Company B. For delivering the materials on the site, the GC should authorize beforehand.

During the empirical study, Company B was involved mostly in off-site activities. Little mechanical design had been coordinated with the other disciplines, the scope of the piping had already started, but the ductwork was under some uncertainty, regarding product specification. During this period, the focus was on planning the fabrication and the site installation of the dry side, and understanding the logistical problems involved in those processes. It was a time for testing how to carry out the planning and control process, simulating different production scenarios, and discussing those scenarios with potential fabricators.

When the GC released a new schedule, Company B was responsible for updating their schedule as well. Company B schedule was the main source for the short term planning meetings meetings to control the submittals of the design detailing process to the GC and to release fabrication of the components. The look-ahead planning meeting was carried out also in a weekly basis, prioritizing the activities that could be executed sooner. Figure 7.6 shows how the constraints were analysed for each activity based on the main activities for finishing design and fabrication.



Location	Systems	Detailing				Fabrication					% Ready	Issue resolution	By when	Installation date
		Coordination signed off	Shop drawings approved	Submittals approved	RFIs answered	Spool drawings complete	Pricing exercises complete	Material Purchased	Contract signed by fabricator	Installation Coordinated				
Below grade														
A	Example of activity 1	y	n	n	y	n	n	n	n	n	22%	Will be submitted 9-30-14		16/12/2014
	Example of activity 2	y	n	n	y	n	n	n	n	n	22%	Will be submitted 9-30-14		22/10/2014
	Example of activity 3	y	n	n	y	n	n	n	n	n	22%	Will be submitted 9-30-14		18/11/2014
	Example of activity 4	y	n	n	y	n	n	n	n	n	22%	Will be submitted 9-30-14		16/12/2014
	Example of activity 5	y	i	n	y	y	n	n	n	n	33%	Will be submitted 9-30-14		04/11/2014

Figure 7.6: Example of the look-ahead spreadsheet used by Company B

Before the short-term planning and control process took place, a network of activities highlighting their interdependencies was developed, in order to understand the impact of the delay in one activity to the remaining ones under their scope. Weekly, the course of actions were analysed and each responsible for carrying out the activity should commit to do it. During the period of analysis, Company B were not collecting metrics regarding the percent of plans complete (PPC) or the causes for non-completion.

The short-term planning and control process of Company B was carried out on a weekly basis, looking to the following week. The processes that Company B controlled internally were mainly related to the design activities. The activities related to the production on-site were controlled in the GC short-term meetings, in which the superintendents commit with the production and became aware of the process of other trades defining the windows of opportunities.

Regarding on-site activities, Company B did not have a systematic routine to plan and control their work, during the period of analysis. It is worth noting that during this period, a small number of activities had already started installation. At this time, the company realized the necessity of confirming the production and the requirement for equipment by the on-site trades. Those confirmations were made in a daily basis by one of the project managers who visited the site at the beginning of each day to confirm the activities of that day and possible impacts later.

7.1.3 Analysis of the Critical activities

The schedule of Company B in the project described was very dependent on the status of other trades. Due to the just-in-time requirement for the delivery of components and the space constraints Company B was interested in developing pull mechanisms for starting the fabrication of the most critical activities, based on some trigger mechanism from the construction site. The critical activities selected refer to the repetitive activities in the zones described in Figure 7.1, namely the offices ductwork, the installation of the risers, the installation of the air-handling units (AHUs), and the installation of different equipment in the roof-level.

For understanding what could be these triggers, there was a need first to understand the window of opportunity available for carrying out each activity. The second step was to confirm when the installation should take place looking at some constraints such as the equipment and space required. In this step, it was possible to create some scenarios considering different triggers for starting the fabrication. The third step was to include the fabrication lead-time in the analysis to achieve, then, the fourth step regarding the analysis of product modularity to understand the required mix of production. For analysing the window of opportunity, the researcher suggested the use of a line of balance (LOB), based on the most current version of the schedule for the specific scope of work.

After the description of the implementation process, it is revealed an important practice used by the piping side, demonstrating a strong integration between the design, the transportation constraints and the production sequence on the site.

7.1.3.1 Ductwork

The first analysis made in this study was about the unloading of the ductwork in the floors. In order to make the researcher aware of the problem of unloading the ductwork, the vice-president organized a meeting in which the superintendent of the dry side, the project manager of the dry side, the researcher, and himself were present. In the ductwork analysis, this group of people are referred as company team. The idea of the company team was that there would be a need to make several deliveries per day in order to accomplish the unloading process. This idea would be a challenging because the amount of product delivered would be higher than the fabrication capacity, demanding large inventory areas.

There were several constraints in this process. First, the material should only be unloaded after the slab of the above floor was ready. Second, the unloading process should finish before the glass was installed in the façade. Last, the unloading package should ensure minimum movement for installation, since this process should only take place after several activities were finished on the floor, being the underfloor walls the last one. These interdependences are illustrated in Figure 7.7.

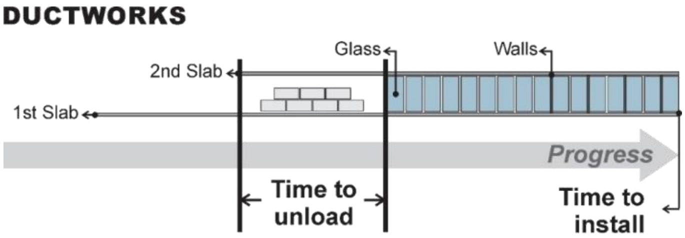
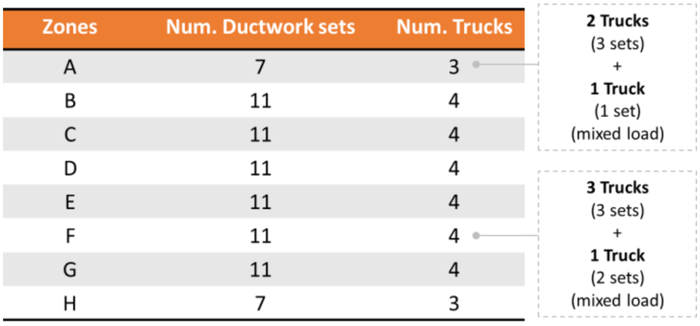


Figure 7.7: Window of time for unloading ductwork

Regarding the fabrication process, there were also some important concerns. Company B have a manufacturing plant located in Minnesota, US. The laws from California, where the project was located, do not allow the fabrication to be performed outside the state. The solution found by the contractor was to build a prefabrication facility for the final assembly of the ducts with internal labour. In this new facility, they would have the capacity to produce up to four sets of ductwork per day.

The zones of the building were, in turn, divided in gridlines. In each gridline one set of ductworks should be installed. On average, each zone had ten sets of ductwork to be received. One truck could deliver up to three set of ductwork. The amount of trucks required for each zone of the building is presented in Figure 7.8.



Zones	Num. Ductwork sets	Num. Trucks
A	7	3
B	11	4
C	11	4
D	11	4
E	11	4
F	11	4
G	11	4
H	7	3

2 Trucks
(3 sets)
+
1 Truck
(1 set)
(mixed load)

3 Trucks
(3 sets)
+
1 Truck
(2 sets)
(mixed load)

Figure 7.8: Amount of trucks required in each zone

Considering this data, it was necessary to identify the window of opportunity, in other words, the period of time in which the area would be available for the delivery of material. However, at that time, the activities related to the glass installation were not available yet, so the GC agreed with Company B a period of at least two weeks for this process, in each of the floors. This agreement illustrates the strategy adopted by the GC to deal with the process of gradually increasing the level of detail of the schedule.

Figure 7.9 shows how this analysis looks like. The LOB was organized according to the levels of the building, since the delivery of the topping slabs followed this sequence. When the release dates of the areas were plotted, it was possible to see that there would be no need for more than one delivery per day. This analysis strived to avoid the use of more than one truck per day, and to stop the delivery for a certain period.

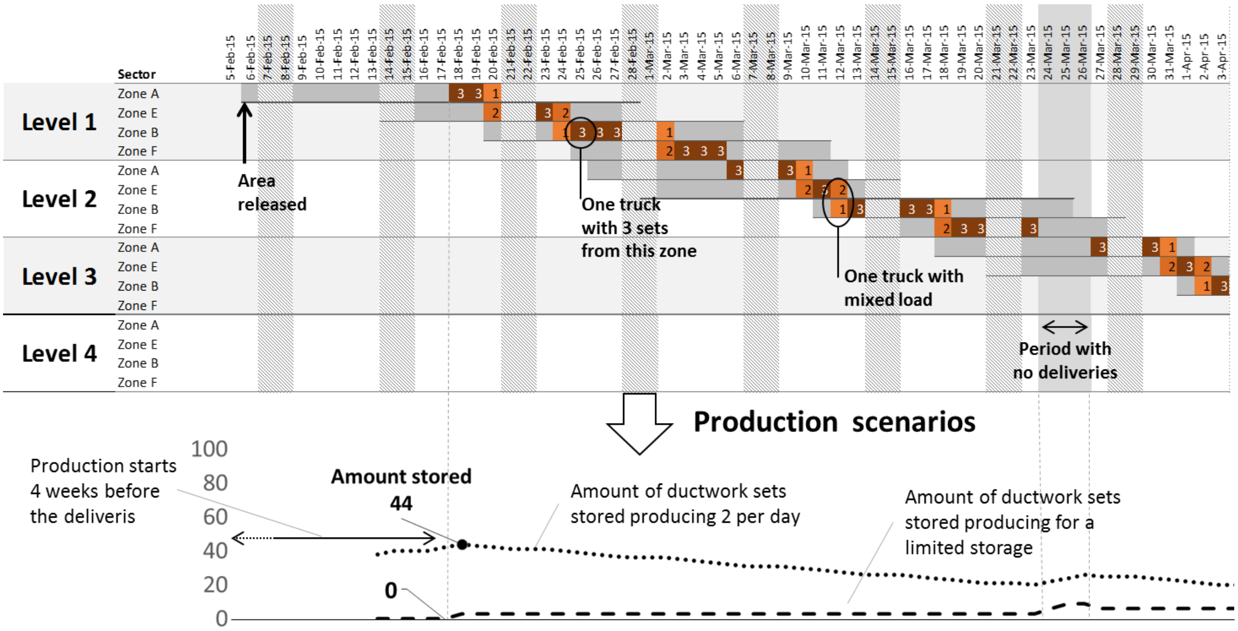


Figure 7.9: Example of how the analysis of the ductwork was conducted

By decreasing the delivery rhythm that the company team had previously in mind, the logistics and the synchronization with the final assembly process were facilitated. However, a problem for this synchronization was the period between phase 1 and phase 2, when there is no deliveries. Here the company team had to decide if they want to have a dedicated team, producing in a continuous flow, but with a large amount of inventory; or a small amount of inventory by producing only when needed. Both these scenarios were simulated using the LOB in the analysis, the summary of the results are shown in Figure 7.10.

	Scenario 1	**Scenario 2**
Start *(related to the beginning of the deliveries)*	4 weeks before	One day before
Maximum amount stored	80	9
Production flow	Continued	Discontinued

Figure 7.10: Summary of the scenarios

Before choosing the best option for this situation, the client decided to make a change in the ductwork product, using a fabric duct instead of a sheet metal duct. This decision directly affected this analysis, which had to be left aside until the final decision was made. Changing the product specification would have an impact of approximately 11 million dollars. Company B was responsible for testing the performance of the fabric duct and send a feasibility analysis for the client. As the final answer was positive for changing to fabric duct, the unloading process was not a critical activity anymore, therefore the analysis was not used anymore.

Nevertheless, there was some important lessons learned in this phase. It was the starting point for the following analyses. It revealed how hard it was for the company team to understand the rhythm imposed in the GC activity-based schedule. The discussion with the superintendents also revealed the importance of understanding the fabrication capacity based on reliable data. Another important lesson learned was the window of time negotiated with the GC. The fact that the activity responsible for closing the available window was not confirmed did not hinder the analysis. Later in the process, the confirmation of the glass installation revealed that this window would be much larger than the two weeks previously agreed.

7.1.3.2 Risers

A riser consist of a vertical sheet metal duct connecting the ductwork of each floor to a fan and a plenum unit in the roof-level. The installation of risers is critical because it comes in one single 24-meters-heigh piece, which has to be hoisted, rotated and installed at once, in half of a day. There were 80 risers throughout the project.

An important characteristic of the riser is its modularity. There are five different types of risers; two of them are one-of-a-kind, while the other three types can be used interchangeably in the project. Figure 7.11 shows the amount of risers of each type. Because of its modularity, the risers have fewer chances to suffer with the matching problem, as discussed in Tommelein (1998). The production can easily deal with changes in the project sequence, without delaying the installation.

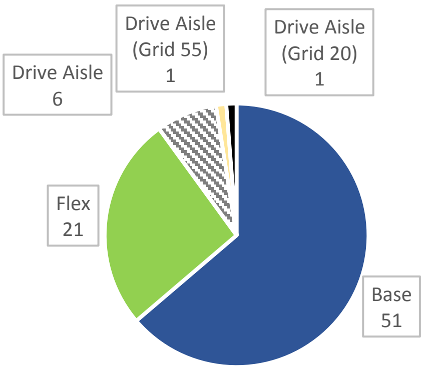


Figure 7.11: Risers Types

The first step was the confirmation of the window of opportunity, which would start with the pouring of the topping slab and was followed by a series activities from the mechanical contractor. Therefore, the main constraint for the end date was to optimize the use of resources. The second step was to **confirm the installation** rhythm, based on the crane usage. In this phase, the dry side superintendent realized that they could share the use of the crane with the electric trade, which would need to install their risers in the same shaft as the mechanical. Figure 7.12 compiles the data from the GC schedule and the confirmed schedule, taking into account the crane utilization.

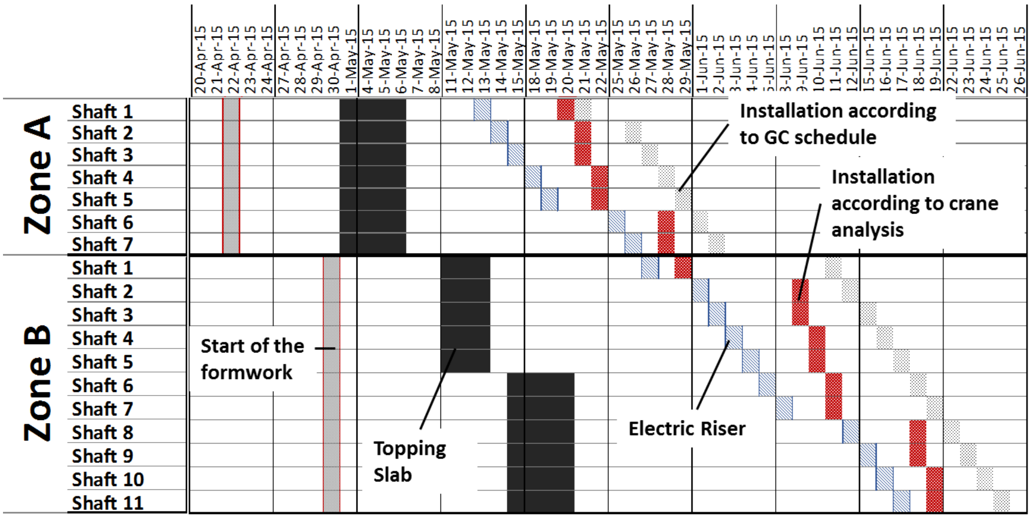


Figure 7.12: Details of the installation schedule, according to the crane utilization

The third step was to take the information from the fabricator regarding lead-time and how many risers could be produced concurrently. Each riser should take 5 workdays to be produced and there was enough room for producing two of them concurrently. This was the data used in the first scenario for production, as shown in Figure 7.13. As it is possible to see in the LOB, the difference in the rhythm of field installation and the rhythm of fabrication, lead to a huge amount of risers to be stored.

For that reason, Company B decided to use the facility rented for the final assembly of the ductwork for storing the risers, buffering from the uncertainty of the construction site. The idea was to have a backlog for the start of the installation process. The problem in this strategy was that it required the fabrication to start 15 weeks before the installation. However, at that time, the client has not decided yet about the insulation material of the riser and, therefore, the design could not be released to fabrication. There was also some space constraints, since the warehouse was able to store 20 risers, while the total accumulated in this scenario was 32 risers.

The second scenario developed for the fabrication of the risers, simulated a larger capacity in the fabricator. There was a possibility for the fabricator to build more capacity, although the need for training new people for welding is still an issue. Figure 7.13 shows that the fabrication could start only 5 weeks before the installation. By decreasing the fabrication lead-time, it is possible to establish triggers from the construction site to start the fabrication, developing a more reliable production system. In the case of the second scenario, the beginning of the formwork of the topping slab could be set as a trigger for the fabrication, so it would be possible to make the fabricator react according to what was happening in the field. The amount of risers that need to be stored would be much lower, a maximum of 20 risers, which is within the capacity of the warehouse.

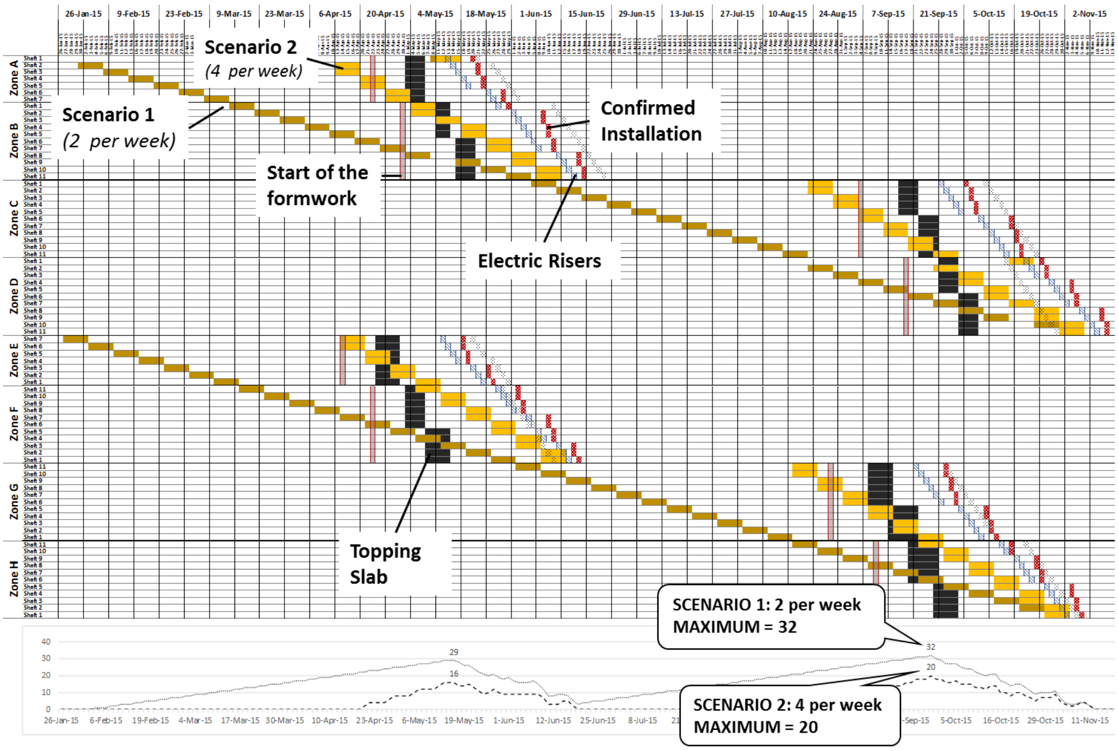


Figure 7.13: Scenarios for the fabrication

Figure 7.14 presents a summary of the scenarios developed. This decision was still under negotiation at the end of this study. The design was not ready because the material for the riser insulation was not defined yet, and the installation had been delayed. Therefore, at that moment, both of the alternatives were feasible. There was a special concern from the fabricator side, which would have to build some extra capacity to be able to accomplish to the second scenario.

	Scenario 1	**Scenario 2**
Start *(related to the beginning of the installation)*	15 weeks	5 weeks
Number of risers produced concurrently	2	4
Maximum amount stored	32	20
Production flow	Continued	Discontinued

Figure 7.14: Summary of the scenarios for the risers' production

The fourth step was to examine the mix of production, for fabrication. Figure 7.15 shows when each type of riser would be under production in the plant, according to the scenarios developed. Then, an important decision was made: the first riser to be installed was one of the one-of-a-kind type of risers. Besides the fact that this type of component could suffer from a design change, the project manager of the dry side realized there was no reason for storing this type of component.

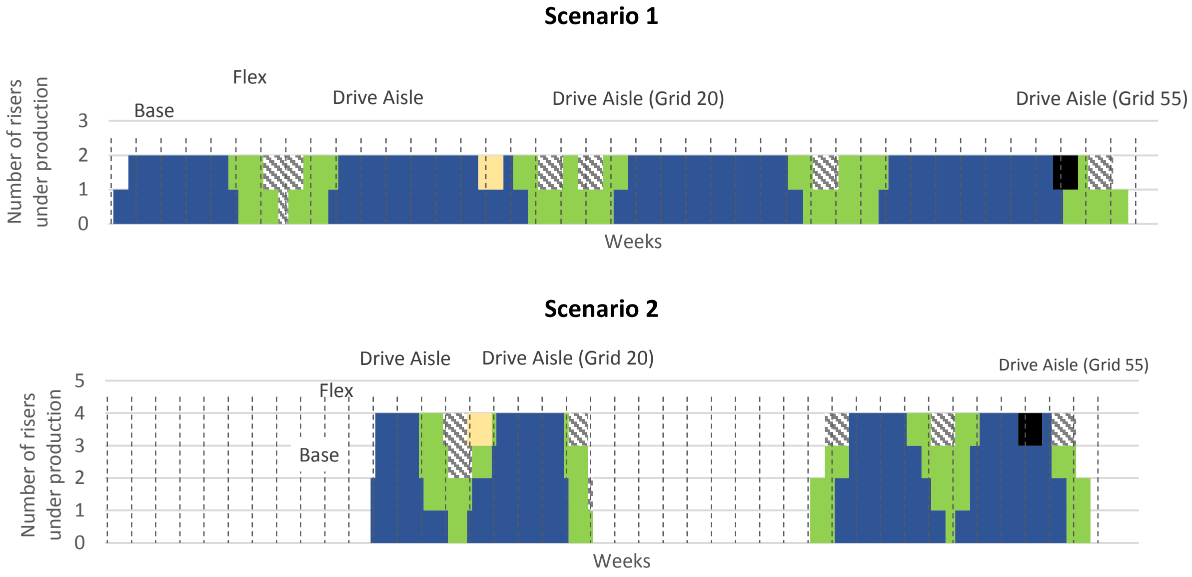


Figure 7.15: Production mix, for the scenario 2

Therefore, the production started with the modular risers so that they could be stored in a first in last out (FILO) fashion, facilitating inventory management. Figure 7.16 shows that the riser from the first shaft is delayed until the last responsible moment (LRM) to avoid unnecessary inventory of this kind of product.

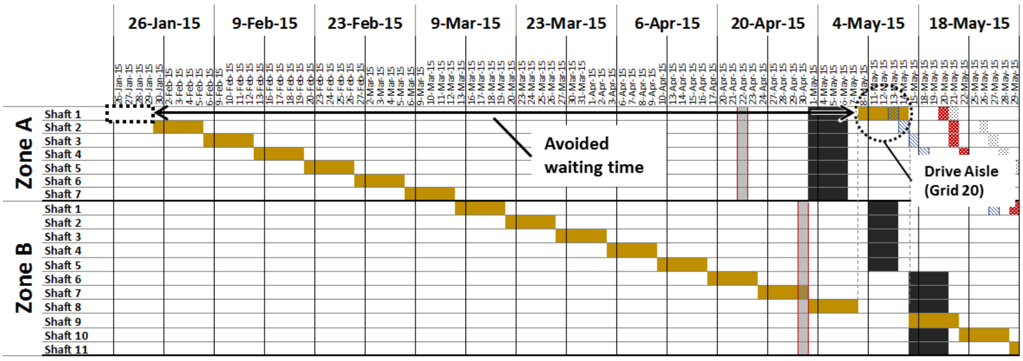


Figure 7.16: Delaying the production of the one-of-a-kind production

7.1.3.3 AHU

The Air Handling Units (AHU's) regulate the air circulation in the HVAC system. There were 90 units in the project. The critical part of this process was the storage constraints. The AHU's should be produced and sent directly to the site for installation. The GC also required that the wiring from the automation system to be installed in the fabrication facility, what could affect the lead-time of the final assembly. The fabricator of the AHU was hired by Company B.

The AHU's contains different types of components such as fans, filter racks, soundproofing systems, and dampers. The fabricator was able to produce the final assembly in up to three days, and could produce up to 16 units concurrently in the 8 cells of the plant. However, the production of the components could take up to 8 weeks, and there was not much room for design changing, since the design should be delivered 16 weeks before the final assembly. Given this, there was a need to send the designs early in the process, but the final assembly could be postponed to the last responsible moment. Figure 7.17 illustrates this production process.

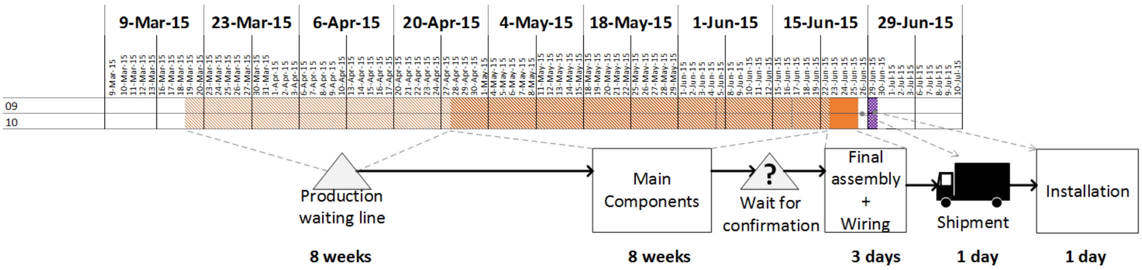


Figure 7.17: Main cycle times for the AHU production

Differently from the risers, there are almost 20 different types of AHU's (Figure 7.17), what makes it more important to confirm the production of the unit that can be installed in the field. Although there were long lead times before the final assembly take place, the storage of the components in this phase was not so critical. Therefore, it was possible to delay the moment to start the installation until a reliable trigger from the construction site.

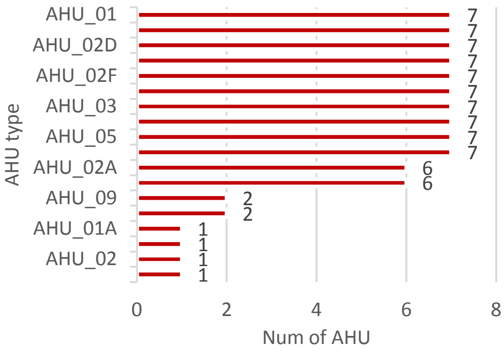


Figure 7.18: Type of AHUs

The first step of the analysis of the AHU's was to consider the installation as planned by the GC, which considered a large batch for the installation process, as shown in Figure 7.19. This first analysis exceeds the fabricator capacity, but it was developed as a tool for communicating with the fabricator, when the installation dates had not been confirmed. Although the analysis with the installation confirmed dates is shown in Figure 7.19, it required a broader understanding of the components that would be delivered in the roof-level, corresponding to the next section.

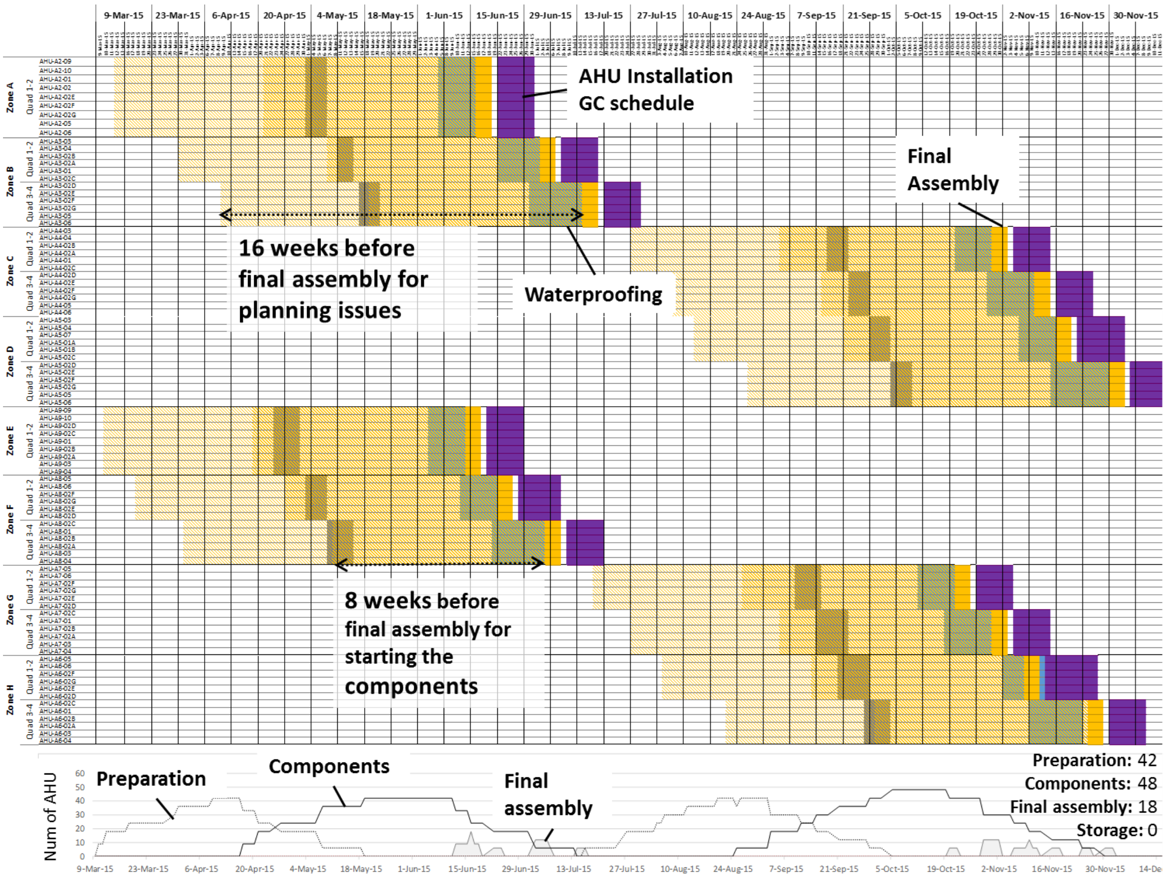


Figure 7.19: First scenario for the AHU’s production, according to the GC schedule

The important information used for discussing with the fabricator was the possibility to link the fabrication of the final assembly with the performance of the waterproofing in the field, to avoid producing an AHU that could not be delivered. The short lead time of the final assembly, together with the large capacity of the plant made it possible to have this kind of attachment. Similar to what happens in the second scenario for the risers’ fabrication. The difference is that the fabrication of AHUs can be triggered by the last activity that constraints the installation, which is the waterproofing, making the process more capable of dealing with the uncertainty from the site. It is worth noting that for the plant to be able to respond sharply to the construction site needs, the process must be very reliable. This was an important criterion for Company B to choose their suppliers.

Figure 7.20 reveals the second scenario based on a more detailed analysis on the crane usage, as described in the following section. In this case, there is an increase in the number of AHU at the preparation phase, which is in fact an inventory of detailed design; the production of components remains the same, but the number of units in the final assembly decreases for ten. As this is the most critical phase of the production, it reveals that the new scenarios fits better the fabricator capacity.

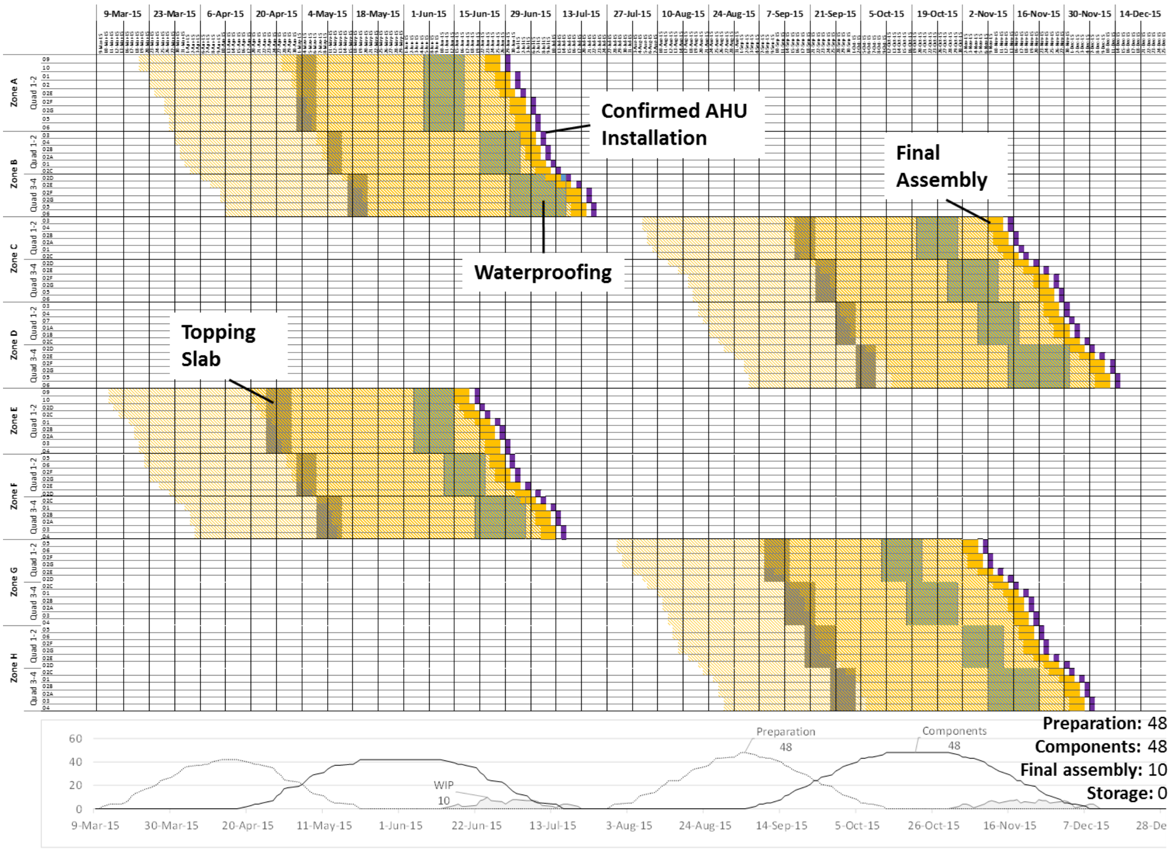


Figure 7.20: Second scenario for the AHU's production, according to the crane use

The possibility of delaying the final assembly of the AHUs was an important characteristic of this process; it made it possible to postpone the decision to start the most critical part of the fabrication process, waiting for the production in the field. The flexibility in the production mix is critical in this case. The fact that the very last activity in the field, namely waterproofing, can trigger the fabrication is a contribution for a more reliable process.

7.1.3.4 Penthouse

The penthouse was the most challenging installation area of the project, concerning the technical area between the roof and the last slab. In this area, most of the mechanical contractor activities starts after the waterproofing of the slab, and finishes when the structure of the roof is installed. Some fans and plenums installation were only dependent on the riser installation. The structure of the roof was a steel structure that would physically lock the installation work in the level, and made it unfeasible for further loading. The level of detail of the GC schedule was low, considering a large batch of installation spread along a certain amount of time, as shown in the mechanical equipment in Figure 7.21. This strategy was not matching the way Company B was going to do the work.

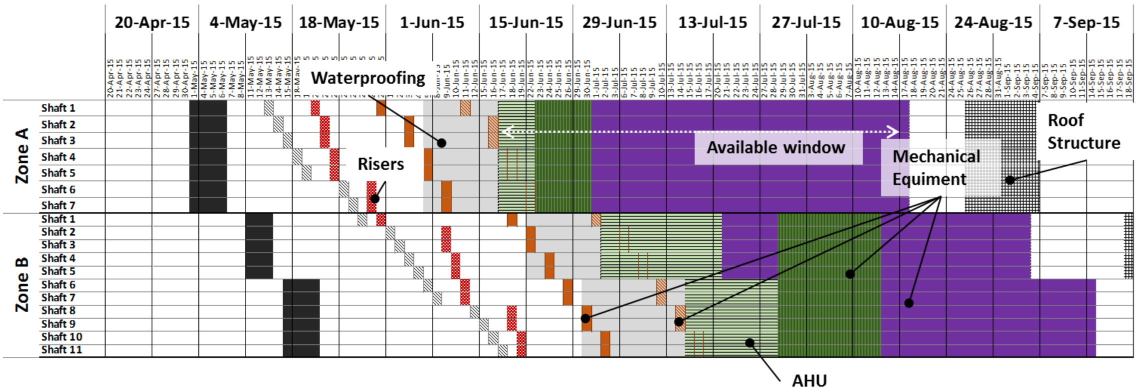


Figure 7.21: GC schedule of the penthouse

Considering the time Company B should perform each activity in the zone according to the GC schedule (Figure 7.21), the crane usage for zones A and B would look like Figure 7.22. Here the time for performing the activities was only divided by the number of smaller units of production to reveal the irregular use of the resources in this case.

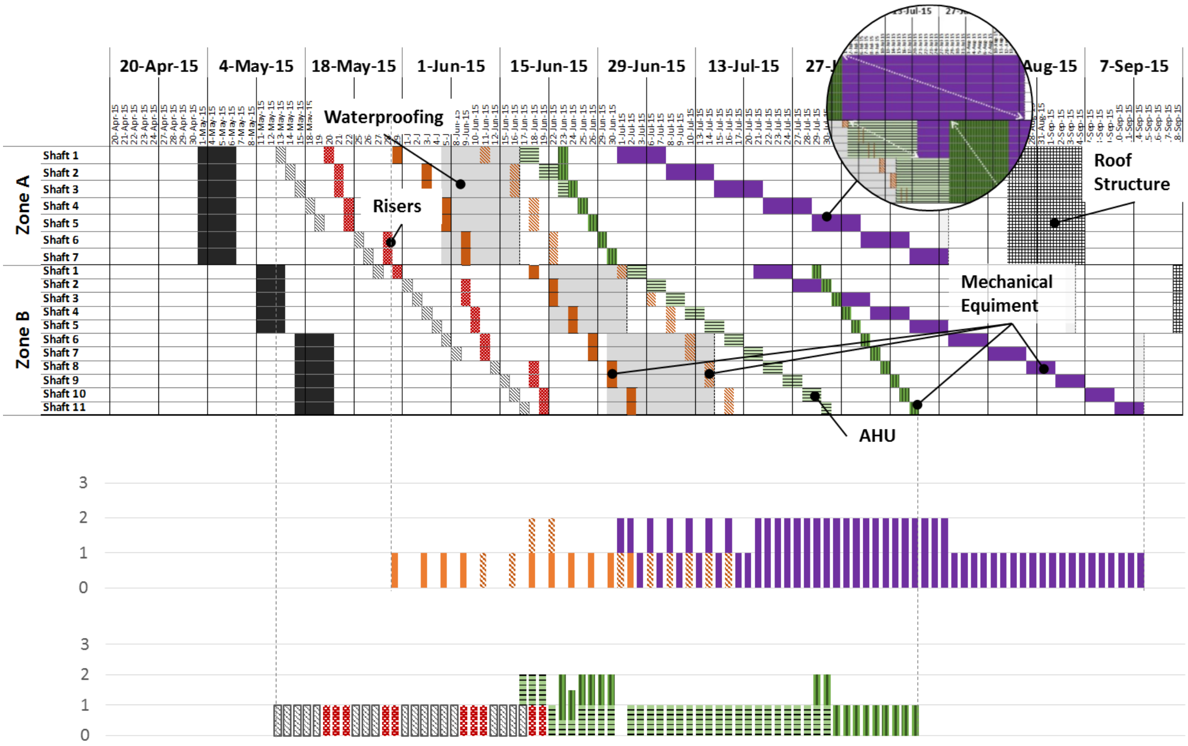


Figure 7.22: Crane usage Zones A and B according to the GC schedule

In order to avoid the misuse of the crane, the researcher in partnership with the dry side superintendent developed an accurate analysis of the delivery process, taking into account the loading capacity, trying to ensure a regular basis and a better use of the cranes.

Figure 7.23 shows the confirmed days of installation, and the number of cranes required in this process. By postponing the beginning of the installation of the mechanical equipment in the roof-level, it was possible to assure a more continuous flow of installation, which could also benefit the fabrication, as seen in the case of the AHU's and the fabrication of the ductworks of this area as well.

The representation of the required rhythm of installation for the penthouse ductwork allowed the fabricator to accommodate that demand in their shop. The LOB also facilitated the identification of logistic challenges due to the shared use of the crane among the different activities of the subcontractors, and also due to interaction between the subcontractor crane and the one from the glass installer.

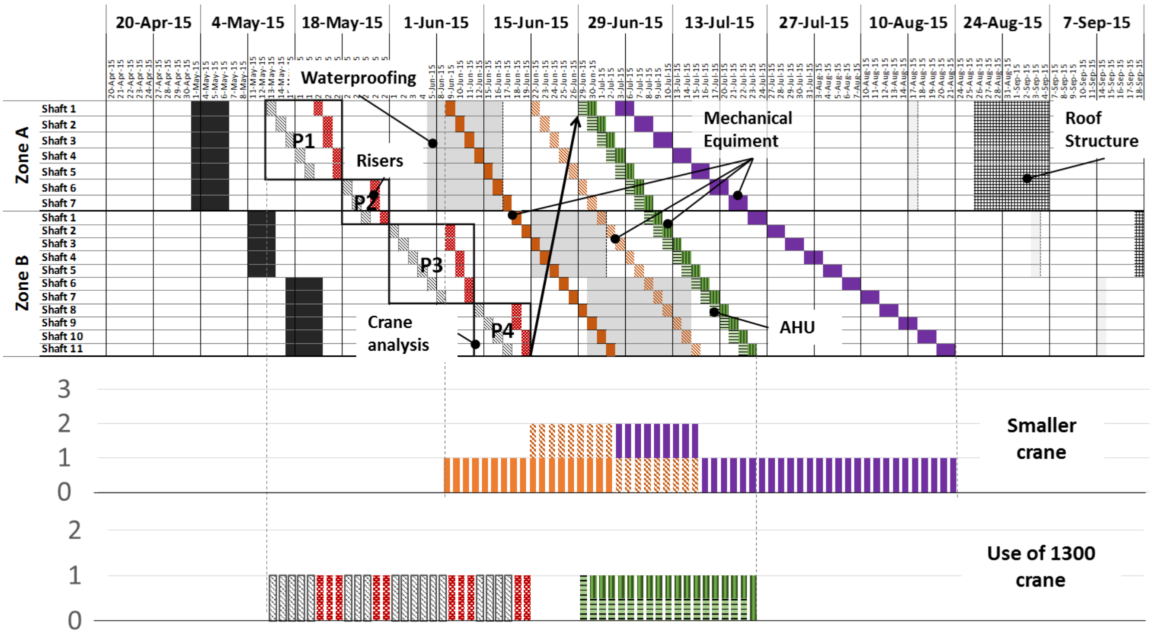


Figure 7.23: Considering GC schedule for crane usage

The analysis of this area of the building was also a source for the refinement of the AHU`s installation analysis, since the first confirmation of the installation dates were made, according to the main logistics constraints. As the project is under construction, there was a need to make new confirmations in the course of its development. This analysis was an important starting point for this understanding.

7.1.3.5 Lessons learned from the Piping

The critical phase of the piping process was the installation in the technical floor located in the building basement. The pipe spools should be delivered in a pre-assembled fashion attached to hangers in order to facilitate the installation. The spool drawings need to take into account the installation sequence, in order to show to the fabricator how to load the trucks. The size of the spools and the location of the hangers were restricted by the size of the truck.

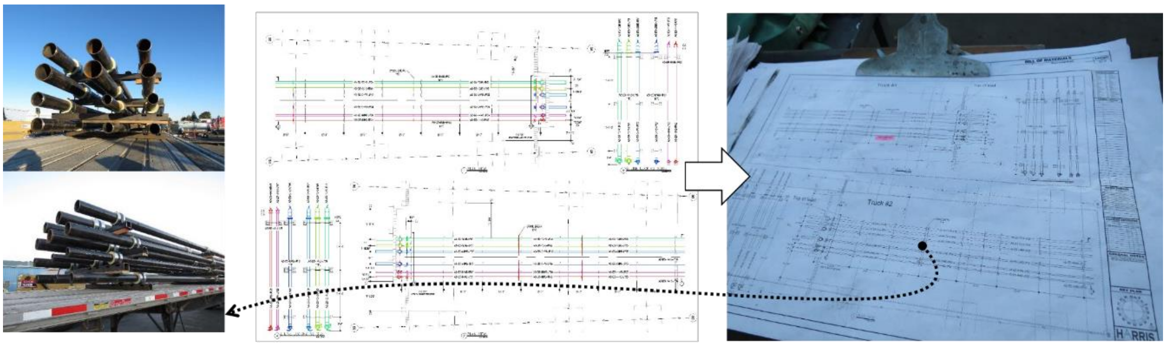


Figure 7.24: Example of integration between design and fabrication

When the study on Company B started, the process of fabrication of the piping was already going on. The researcher did not interfere in this process, but this close interaction between the design and the site installation sequence was an important insight for the final model of an integrated planning and control system.

7.1.4 Discussion

From the perspective of a mechanical contractor in a highly industrialized project, there was a need to understand the time available for the installation process, which was named as windows of opportunity given by the GC. Although there was an initial definition of milestones for subcontractors, those dates are frequently changed. This situation demanded subcontractors to have some degree of flexibility in order to fit the actual dates of the most critical activities on site.

Using a management-as-organizing approach for planning and controlling the project, the GC would frequently confirm dates and sequence of execution. There were two different cycles for those confirmations: (a) at the medium-term planning level, confirming through the development of the collaborative planning sections for three months horizon, monthly updated; and (b) in the site meetings, this carried out three times a week.

The challenge for the Company B was to develop a flexible production system, regarding the volume required, in order to absorb the fluctuations on the demand of their products. Although the GC works with a high level of detail, they acknowledge the need for those confirmations. In the case of the office ductwork, the GC committed for a minimum amount of time for Company B to work, even though the product and constraints have changed, actual data revealed that the window previously negotiated could be achieved.

The main strategy of the subcontractor for dealing with these dynamics in the construction site was to develop a backlog of ready products waiting for the installation. However, besides the size and the amount of products required, there was a lack of design definitions to start fabrication earlier in the process. In this kind of complex project, special attention is given to the activities in the critical path; the challenge for Company B was to be ready for the changing dates released by the main contractors.

The line-of-balance technique, showing only the most important information for each of the most critical activities, enabled a better communication between the subcontractor and the fabricator, between the subcontractor and the other trades, and within the subcontractor teams. This visual method allowed a better alignment among team members regarding the understanding of the schedule, mitigating the disagreements observed due to the multiple schedule versions and frequent changes. It was an important means for dealing with the high level of interdependencies and uncertainty of the project.

Therefore, the benefits were not only for the company but also for the different actors of Company B supply chain. The LOBs were used as a procedural tool to understand the interaction between activities and to provide a means to make decisions regarding the use of cranes and required due dates for design coordination. It enabled the teams to work with the most current version of the schedule, understanding the required rhythms for delivering and for site installation. Besides the communication improvements, the analysis raised the importance in thinking about the synchronization between fabrication and site installation and made the superintendents aware of the impact of the batch size reduction.

Generally, the starting point for these analyses was the schedule from the GC, including the most relevant activities; then, there was a process of confirming installation dates by analysing space and resources constraints; then, including information from the fabricator to develop different scenarios; and analyse the mix of products for fabrication.

It is worth noting that although the last planner system have been used for the project, from the subcontractor perspective it was hard to shield production in this phase of the project. There was a need to develop different communication mechanisms to confirm the production, and it was hard to avoid building some extra capacity, regarding fabrication and space for storage, in order to be able to deliver what the construction site need.

The period of time when this study took place did not allow the monitoring of actual production in relation to plans. Therefore the contributions of this study are mainly related to the improvement in the communication tools and the extent to which different constraints were considered.

7.1.5 Contributions to the final model

Regarding the development of the integrated planning and control model, the study on Company B had some contributions. Firstly, it was possible to observe closely the interdependency of the activities on the site. Therefore, the method for confirming the status of the construction site could be based on some important activities from the site. Comparing to the case from Company A, the process called **preliminary analysis of the sites**, could use this idea for developing a fabrication plan based on the triggers for each production stage. Depending on the size of the project, those triggers could be used in a continuous basis.

The integration of the design in understanding the site needs provide important benefits to the product modularity and ease of loading trucks. Before the fabrication of components started, it was possible to make a discussion among detail designers and site superintendents to ensure that the ease of installation and the less number of different parts have driven the process. Moreover, as it was the case of the piping process, this also enabled integration between the design and the logistics challenge for the delivery, requesting the fabrication according to the installation sequence. This connection should be present in the model.

Another important factor to be considered in the design process that facilitated the integration between the design-plant-site production units was the level of repetitiveness of the components. In the case of the risers, in which the 98% of the components were not for a specific area, enable the production system to be flexible in the case of having a change on the site production sequence. This kind of components can follow a make-to-order production strategy where a supermarket can help to control inventory. The production of the two one-of-a-kind risers was delayed until the last responsible moment for this production.

These contributions reveal that the relation between the design, fabrication and production on site should not be seen linearly. The synergy between design and the construction site is fundamental for the integration of the processes.

7.2 EMPIRICAL STUDY ON COMPANY C

This section is dedicated to the description of the study in Company C. It is divided in three parts. The first refers to the description of the technology, second, to the production planning and control system of the company. Third, the contributions to the final model are presented.

7.2.1 Description of the Technology

The head of Company C realized that in most cases the value of the structural system was not in its shape, but in its functionality. This was the starting point for the development of a modular system with a limited set of options. Using this mass-customized strategy, Company C was able to create a large number of design configurations. This decision was based on the needs of a specific market. The creation of each of the connections described here was focused on fulfilling the design requirements of a specific market segment, ranging from high-rise buildings to the industrial buildings.

The sections of the beams and columns provided by Company C are always the same: flange beams and squared columns, also called hollow-structural section (HSS) columns, which are connected through a set of three different types of connections: R-type (Figure 7.25), L-type (Figure 7.26), and the gravity connection (Figure 7.27). The differences between the L-type and R-type of connections are the size of the intersection it links, and the clearances allowed.

While R-type has a single component welded in the column, which constraint the depth of the beam to the connection height, L-type is developed to fit different heights. The latter connector is divided in two pieces welded to the beam, and other pair to the column, working as a trail to fit different dimensions. There is also the gravity connections used when no moment resistance is needed. It can be utilized around the perimeter of a building where there is less tributary load.

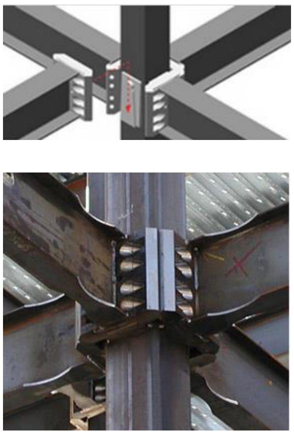


Figure 7.25: R-type connnection

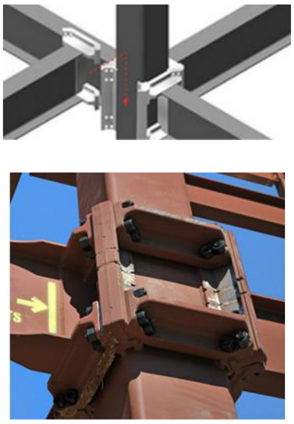


Figure 7.26: L-type connection

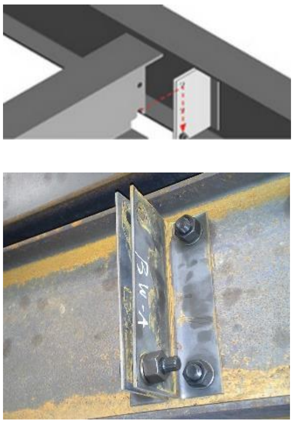


Figure 7.27: Gravity connection

Using the connections described above, the company is able to offer four different systems: R-type 100, R-type 200, L-type 300, and L-type 400. The number stands for the dimension of the square column in millimetres. Each system is supplemented with the use of gravity beams, where required. All the systems are able to support a building up to 12 stories. The R-type systems are ideal for 4 to 8 stories, while the L system for 2 to 10. According to the company records, the productivity of erection is higher in L systems since it covers larger spans, as shown in Figure 7.28

		Ideal for	Column size	Beam depth	Beam spans
R-type	**R-TYPE 100**	Small scale pipe rack structures and platforms for automated pallet retrieval systems	100mm	6" (variable weight)	4' to 16'
	R-TYPE 200	High-density residential and pipe rack projects.	200mm	12" (variable weight)	8' to 20'
L-type	**L-TYPE 300**	High-density residential and pipe rack projects	300mm	14" to 24"	12' to 30'
	L-TYPE 400	Healthcare, military, data centre, commercial office, institutional, R&D, parking and processing structures for industrial and energy & natural resource applications.	400mm	18" to 30" for SMF and deeper for OMF	18' to 45'+

Figure 7.28: Characteristics of the connection systems

The use of common shapes and sizes of structural elements was part of the company strategy to be easily supplied with their raw materials. The angle between pillars and beam starts from 90^o and can be increased in 7 degrees increments horizontally or vertically. Figure 7.29 illustrates the wide range of different structures that can be built using this technology

a. Hospital project **b. Pipe rack**

c. Residential Project **d. Office building**

Figure 7.29: Examples of projects using Company C steel structure

According to Duray *et al.* (2000), in this type of modular design, the customer is involved before the fabrication starts. Although Company C is not in charge of the design, the company collaborate with the design team during schematic design in order to determine how their system can be used to achieve the best results for the project. The development of the detailed design was facilitated by the use of a family of products that designers can incorporate in the building information model of a project.

For facilitating the specification of the company products, Company C developed a BIM components library of their products that can be used in different BIM application, such as Revit, ArchiCAD, Tekla, etc. This BIM tool facilitated the production of the design in accordance to the structural system constraints. Its use enables the designers to test product specification, since the very beginning of the design process, avoiding incompatible solutions, and reworks. In this fragmented supply chain, in which the design is separated from the fabrication, developing partnerships with designers were fundamental for the success of the tool use.

Using the modular design strategy, facilitated by the use BIM, Company C is reducing design lead times and the rework for turning schematic design into a shop drawings, for the manufacturing process. This strategy also enables the company to provide promptly cost estimates for the project. In an ETO environment in which the customer demands cost and time estimates at the very tender stage of the project (BERTRAND; MUNTSLAG, 1993; STEVENSON; HENDRY; KINGSMAN, 2005), these abilities are a very important for competitive advantage.

The main difference between Company C connection, and the previous developed beam-to-column connection systems, such as the one from the Advanced Technology for Large Structural Systems (ATLSS) center (FLEISCHMAN; VISCOMI; LU, 1991) was the way tolerances were considered. For making structural steel, the hot-rolled steel plates have a higher deformation, while cold formed steel components are more stable (GINZBURG, 1993). The tolerance for a sheet hot rolled of 305 mm width can have a thickness variation starting from 1,14mm, while in the cold rolled this variation start from 0,36mm (GINZBURG, 1993).

The collar connections are produced under a more rigorous tolerance control process allowing only a few thousands of an inch of variation. By contrast, the commodity beams and columns can lack dimensional accuracy, e.g. a squared section may be not precisely squared. This imposed a huge challenge in the manufacturing process of Company C. Instead of understanding this as an inherent characteristic, the company developed a set of jigs and fixtures in the manufacturing process to overcome dimensional intolerance.

This struggle for an accurate production process promoted the development of a series of standardized procedures for the production, eventually achieving some mistake-proofing processes. The welding of connection to the beams and columns is a critical process; here is where there is no room for tolerances. A jig is used to enable horizontal welding both in the beams and in the columns, as shown in Figure 7.30.

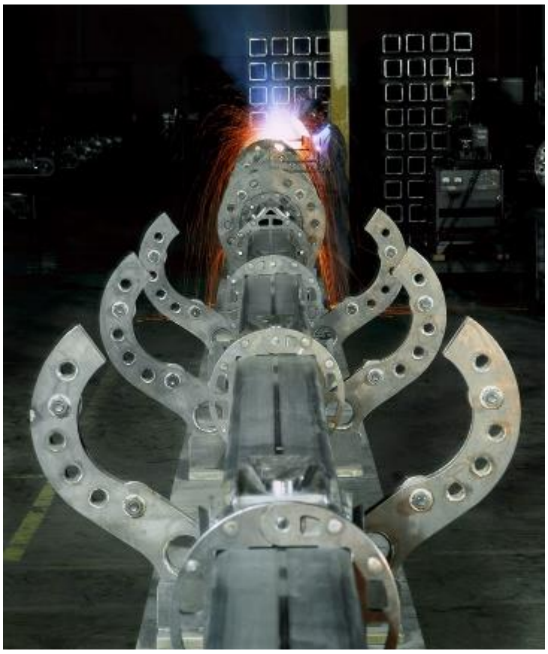


Figure 7.30: Jig to rotate beam assembly to allow for horizontal robotic welding

The welding process of the collar connections in the beams and columns is done robotically in order to achieve tolerances in the thousandths, regardless the tolerance of the structural component, as shown in Figure 7.31. The automated welding process could avoid alignment mistakes. Its accuracy was able to overcome allowable tolerance of the structural elements.

Figure 7.31: Robotic welding

In the construction site, one of the challenges of using such a precise connection system was the allowable tolerances in the foundations where the columns should be placed. The strategy adopted by the company was to decouple the uncertain and inaccurate process of construction to the foundation. To achieve that, the company developed a jig to precisely position the anchors in the foundation, as shown in Figure 7.32.

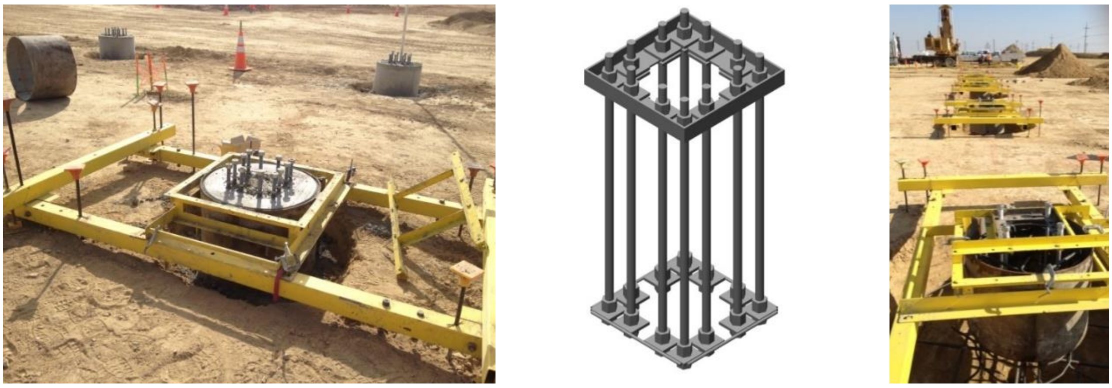


Figure 7.32: Jigs to position foundations correctly

After the anchors are in place, columns are delivered and erected first, one by one. Then, the interior of the columns are filled with concrete to enhance strength and stability. After the columns are ready, the beams are dovetailed in the columns. At this moment, the structure is already stable, and the workers can come for the bolting stage. It is worth noting that the building is erected full height, in small areas so that Company C quickly releases the structure for the remaining trades, as shown in Figure 7.33.

Figure 7.33: Example of the erection process

During the erection process, there is no need for field welding. Two workers are able to place the beam and make the bolting, as shown in Figure 7.34. The bolting process has a visual aid to avoid variability in the bolt tensioning; it is called Direct Tension Indicating (DTI) Squirter® washers. It consists of a nut with a flexible silicone embedded in the depressions under the bumps. The worker should tight the bolt until the calibrated amount of orange silicone appears from under the DTI's squirt locations, then stop tightening. Therefore, only visual inspection is required, reducing reworks in this process.

Figure 7.34: A worker placing the beam in the correct place

When technology developed by Company C started to be used in the market, the number of projects increased more than their production capacity. As a result, the company decided to develop a licensee program. In this program, they train a company to make the welding process using their standard procedures, and, in exchange, the licensee has to buy the connections from Company C.

According to a research report of the Construction Industry Institute (CII) (GOODRUM *et al.*, 2013), this kind of technology can make significant contributions to the overall productivity of steel construction. In that report, a cost and productivity comparison was made between the technology from Company C and the conventional method, analysing the processes shown in Figure 7.35. Data from nine different projects from Company C were used to provide evidence. The identification of the analysed processes, reveal a high number of production processes required in the conventional method. While in the conventional method, there is a need to make a first alignment, then installing temporarily bracing to finally make the permanent connection, using Company C technology when the beam is placed the connection lock the structure, so it is possible to make the final bolting quicker.

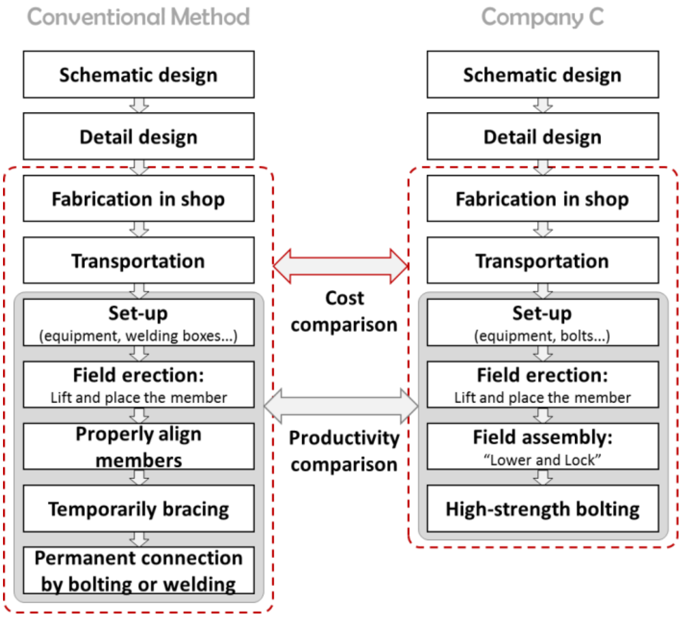


Figure 7.35: Differences on the production process between the conventional method and the Company C (GOODRUM *et al.*, 2013)

It is worth noting that for such an accurate process the fabrication has to deal with precise processes and machinery, making the cost for fabrication in Company C higher than the conventional. Figure 7.36 shows the results of the comparative analysis regarding cost and productivity from Goodrum *et al.* (2013). The unit used to measure productivity was men-hours per tons produced, so the less the better. These data indicates that the productivity of Company C's projects is much better than the conventional, while the costs are almost the same.

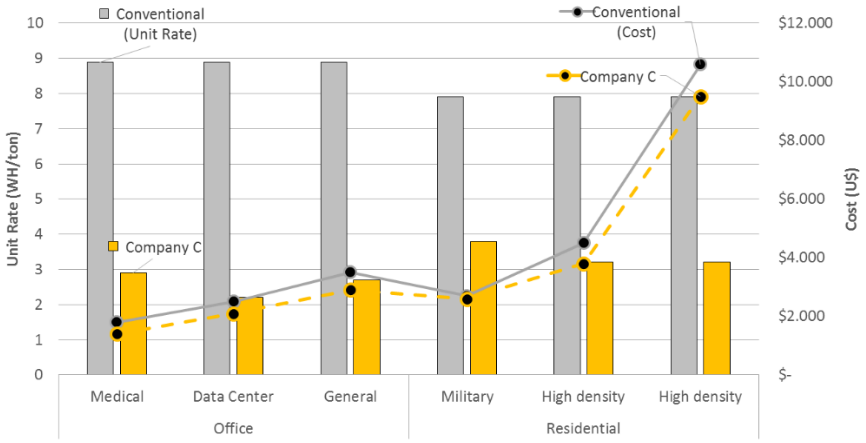


Figure 7.36: Productivity and cost comparison between Company C and RSMEANS (GOODRUM *et al.*, 2013)

This analysis made by the CII report is an important starting point for the understanding of this production system. It indicated that the company used much less men-hour resources in the construction site than the traditional methods, but without decreasing the overall costs.

This means that the fabrication process of this system is more expensive than the traditional and, therefore, the control over resources and over the lead time for the on-site production process are crucial for the project benefits from this system.

7.2.2 Production Planning and control System

As any engineer-to-order production system, the production only starts with a client order. Figure 7.37 shows a simplified Value Stream Mapping (VSM) of the production process, in which the process is started when the client places an order. In this phase the company assist the development of the design.

The structural elements were bought-to-order by a service centre, not directly from a mill, in order to decrease the delivery lead-time. The company had some partner suppliers in order to decrease buying lead times, but when a higher demand was required the use of common shapes and sizes, facilitated the procurement of these materials. The connections were produced by a foundry, and used to be bought-to-stock, as these are standard components.

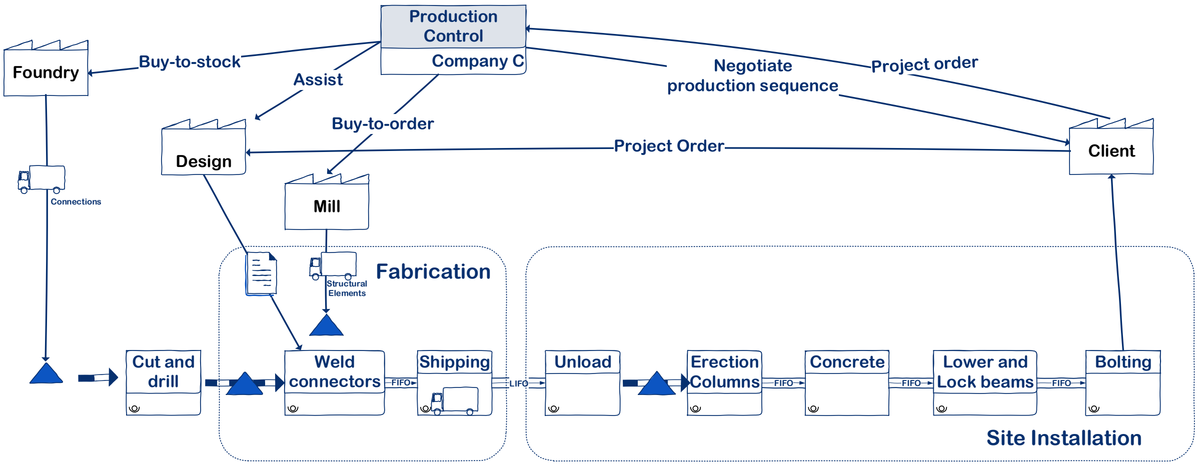


Figure 7.37: Simplified VSM

The first process in the plant is to cut and drill the connections, which is the longer process in the plant, taking up to 1h 18 min for an R-type and 3h for L-type to be produced. The process of welding connections in the structural elements uses a five-minute takt-time. This process is carried out uninterruptedly. The production sequence is established together with the client, according to the attack determined for the building.

The batching of products is made according to the size of the truck that delivers the products in the right erection sequence. This is an important characteristic of this production system.

The products are loaded in the truck in a last-in-first-out basis, so there may be adjustments in the batch to produce in the correct order.

Company C works with up to five different projects concurrently, while the welding process of the plant produce one project at a time. The main logistics objective of the company is the control over lead-time, which is one of the most important competitive advantages of the company. Here the focus on lead-times reduction is clearly established as more important than the maximum use of capacity.

The production in the plant follows standardized procedures and poka-yokes, as described in the previous section, to avoid wasting time on defect materials. Figure 7.38 depicts a typical schedule of a 3-story building of 5.000 m² (five thousands squared meters). It shows how the phases overlaps and the short time spent in the construction site in relation to the overall duration.

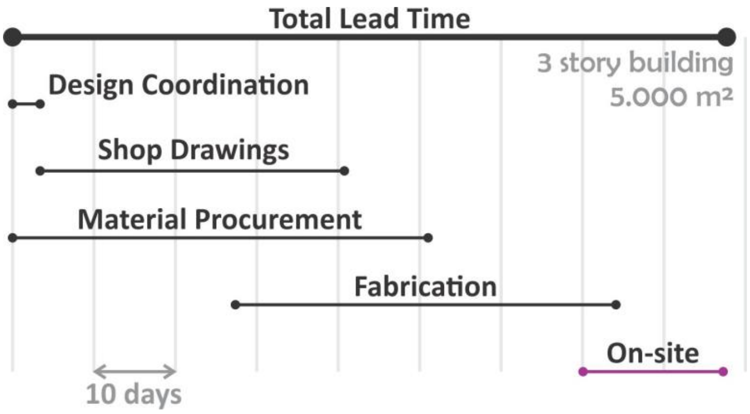


Figure 7.38: Typical project schedule

The logistics process in the site also benefits from the BIM tool developed by the company. Using the building model, it is possible to make a logistics plan for the construction site, including the phases of the project, use of cranes and lay down areas through 4D visualizations of the construction process, as shown in Figure 7.39.

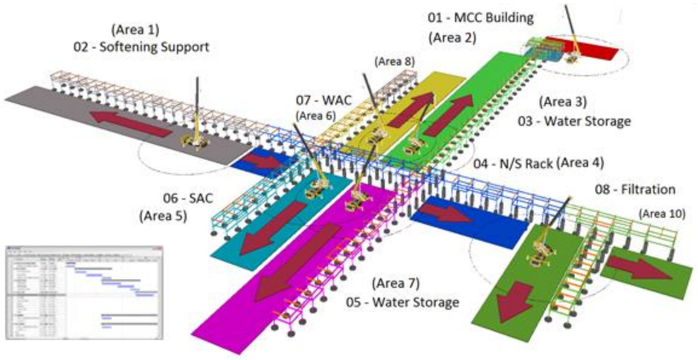


Figure 7.39: Logistics analysis

7.2.3 Contributions to the final model

The case of Company C reveals a different way of looking to the problems of planning and controlling ETO prefabrication systems, creating new assumptions regarding how components should be produced and even rethinking the role of the fabricator in the supply chain of the construction process. This was possible by overcoming the tolerance problem from the upstream process and creating reliable procedures for the production in the plant and in the construction site.

Figure 7.40 illustrates the main contributions to the model development highlighted by the analysis of this production system. The idea of simplifying the number of parts from the steel structure have a huge impact in promoting a better integration between the production units, since it enables shorter lead times and fewer mistakes during the production in the plant and site. The use of the information from the construction sequence for planning the plant avoids having inventory of structural components. Together with short lead-times this practice also become a strong tool for dealing with the uncertainties of the construction site, as long as it is possible to produce after important decisions on the site are made.

The tools used for reducing variability in the foundation reduce the unexpected errors while placing the structures. For this reason, after the foundation is placed, the erection process becomes a very reliable production process. In a traditional connection system, such as the one of Company A, there are misalignments between the components that have to be overcome in a critical situation in terms of safety, since structural components are hoisted and face difficulties to be bolted to the main structure.

Another important characteristic of Company C planning and control system is its logistics objective based on the project completion. There is no separation between the goal of fabrication and site installation, the focus remains on the final product. As pointed out by Wiendahl *et al.* (2005), this means that the plant is not using the maximum utilization if their capacity. In the case of Company C the target is the shortest possible throughput time, which means that a minimum amount of WIP is required.

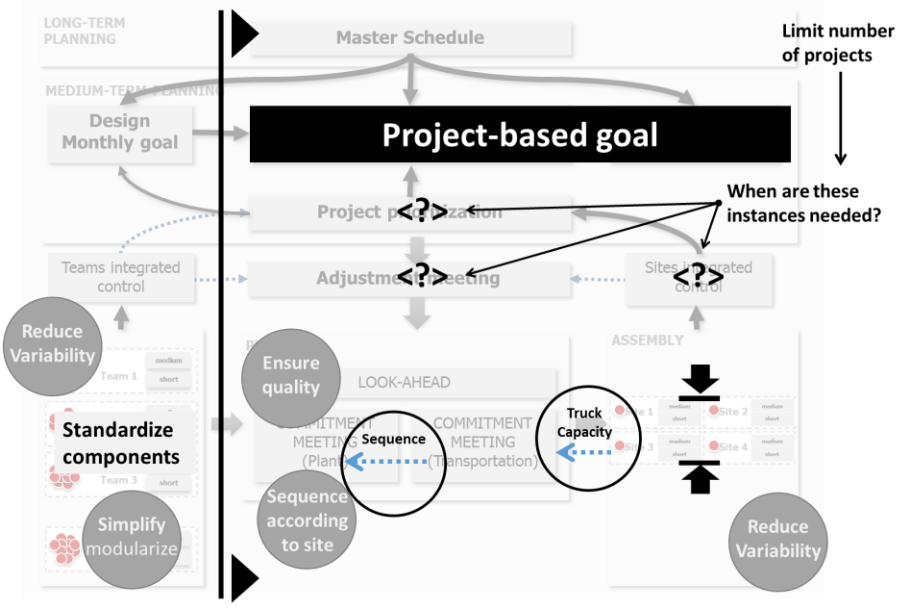


Figure 7.40: Contributions to the final model

The use of modular systems enabled Company C to strongly reduce the amount of complexity from this type of production system. The whole production strategy adopted provided less client interference, a reliable and predictable fabrication process, and less interference from other trades in the construction site. Although the company is able to provide different design configurations, the complexity of the production system is more similar to an Assemble-to-Order production system.

This decrease on the overall perceived complexity together with the small amount of projects carried out concurrently, highlighted the possibility to include the role proposed for the integrated planning instance in the model to the master schedule level, there would be no need to define a new planning and control process on this context. This possibility reveals the character of a countermeasure that this integrated instance plays in the planning and control model.

8 MODEL FOR INTEGRATED PRODUCTION PLANNING AND CONTROL ENGINEER-TO-ORDER PREFABRICATED BUILDING SYSTEMS

This chapter presents the final version of the model. The presentation of the model was divided into hierarchical levels. Section 8.1 provides an overview of the model. Section 8.2 presents a detailed description of integrated planning and control, which deals with project flow control, while Section 8.3 describes the modules of the model that deal with production unit control: design and engineering, manufacturing plan, and site assembly. Section 8.4 summarizes the discussion of the model. Section 8.5 discusses the evaluation of the model, based on the constructs described in the research method. Finally, in Section 8.6 the theoretical contributions of this investigation are pointed out.

8.1 OVERVIEW OF THE MODEL

Figure 8.1 shows the final version of the model, including the contributions from the previous empirical studies. The most important contributions came from the implementation on Company A. The integrated planning and control model is divided into four modules, one of them refers to project flow control, and the other three are concerned with different production units. In each module, planning and control is divided in distinct hierarchical levels. Therefore, the model is divided into a set of planning and control processes that are connected, in order to avoid a centralized push planning approach. Each planning and control process has specific roles, which are presented below.

Module 1 is responsible for converting the information from the master schedule into feasible plans to the production units. The aim of this module is to confirm the demand for the projects, using updated information from the production process. It deals with three different hierarchical levels. The information from the master schedule is confirmed using information from the construction site, fabrication and design production status. The process of confirming the schedule is the integrated look-ahead planning and control. This confirmed schedule is further developed into the look-ahead for each production phase, which will be further detailed for each production unit.

The design and the site assembly processes are the most affected by the client, making the projects in these phases more likely to be changed, or even halted. Therefore, besides the integrated look-ahead, there is also a short-term integrated planning and control process, which regards small confirmations realized by the Logistics Department, which could be responsible for the interface between all the production phases. This role of the Logistics Department is further discussed below.

In Modules 2, 3, and 4 the Production Unit Control is carried out. Each of these modules corresponds to a production phase, compounded by a number of production units. The planning and control approach proposed for these modules is the Last Planner System. Depending on the type of production, it deals with a different number of hierarchical levels. It is within the production units that the work is carried out. The actual information of the production process in each phase should be available in the master schedule, so that the look-ahead from the project flow control can be based on reliable data.

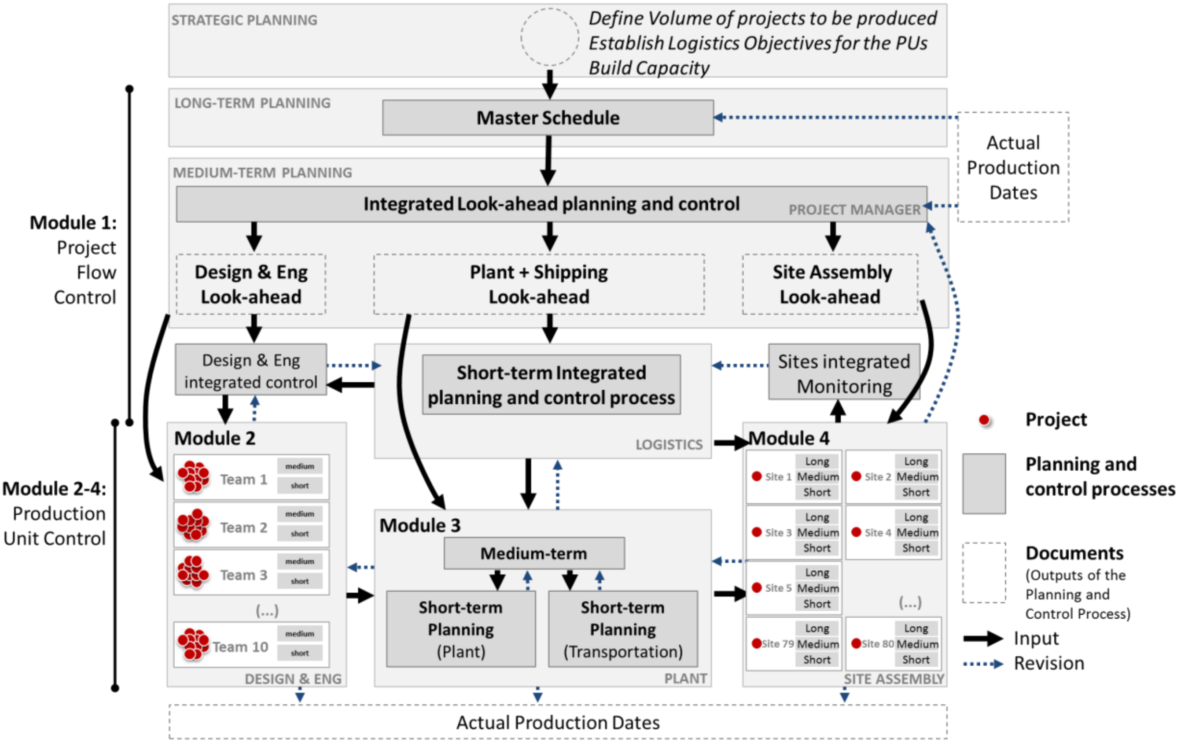
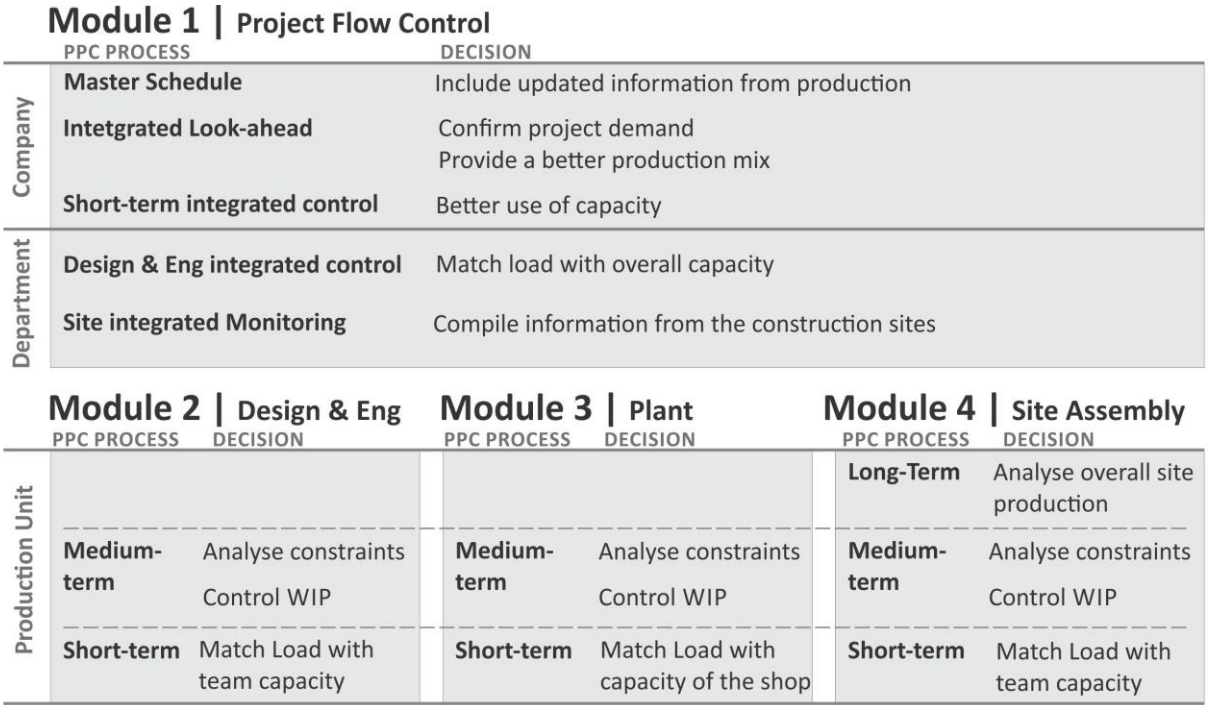


Figure 8.1: Final Version of the model

Figure 8.2 depicts the hierarchical levels on each of the modules of the model, and the main decisions that should underpin each planning and control process. The definition of those decisions is not meant to be the only ones to be taken, but the ones that differentiate the model from a management-as-planning approach.



Module 1 | Project Flow Control

	PPC PROCESS	DECISION
Company	**Master Schedule**	Include updated information from production
	Intetgrated Look-ahead	Confirm project demand Provide a better production mix
	Short-term integrated control	Better use of capacity
Department	**Design & Eng integrated control**	Match load with overall capacity
	Site integrated Monitoring	Compile information from the construction sites

	Module 2 | Design & Eng		Module 3 | Plant		Module 4 | Site Assembly	
	PPC PROCESS	DECISION	PPC PROCESS	DECISION	PPC PROCESS	DECISION
Production Unit					**Long-Term**	Analyse overall site production
	Medium-term	Analyse constraints Control WIP	**Medium-term**	Analyse constraints Control WIP	**Medium-term**	Analyse constraints Control WIP
	Short-term	Match Load with team capacity	**Short-term**	Match Load with capacity of the shop	**Short-term**	Match Load with team capacity

Figure 8.2: Important basis for decision-making for each production planning and control processes

The four modules depicted in the model refer to tactical and operational decisions. Tactical planning and control processes might be related to the company as a whole, a department, or a specific production unit. Operational planning and control processes are concerned with production itself and, for this reason, refer to production units.

At the strategic level, decisions typically refer to choice of relevant markets for the company, the number and volume of projects to be produced, and the investment to be made on building capacity. The strategic planning might be updated yearly and defines goals for the company as a whole, which are used to define priorities and incentives for different production units. At this level, it is important to avoid inconsistencies, such as trying to maximize utilization of capacity and reduce the work-in-progress, as suggested by Wiendahl, Von Cieminski, and Wiendahl (2005). This level of planning is not tackled by the model but its decisions affect lower levels of decision making.

The process for developing the master schedule is responsible for merging the long-term schedules of all the projects under development by the company. This master schedule should provide reliable information from the projects for each department. Based on the development of transparent plans, this master schedule could include both information of the schedules agreed with the client, and updated information from the production processes (design and engineering, fabrication, and site assembly). This transparency can be achieved by adding the confirmed days of production in the master schedule, and struggles for the less bureaucratic possible process for the update of the project schedules. As it is used as a communication and contractual agreements with the client, it is worth acknowledging that it is not possible to make frequent changes in the schedule of each project. However, the use of actual data together with the contractual dates enable a better planning in the more operational levels.

The main production planning and control process in the first module is the integrated look-ahead planning and control, as illustrated in Figure 8.3. It refers to tactical decisions to define what is important for the production units by confirming the demand of projects based on the construction site status and also based on the design, and fabrication capacity. As it is focused on the project as a whole, it should be conducted by the project manager, or another project representative. The challenge of this process is to develop plans that do not affect the main milestone from the master schedule of the project with a confirmed demand, but still providing a good production mix for each phase. The main outputs of this process are integrated look-ahead plans for the three main production phases: design and engineering, fabrication plant, and site assembly, represented by the adjusted look-ahead. The number refers to the processes that are connected across the modules.

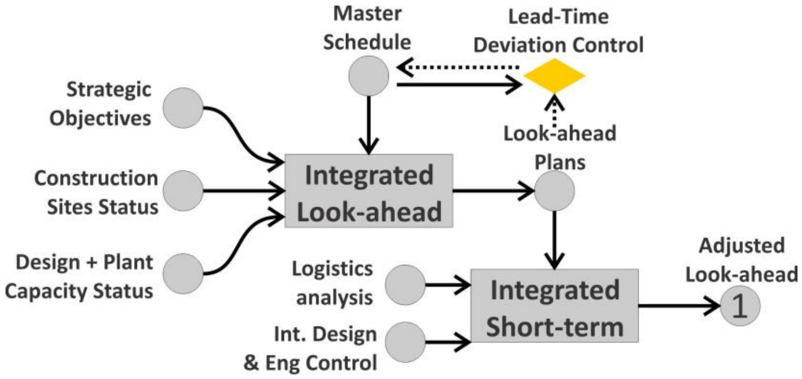


Figure 8.3: Project Flow Control Level (Module 1)

The look-ahead generated from this process is confirmed by the Logistics Department in a short-term integrated planning and control process. In the proposed model, the Logistics Department is considered as managerial process responsible for more than the shipping process, managing the demand for project batches, using the connection this department has with the site assembly process in the different production sites. This role played by the

Logistics Department could also be carried out by a Supply Chain Management Department, in the case of a less vertical integrated ETO companies. Those responsibilities were called as “Logistics analysis” in Figure 8.3. The relationships of the logistics with the different departments are illustrated in Figure 8.4.

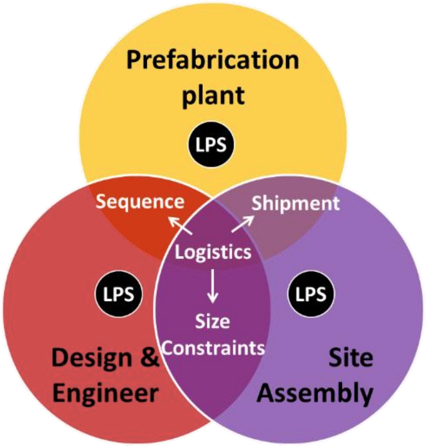


Figure 8.4: Logistic roles in the interaction between the production units

In this process, the most important definition refers to a “better use of capacity”, which means the analysis of the batches of projects required by the construction sites, helping the production units not to increase the amount of WIP of products that cannot be shipped. An important source for this process is the compiled information from all production units in each department. In the case of the plant and site assembly, this source can be provided through a document merging the plans for the PUs. In the case of the design, where there is a higher uncertainty in the process of design approval, there is a specific planning and control process that is the design and engineering teams integrated control. In this process, the demand of each team is compared to avoid delays due to overloading.

Figure 8.5 shows a suggestion for the definition of the planning horizons and how they feedback one another, based on Company A production planning and control system. It is not possible to generalize the planning horizons for the model, since it depends very much on the level of uncertainty involved. Here it is suggested the development of the look-ahead for the departments as a rolling plan of 6 weeks, avoiding the constraint over the month period. This planning horizon could not be applied because of the internal month-based monitoring procedures.

The look-ahead for the fabrication and shipping should be the same, and be based on the information from construction sites. The Design and Engineering look-ahead, in turn, should be defined according to the design coordinators decision, regarding the situation of design approval and risk of design changes. The project managers should have the information about when the site assembly process is able to start, whereas the design coordinator can predict which projects are more likely to have a final approval or definition from the client.

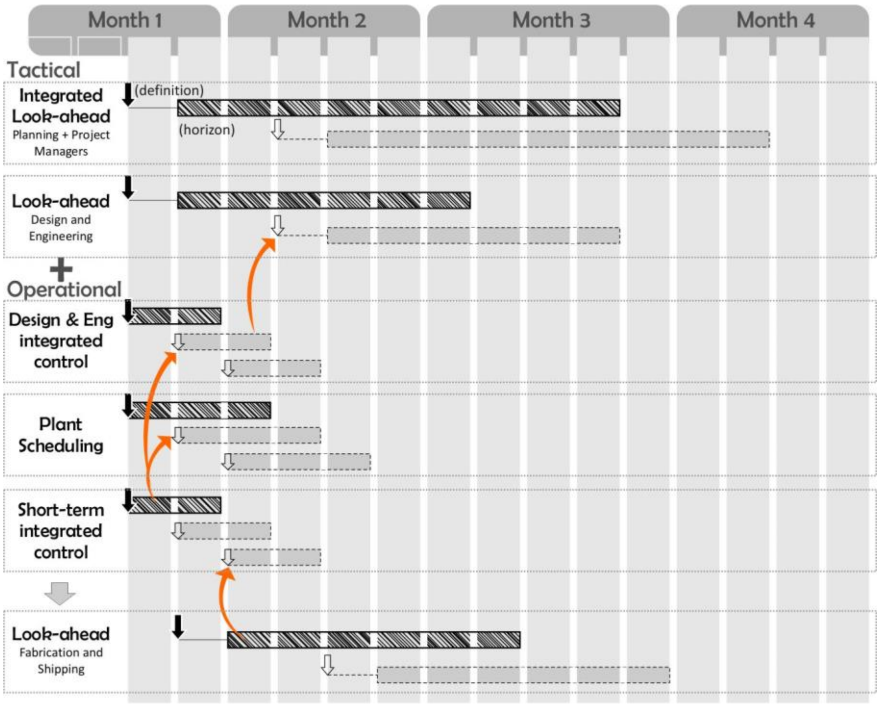


Figure 8.5: Relationship between the different planning horizons

The control mechanism at the short-term integrated planning and control process should use a shorter horizon, being suggested a weekly basis for Company A. This is where the adjustment meeting took place, in Company A. There is a need to reconfirm the requirement of the site assembly processes for the projects. At the operational level, there is a weekly control within the design and engineering and in the plant. In this regard, it is important to use the same horizon in both of these processes, to be able to deal with the changes in the production units, which affect the production of further processes.

Figure 8.6 illustrates the relationship between the two main levels of control. The project flow control makes a holistic analysis of the main production phases of the project, while the production unit control is responsible for the specific production decisions of a given production phase.

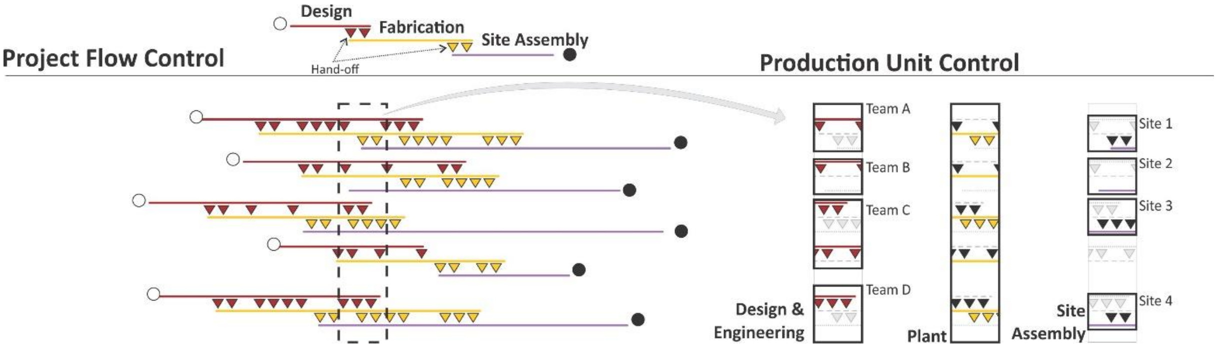


Figure 8.6: Relationship between Project Flow Control and Production Unit Control

8.2 PROJECT FLOW CONTROL (MODULE 1)

In the project flow control, there is a need to understand the flow of the projects through the production units, providing guidelines for the decision-making on the operational planning and control level. As this model is based on a management-as-organizing approach, there is a need to develop rolling plans, where the demand for a project is frequently confirmed, so that it is possible to learn in the planning process from what happens in production.

The overview of the projects is given by the master schedule. Although it would not be possible to make frequent changes in this schedule, the same tool that share the information about the master schedule should reveal actual production data, as suggested in **Erro! Fonte de referência não encontrada.**. Therefore, the project batches that have already been scheduled in the PU short-term appear as “confirmed”, and can be marked as “halted” if there is a problem in the execution. This provides a better source of information for the other production phases to understand the status. **Erro! Fonte de referência não encontrada.** is based on the tool used by Company A, which used to reveal only planned and actual dates, avoiding each production phase to understand what was under production in the previous or following phases.

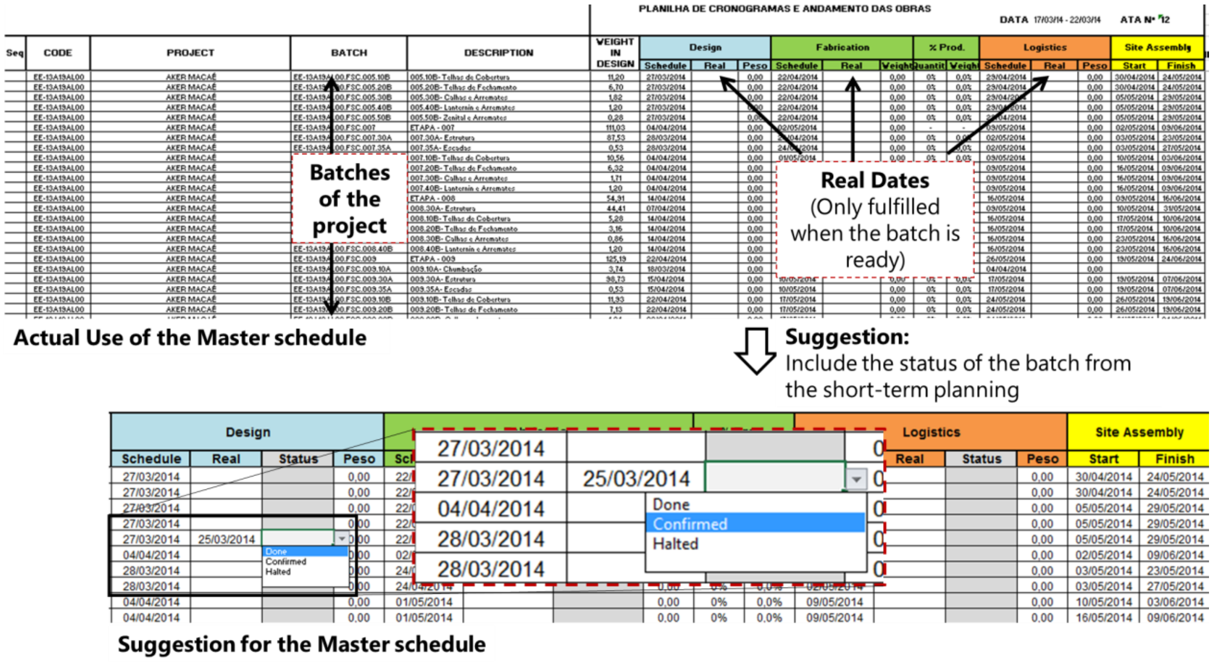


Figure 8.7: Suggestion for having updated information in the master schedule

The most important process of project flow control is the integrated look-ahead, since it enables a reassessment of the data from the master schedule, creating strategies to meet important dates and delaying projects with no site demands. In the empirical study in Company A this process was carried out by the Planning Department, who conducted the prioritization meeting, and was responsible for gathering short-term information from the Design and Engineering, Plant and Logistics Departments to develop the monthly targets.

In that study, the aim was to provide information about the status from construction sites to make it possible to revise monthly targets. The practice used by Company B could be adapted by some of the most complex projects of Company A. Instead of giving a status for the construction as a whole, in some cases project managers could analyse the most critical activities constraining the production under their scope, managing the window of opportunity they have to perform the work. These activities can be either from the same company or from another contractor, as it was the case in Company B.

Both the empirical studies A and B revealed the difficulty of having a flexible master schedule. One of the reasons is the contractual role of this document. In Company A, it reflects the contractual agreement established with the client, so that any change in the master schedule would cause a timely contractual change. In the case of Company B, the master schedule was established by the GC, and determined most of the contractual constraints for hiring the sub-contractors. The on-site production plans need to be confirmed through several stages. Figure 8.8 illustrates the relationship between the plant and the construction process, revealing the possibility to confirm the fabrication sequence with some activities going on in the construction sites.

It is clear that in an environment where a large number of projects are required it is not possible to analyse those triggers in detail for every project. Company B was able to work like this because the analysed project was very large, and they were able to have a dedicated office, with around 15 technical staff. In the case of Company A, project managers have to deal with a large number of projects. However, in the case of large projects for very relevant clients a similar solution could be adopted by that Company, allocating a specific team for those projects. A dedicated team could help in the implementation of accurate confirmation mechanisms.

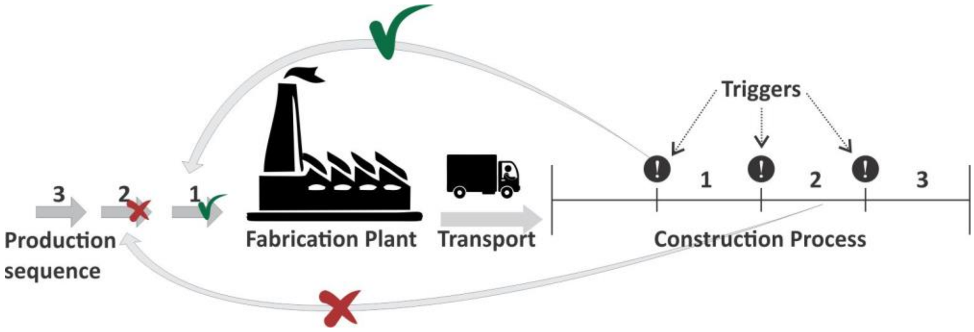


Figure 8.8: Illustration of the confirmation process, through the use of triggers from the sites

As the aim of this level of control is to ensure project flow, there is a need to control the overall lead times, based on confirmations of demands from construction sites. Bertrand and Muntslag (1993) suggest that in ETO production systems, work in production units should be released by the team in charge of project flow control[1]. Therefore, the output of the project flow control should be a look-ahead production plan for each department, which in fact reduces the role of the look-ahead planning within each production unit.

The adjustment planning from Company A was considered as an integrated short-term planning and control. Analogously to the empirical study, this planning and control level is responsible for making small adjustments in the look-ahead plans. This process should be understood as a countermeasure of the system, required according to how complex is the system. The development of transparent plans for each production unit, with some degree of information technology to signalize important issues might make the establishment of the

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[1] The original paper of Bertrand and Muntslag refer to this level of control as “Goods Flow Control”, which is a generic term for any ETO environment. In this investigation, it is rather used the project flow control because it is specifically related to the development of building systems for specific construction projects.

integrated short-term planning and control process useless. The implementation case in Company A reveals that the more reliable were the information for carrying out the meetings, the less time consuming they were.

Therefore, this process is considered a countermeasure, since it increases the need for developing different plans, and carrying out meetings, due to failures in higher levels of management, or due to unexpected events. The decision of designing new production planning and control system using this integrated short-term instance will depend on how complex this production system is perceived. In the empirical study C, different strategies for reducing the complexity of steel structural systems were discussed. In that study, that level was not necessary, since the information from the site was directly connected to the project flow level of control.

The integrated short-term planning and control process provide the adjusted look-ahead for the PUs. However, it is slightly different from the process proposed in the Last Planner System, which focuses on the identification and removal of constraints for ensuring the project flow. The role of this planning and control level is to provide updated information for the better use of the available capacity, avoiding the inconsistent logistic objectives, and providing a sequence of projects to be produced according to a confirmed demand.

In the case of Company A, the decisions made within the production unit had to be reassessed from the point of view of the department as a whole. Especially in the case of the Design and Engineering Department, in which the teams were not aware of the load of work from one another. The implementation of an integrated control of the Design and Engineering Department was crucial for understanding the main problems in delivering designs to the plant. By using a visual device at this level, plans became more transparent and the workload could be better distributed among the design teams. This process is also important for the plant to have confirmed dates about the delivery of projects, facilitating the planning of the following period.

In the case of the site assembly, Company A did not implement an integrated monitoring of the sites. The role of collecting short-term and analysing information from site assembly was taken by the Logistics Department. However, this was done informally, only for the projects they considered more critical, not in a comprehensive and systematic way. In the site assembly there would be no need for a jointly analysis of the capacity of the sites, since they seldom make use of the same resources. Rather, it would be important to have a document compiling that information.

During the implementation of the adjustment meeting, the Logistics Department were able to provide and confirm some important information from construction sites for the plant and Planning Department. As this model is a proposition of the best possible practices analysed, it is suggested that the logistics department should incorporate this role of integrating the information from the sites in a systematic way (cf. Figure 8.4). The inclusion of this role under the Logistics Department scope would require for this department a more tactical view of the project production, being responsible for the systematization and sharing of the most important information to integrate the production system.

When considering plant production, in this planning and control process information from the design and from construction sites should be used to define a feasible and useful plan. In terms of feasibility, this plan should consider constraints imposed by the client during the design phase that might hold the release of the project to fabrication. Useful refers to the demand of the products to be fabricated by the construction sites.

8.2.1 Performance Metrics

A set of performance measures have been suggested in the model for project flow control:

a) Adherence to the monthly target (Figure 8.9): it can be measured by the volume of work produced (e.g. tons of steel, gross floor area or volume of concrete), in relation to the planned target. It is important to use the final product as a basis for this metric.

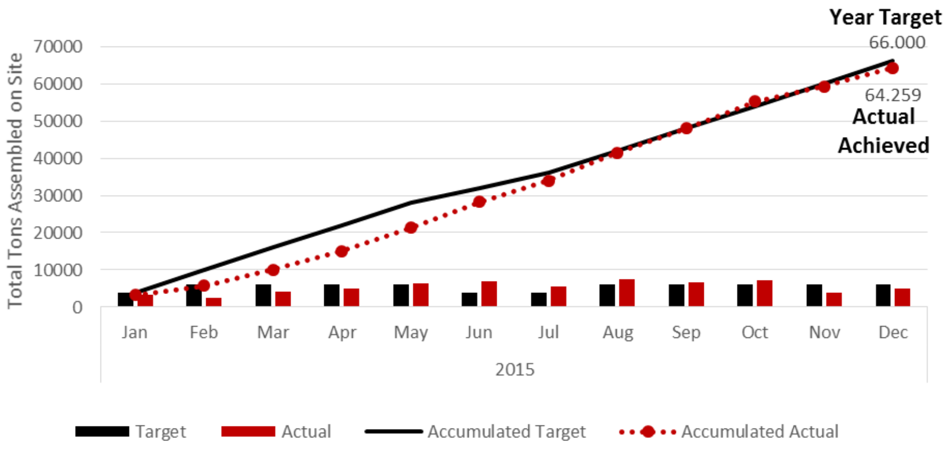


Figure 8.9: Adherence to the monthly target

b) Adherence to look-ahead batching sequence (Figure 8.10): it can be measured by the percentage of batches included in the look-ahead plan that were actually produced. For calculating this metric, completion control should divide batches in categories, such as planned and produced, planned and not produced, not planned and produced;

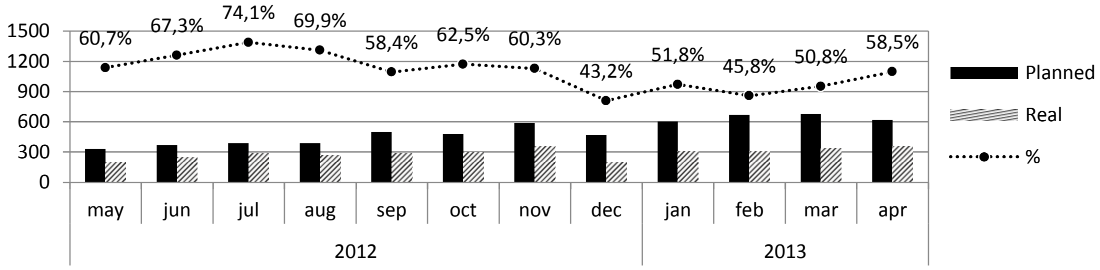
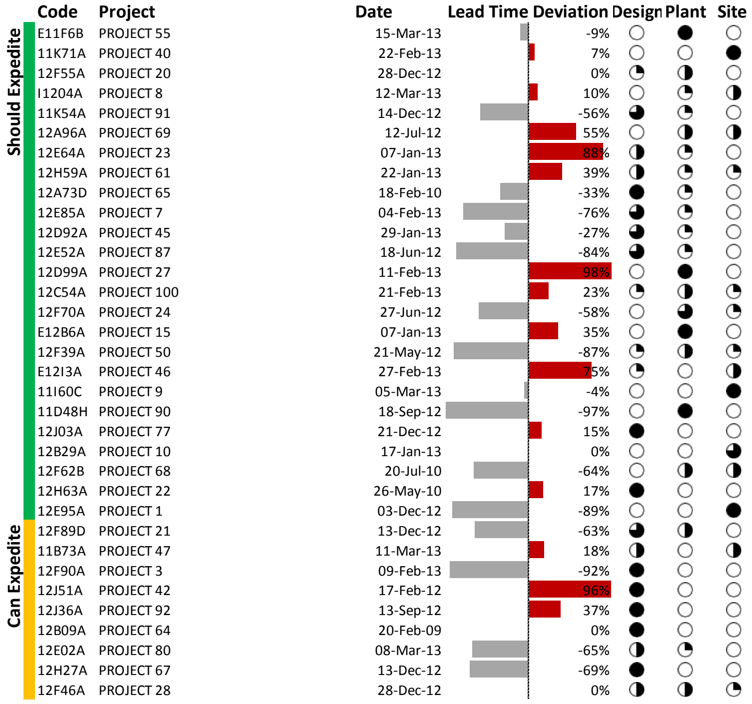


Figure 8.10: Adherence to look-ahead batching sequence

c) Lead-time deviation control: this measure should be based on the actual predicted lead-time of the project minus the lead-time planned divided by the planned lead-time. A positive deviation means that the project is in delay. This metric should be analysed together with the overall situation of the projects should include the project name, the type of building, current phase of production and overall lead time (Figure 8.11), so that the top managers can have an overall picture of deliveries, delays and stopped projects.



	Code	Project	Date	Lead Time Deviation	Design	Plant	Site
Should Expedite	E11F6B	PROJECT 55	15-Mar-13	-9%	○	●	○
	11K71A	PROJECT 40	22-Feb-13	7%	○	○	●
	12F55A	PROJECT 20	28-Dec-12	0%	◔	◑	○
	I1204A	PROJECT 8	12-Mar-13	10%	○	◔	◑
	11K54A	PROJECT 91	14-Dec-12	-56%	◕	◔	○
	12A96A	PROJECT 69	12-Jul-12	55%	○	◑	◑
	12E64A	PROJECT 23	07-Jan-13	88%	◑	◔	○
	12H59A	PROJECT 61	22-Jan-13	39%	◑	◔	◔
	12A73D	PROJECT 65	18-Feb-10	-33%	●	◔	○
	12E85A	PROJECT 7	04-Feb-13	-76%	◕	◔	○
	12D92A	PROJECT 45	29-Jan-13	-27%	◕	◔	○
	12E52A	PROJECT 87	18-Jun-12	-84%	◕	◔	○
	12D99A	PROJECT 27	11-Feb-13	98%	○	●	○
	12C54A	PROJECT 100	21-Feb-13	23%	◔	◑	◔
	12F70A	PROJECT 24	27-Jun-12	-58%	○	◕	◔
	E12B6A	PROJECT 15	07-Jan-13	35%	○	●	○
	12F39A	PROJECT 50	21-May-12	-87%	◔	◑	◔
	E12I3A	PROJECT 46	27-Feb-13	75%	◔	○	◑
	11I60C	PROJECT 9	05-Mar-13	-4%	○	○	●
	11D48H	PROJECT 90	18-Sep-12	-97%	○	●	○
	12J03A	PROJECT 77	21-Dec-12	15%	●	○	○
	12B29A	PROJECT 10	17-Jan-13	0%	○	○	◕
	12F62B	PROJECT 68	20-Jul-10	-64%	○	◑	◑
	12H63A	PROJECT 22	26-May-10	17%	●	○	○
	12E95A	PROJECT 1	03-Dec-12	-89%	○	○	●
Can Expedite	12F89D	PROJECT 21	13-Dec-12	-63%	◕	◑	○
	11B73A	PROJECT 47	11-Mar-13	18%	◑	○	◑
	12F90A	PROJECT 3	09-Feb-13	-92%	●	○	○
	12J51A	PROJECT 42	17-Feb-12	96%	●	○	○
	12J36A	PROJECT 92	13-Sep-12	37%	●	○	○
	12B09A	PROJECT 64	20-Feb-09	0%	●	○	○
	12E02A	PROJECT 80	08-Mar-13	-65%	◑	◔	○
	12H27A	PROJECT 67	13-Dec-12	-69%	●	○	○
	12F46A	PROJECT 28	28-Dec-12	0%	◑	◑	◔

Figure 8.11: Overall situation of the projects

d) Effectiveness of the confirmation process: this can be indirectly measured by the amount of material waiting on the plant yard (Figure 6.31). In this metric, the total amount of products in one day is divided according to two main information: if the production have already finished its batch, and if it is halted by client, constrained by the client or if it is ready to be shipped.

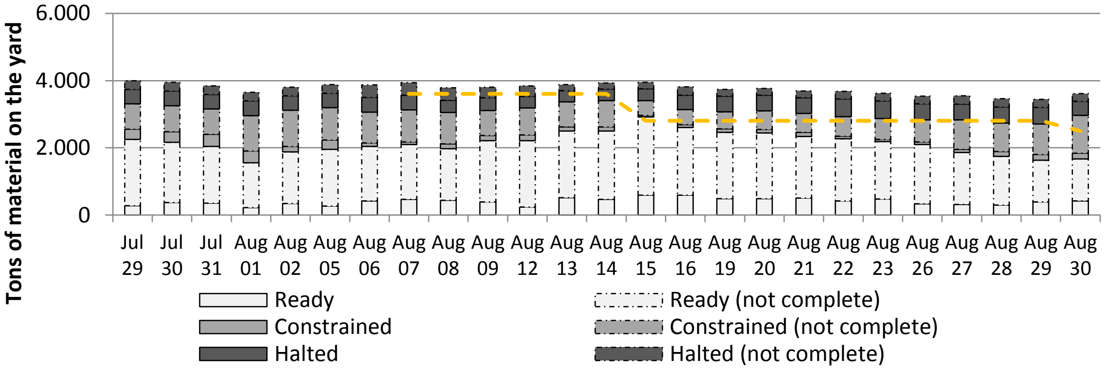


Figure 8.12: Amount of components in the yard

It is worth noting that in the ETO environment, the costumer is waiting for receiving the final assembled product, namely the building system in this investigation. It means that while the site assembly is not finished, the ETO company is spending resources on that project. Even considering that the higher proportion of the payment simply depends on the delivery of components, it is important to ensure that the final product has been delivered to the client according to the company policy.

8.3 PRODUCTION UNIT LEVEL (MODULES 2, 3, AND 4)

At the production unit level, the workload must be matched with the available capacity. The use of the Last Planner System at this level is very important to enable the development of reliable plans and to make the production units aware of their actual capacity. This level of planning in each production unit, especially from site assembly units, provides feedback to project flow control, enabling the development of more reliable plans at that level.

It is within the production unit that the decision about what is going to be produced is made. However, this decision should follow the main guideline from the integrated look-ahead process regarding the importance of each project. This level should also follow a strategic guideline regarding the amount of allowable WIP and the volume of production required. As a result, the project flow will determine how much should be produced, while the production unit will determine which specific products can be produced. The key principles of the LPS must be adopted at this level.

Since the beginning of the implementation in Company A, the transportation of material to the site was suggested to be considered as part of the plant goal. It is worth noting that the company does not benefit from fabricating to the yard. Therefore, the goal of the plant should be to deliver the components to construction sites, ensuring that the products fabricated are the ones required or, at least, the ones that can be shipped. For this reason, a unified plan plant and shipping was considered.

This consideration was also important to avoid one of the stumbling blocks highlighted by Wiendahl, Von Cieminski, and Wiendahl (2005), the missing responsibility for inventories. While the plant could produce without taking into account the amount of products stacked on the yard, it would not change its production strategy in order to avoid that. Therefore, it is only after attending the priorities established by the integrated look-ahead, that the logistics processes can think about the shipment in terms of freight optimization, analysing how to deliver efficient loads for different sites.

8.3.1 Design and Engineering Department (Module 2)

The combination of the production units from the Design and Engineering Department compound the second module of the model. Each of these production units has to deal with multiple projects and, therefore, there is a need to perform the integrated control of the department, analysing the workload, and delays for each team jointly. Using the deliberations from this plan, the design team can proceed with the constraint analysis and commitment with the projects batches without constraints. Figure 8.13 shows the production planning and control process in this module.

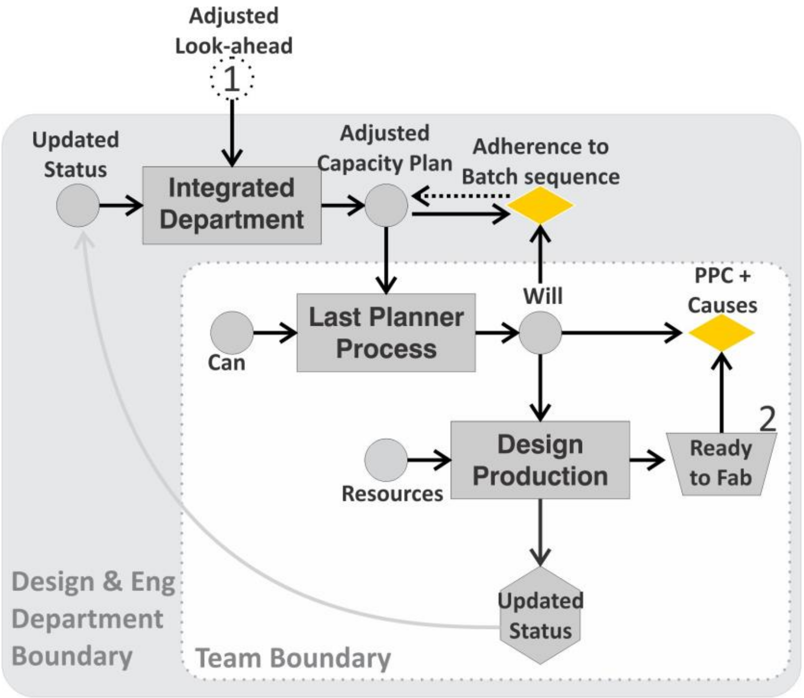


Figure 8.13: Planning and control processes in Design and Engineering Department (Module 2)

Module 2 is divided in two main hierarchical levels. The medium-term, in which the projects that “can” be produced are analysed, and the short-term, in which the commitment meeting is carried out. As discussed above, the analysis of the look-ahead in this level is facilitated through the development of a confirmed look-ahead schedule for the department.

8.3.2 Plant Department (Module 3)

In this model, it was considered that the fabrication is only ready when it is delivered on-site. This makes the Plant Department to be responsible for the inventory in the company yard and avoids this department from reaching a target producing products that cannot be shipped. Figure 8.14 illustrates the planning and control processes in the Plant Department, which refers to the third module of the model.

It is worth noting that the control of the products done is based on a backlog of ready to ship material, emphasizing the need for producing a complete batch able to be shipped to be considered as done. Moreover, at the department level, the control is based on what has been shipped. This proposition is an attempt to avoid the stumbling block of missing responsibility of inventory (WIENDAHL; VON CIEMINSKI; WIENDAHL, 2005). As well as in module 2, the Plant Department works with two main hierarchical levels the medium and the short-term.

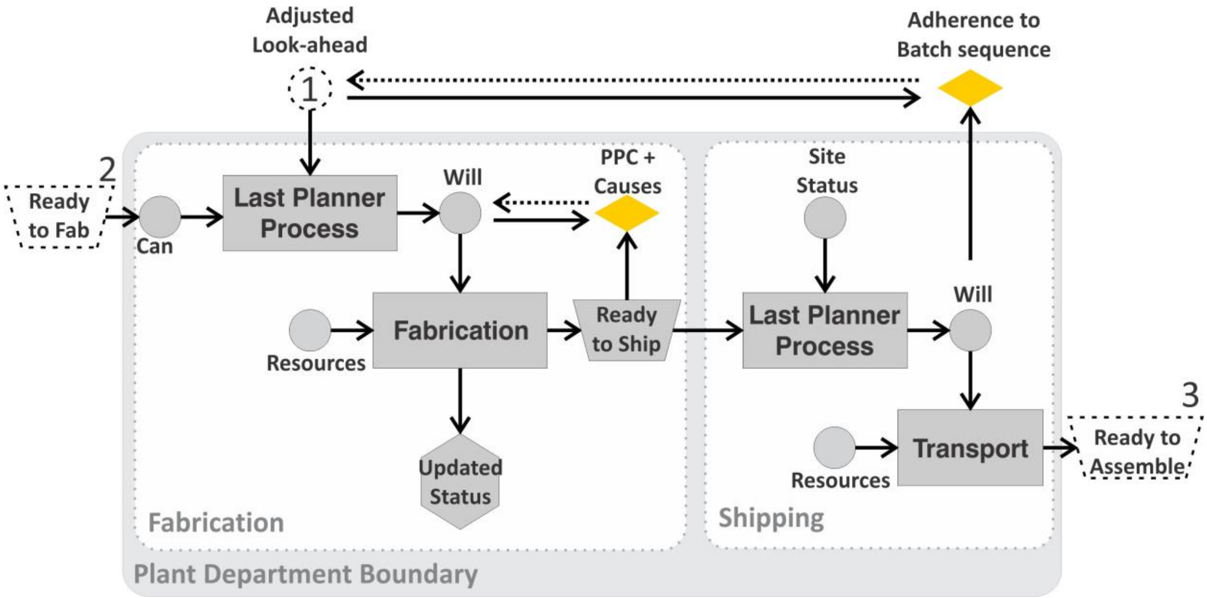


Figure 8.14: Planning and control process in Plant Department (Module 3)

8.3.3 Site Assembly Department (Module 4)

The fourth module of the model corresponds to the site assembly department. Because of the fact that the construction sites usually do not share resources with one another, the only process concerning the collection of sites is the integrated site monitoring, which is used in the model to give the construction status for the other modules. The production planning and control processes from module 4 are depicted in Figure 8.15. The processes are very similar to the way LPS was proposed. In comparison to the other modules, this is the only one that presents a long-term planning in order to schedule the project as a whole. The medium and short-term planning processes follow the same idea of the Design and Engineering module.

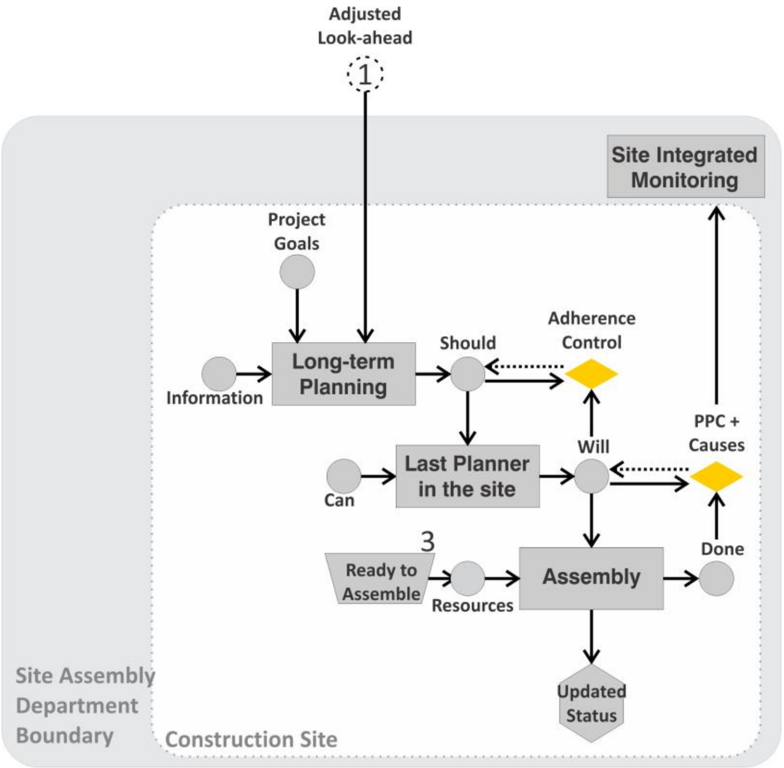


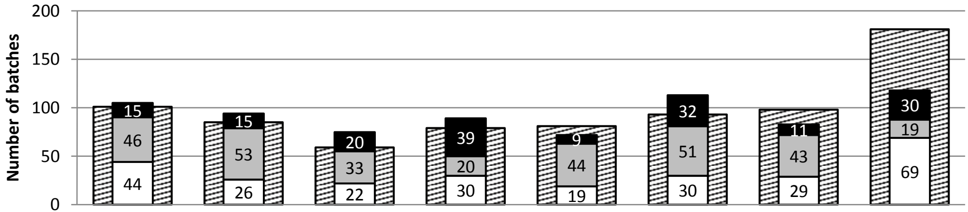
Figure 8.15: Planning and control process in Site Assembly Department (Module 4)

8.3.4 Performance Metrics

As this is a multiple project environment, there was a need to monitor project completion rather than just planning reliability, which is not possible to assess through PPCs. The batches of products are addressed to slots of time in the plan; the metric named adherence to the batch sequence could be used at this level, as shown in Figure 8.16 in a weekly basis.

Five key pieces of information can be extracted from this graph, divided in three groups:

1) Total amount of batches produced in the week period, summing up:
    a) Number of batches planned and produced within the week;
    b) number of batches produced within the month, but not in the right week; and
    c) number of batches produced from outside the plan, which should be analysed carefully to avoid the increase of the WIP.
2) Total amount of batches planned; and
3) Adherence to the batch sequence, given by dividing the number of batches planned and produced within the week divided by the total amount of batches planned.



	Week 31	Week 32	Week 33	Week 34	Week 35	Week 36	Week 37	Week 38
▨ Planned	101	85	59	79	81	93	98	181
■ Not Planned	15	15	20	39	9	32	11	30
▩ Within the month	46	53	33	20	44	51	43	19
□ Within the week	44	26	22	30	19	30	29	69
Adherence %	44%	31%	37%	38%	23%	32%	30%	38%

Figure 8.16: Adherence to the batch sequence

The projects that have been produced but were not planned for the month are an important source of information for the upper levels of planning and control. The production of those projects probably means a low level of information from the construction site, since look-ahead plans are based on project demand.

8.4 DISCUSSION

The main production planning and control processes proposed in this model have some relationships with the models presented in the section 4.3. The master schedule is based on an ERP system, in which all the batches for all projects can be seen jointly. Through the ERP system it is possible to evaluate the capacity for future projects. It was acknowledged in the model the difficulty in making frequent changes in the master schedule. For this reason, in this phase it is important to share the information from the short-term planning, so that each production unit can plan the following period accordingly.

In the WLC model, the batches are confirmed in three different instances before going to production: confirming the customer order, the availability of resources, and WIP in the plant-level. Based on this idea, the proposed model deploys the master schedule in three different planning and control processes: the integrated look-ahead, the integrated short-term, and the short-term within the production units.

The integrated look-ahead planning and control process is in charge of developing the targets for each department. Differently from the WLC, the confirmation of the customer comes from the information of the construction sites, revealing their suitability to receive projects batches. The targets are defined based on the last process in the chain, defining consistent goals among the production phases. This is an idea that comes from the TOC, adapted in the CCPM. The amount of work assigned for a whole production phase is also limited by its actual capacity. The development of the integrated look-ahead in rolling plans is based on the look-ahead from the LPS, although the constraints are mainly discussed in the production units, as discussed before.

The short-term integrated planning and control process refers to the idea of confirming the availability of resources from the WLC, aiming to make small adjustments in the plans established as the target for the following period. The control over the WIP of the plant as a whole is important to be carried out in this level, since the production units are focused on a smaller bunch of projects and can be blind for this type of inventory. For this reason, this process should be carried out by the Logistics Department, or a Supply Chain Management Department, in the case of less vertical integrated ETO companies.

In the different production units, the model follows the idea of the LPS with some adaptations mainly in the plant, in which the completion of the batch for transportation, as well as the delivery itself are considered as important conditions for the batches to be considered complete in the medium and short-term planning and control levels.

8.5 EVALUATION OF MODEL

As discussed in the research method chapter (section 5.5.1.4), the utility of the model must be assessed according to its ability to accomplish its objectives. The objectives established for this model were the development of decentralized and collaborative plans, control of the WIP, use of transparent plans, and the focus on the final product. The assessment made in this section is mostly based in the empirical study in Company A. Figure 8.17 reveals the extent to which the processes proposed in the model were implemented in the model. Most of the processes were at least partially implemented, which gave an important basis for the discussion of this section.

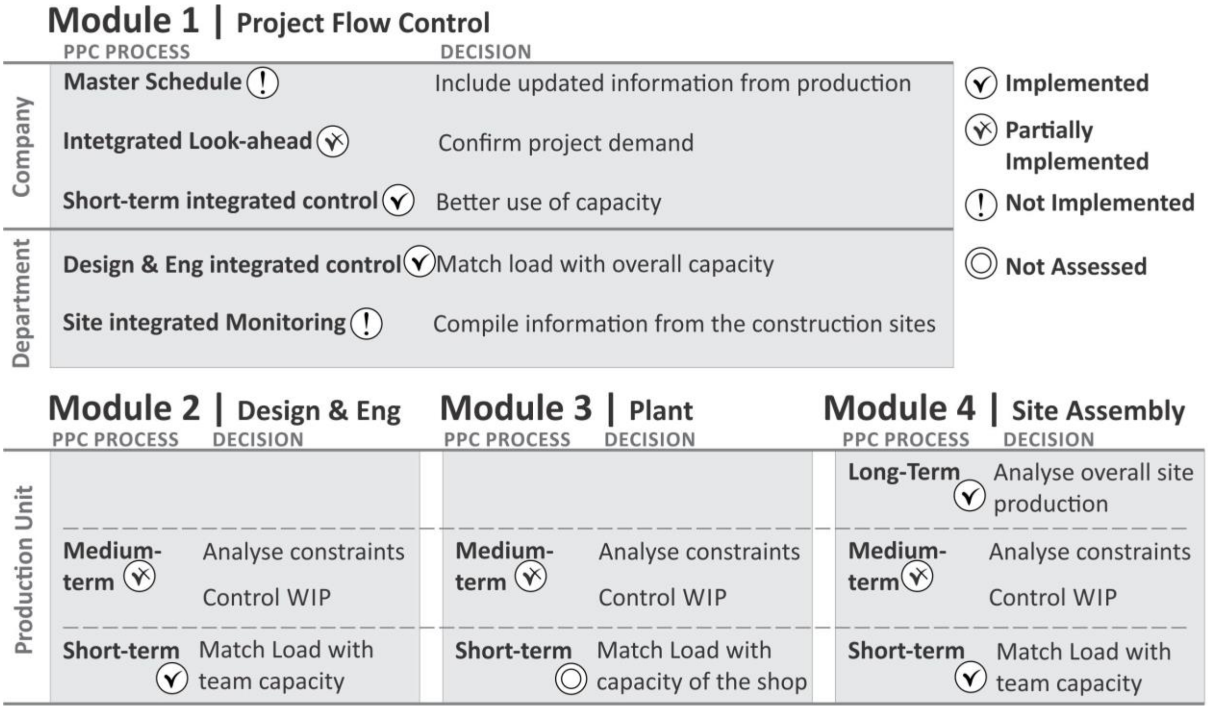


Figure 8.17: Extent of implementation of the model on Company A

The use of **decentralized and collaborative plans** at the operational level was one of the main assumptions for the effectiveness of the production planning and control system of the company. The use of the LPS by the production unit creates a certain level of autonomy of the PU to define plans and control their production. At this level, the LPS also helps the managers of the production unit to understand the existing constraints, and make an effort for the systematic removal of those constraints.

During the implementation revealed some limitations of the use of LPS in the project flow control level, where there is a need to deal with a larger number of projects. The identification of constraints was hard and time consuming. Moreover, most of the problems could be solved in the operational level. Therefore, the model has left the phase of constraint removal to the production unit, while the tactical levels deal with three levels of look-ahead plans.

The **control of the WIP** is required to achieve a manageable environment, making the production phases dependent from one another. For this reason, the model highlighted the importance of confirming the need for designing and fabricating the components using feedback from the construction site, and from the status of the production in each phase. The focus on this type of feedback made Company A aware of the production of components not required by the sites. In this customer-oriented environment, there is a need to understand the WIP control together with the confirmed demand. As the components are not produced in a repetitive way the control only based on the gross amount produced is not suitable.

Nevertheless, the use of a volume metric together with the approach of confirming production in different levels was effective in the case of Company A, turning the coordinators of the production units to feel the responsibility over the inventory of finished components.

The development of **transparent plans** is important to avoid the problems related to the availability of the information regarding the actual available capacity, and also the time consuming meetings for the production units to find out a simple information regarding when products would be released to them. For the former problem, the chosen source of evidence was the feedback from the production units to the Planning Department of Company A.

Using the integrated planning board, the Planning Department became aware of the production in the PUs. The development process of the board also revealed that the targets were not taking into account what should be the driver for the PUs. This understanding per se is one of the benefits of the transparency. Company A used to neglect adjustments in the plans, but the time spent in the informal share of production information from one department to the other seems to be an evidence of the need of the availability of plans.

An integrated planning and control process requires a higher amount of information to be processed than in a centralized and segmented approach. Therefore, it requires the use of transparency in the plans. One of this new information was due the projects highlighted in the urgent lane. This situation made the managers to focus in a set of projects considered as priorities by the site assembly managers. This reduction in the amount of information to deal with reduced substantially the necessary time for the meeting (around 1 hour), also making the logistics, plant, and design and engineering departments aware of the site requirements.

The third objective of the model was the **focus on the final product**, instead of on the production volume. In a manufacturing environment in which an expensive material is used, such as steel, managers are willing to make use of the maximum utilization capacity in order to have a quicker return on investment (WIENDAHL; VON CIEMINSKI; WIENDAHL, 2005). However, if the primarily goal of the production system is on producing volume not on the required products, it opens the possibility to make a misuse of this capacity, system becomes less efficient and effective due to the amount of work in progress. The focus on the final product is aided by the confirmations from the construction site just mentioned.

In a less complex environment, Company C revealed the importance of focusing on delivering the projects with the shortest possible lead-time. The company used to allow some idleness in the fabrication process in some periods, yet being able to fulfil short schedules even when the demand was high.

In Company A, this change of focus has to come together with a change of mindset in order to understand the importance of producing only when needed. The type of performance metrics used to assess the production system is another evidence of this focus. During the implementation, it was possible to observe a gradually change in the company mindset, such as the Plant Coordinator who were always looking for the maximum utilization of capacity, saying: "*Why shall I produce that if it is not going to the site? It doesn't make sense!"*

Regarding performance measurement, the use of metrics concerned with batch adherence helped Company A to decrease the amount of products in the yard. Even using the volume produced as the main metric, the realization of this adherence to plans was an important step in Company A planning and control system.

The implementation carried out in Company A provided important benefits towards a management-as-organizing approach for the planning and control system. At the beginning, the company had a push planning and control system, with no control over WIP. At the end, the company was implementing decentralized approaches, such as the LPS in the design and site assembly, using a transparent look-ahead in which participants could easily understand, and an attempt to use logistics knowledge to increase its responsibility in the integrated planning and control. There are no evidences from those changes, but they were observed by the researcher and by the research team she is part of.

8.6 THEORETICAL CONTRIBUTIONS OF THE MODEL

In the development of this planning and control model there were three main contributions related to planning and control systems for ETO prefabricated building systems. These theoretical contributions have to do with the understanding of the context of an ETO production system that delivers a prefabricated building system, which means that it deals with a customer-oriented fabrication, and it is affected by the uncertainties from construction sites.

The first contribution is the complexity framework adopted to understand the peculiarities of this production system, which was presented in section 4.2. This framework contrasts with the conceptualization of project complexity, often presented in the literature (Williams, 1999), which is mostly related to a single project environment. Moreover, the literature on ETO production systems (Bertrand and Muntslag, 1993) discusses the elements that contribute to increase complexity this environment, but does not address the problems related to project based production systems.

For those reasons, a framework was developed to summarize the view of the aforementioned authors (Figure 2.9, page 46), based on some important assumptions of complex systems from Kurtz and Snowden (2003), who highlighted the contextual character of this complexity view. The framework tries to avoid a hierarchical structure, acknowledging that the impact of each element in the overall complexity is different depending on the internal interaction between those elements in the production system, and on who is making the analysis. The understanding of this complexity is important to differentiate the production systems and verify the need for including the different processes proposed.

The second contribution refers to the emphasis on the control of WIP, discussed in section 3.2.3, which replaces the role of customer order in traditional pull production systems. However, the control of WIP is often based in the overall amount of products (HOPP; SPEARMAN, 2004). In this investigation, it was assumed that qualitative information about the product is required for this control. In fact, in ETO prefabricated building systems, the control of WIP should be based on feedback from construction sites and confirmation from the production units. The amount products stored for projects that were not ready for receiving them was considered more critical than the simple overall amount.

Regarding these confirmations, this research also proposed different stages of confirmation for production, based on the idea of the job pool, discussed by Kingsman (2000). The main adaptation in the idea proposed from Kingsman is the adoption of different hierarchical levels for those confirmations and the use of information from downstream processes and not only client decisions.

The third main contribution of this investigation is the proposition of the core requirements for this type of planning systems, based on the literature (BERTRAND; MUNTSLAG, 1993; KINGSMAN, 2000; LITTLE *et al.*, 2000; STEVENSON; HENDRY; KINGSMAN, 2005), and also on the empirical studies. The model is an attempt to address those requirements. The ones directly tackled during the development were the ability to deal with uncertainty and the need for distinguishing project flow and production unit control. The former was a major focus of the researcher in the four stages of implementation in Company A, and also in the empirical study B. The second step of the implementation in Company A provided evidences that those requirements complement each other, indicating that is not possible to provide confirmation without an analysis of the project flow.

The remaining requirements were also acknowledged in the development of the model, although with an indirect role in the implementation phase. The master schedule can be used as a means to plan the capacity at the customer enquiry, using feedback from lower levels of planning and control to enable an accurate assessment of this capacity. The idea of managing the interface between sales and production is close related to the idea of prioritizing customer needs instead of maximizing the utilization of capacity. The ability to deal with customer-oriented non-repetitive production has to do with the plant configuration, which was not tackled by the model, but has also to do with the way WIP is controlled as just discussed.

9 CONCLUSIONS

This research was motivated by an opportunity to solve a practical problem in a Steel Fabricator Company. The research problem revealed a gap in the literature regarding how to design a planning and control system for ETO prefabricated building systems, in which the peculiarities of this production system in the construction industry could be considered.

Due to the opportunity to interact with a practical problem and develop a solution, the research was framed as a design science research. The research strategy adopted was the action-research, since there was a close collaboration with this steel fabricator, and most of the final solution was designed in collaboration with them. Besides the main study, carried out in Company A, two additional studies were carried out in order to understand different contexts and providing a broader view of this type of production system.

Based on a literature review, the peculiarities of this kind of production system were discussed. An emphasis was given to the different dimensions of complexity involved in ETO production systems, and how these affect the performance of planning and control systems. A framework for understanding complexity in ETO prefabricated building systems was then proposed.

In addition, this investigation highlighted five important requirements for developing an ETO production planning and control system. Those requirements supported the final model development and were important in the discussion with Company A, for making them aware of the need of a change in mindset.

The three empirical studies were carried out considering the proposed framework. Both production systems of Companies A and B were very complex, although the context was very different in those studies. By contrast, Company C had a much less complex production system, due to a technological innovation that increased the degree of product modularity, and a business strategy of involving the supply chain in producing some of the components.

One of the key steps in the development of the model was to investigate how to make this type of production system to benefit from pull production. Since the beginning of the empirical study in Company A, it was clear that it would not be possible to define pull production according to the existence of a customer order. The production system of Company A produced only according to a customer-order and it was clearly very far from the idea of a pull production. Therefore, the definition of pull used in this investigation was strongly on Hopp and Spearman (2004), focused on the limitation of WIP.

In this environment, there was also a need to define how to control of WIP. As the definitions from the customer are uncertain, construction sites are affected by different production processes and stakeholders, together with the uncertainties in the fabrication process, it is not possible for the projects to follow long-term plan defined in the early stages of the project. For that reason, there was a need to establish confirmation points, at different hierarchical levels in order to avoid stacking materials that are not required by the construction sites.

The implementation in Company A confirmed the importance of applying the Last Planner System at the operational levels, where the production units define what to produce. At a tactical level, the LPS required some adaptations for promoting the integration between production phases, such as the disconnection of the constraint removal from the integrated look-ahead process of the different production phases. The reason for this disconnection is that the nature of the constraints relates to the production unit scope.

Performance measurement plays a key role in the definition of the production planning and control systems. The focus on the volume to be produced makes production units to use the maximum utilization of capacity as the main logistic objective. This kind of approach increase the amount of WIP, segregate the production phases, increase lead times, and do not focus on the customer requirements. In a customer-based production system, this approach seems to result in an ineffective planning system. Therefore, the focus of the model was on the adherence to the confirmed plans, product completion, and lead-time control.

In fact, Company A adopted this approach, resulting in different points of inefficiency along the production process. The study on Company B was focused on the understanding of production lead-times and the dependence of the company planning and control process on a window of opportunity given by the GC to deliver and install the components. The use of lead-time for that sake was important to understand the volume flexibility required by the fabrication process.

Therefore, the integrated planning and control model for ETO prefabricated building systems was strongly based on a management-as-organizing approach. Some parts of the model were successfully implemented in Company A, and others could not be fully implemented due to the normal difficulties of implementing such changes in a short period. For instance, the use of systematic feedback from site assembly had not worked as it was proposed, and the planning process was still very centralized. In fact, the isolated incentives for plant output and for the delivery of materials on site seem to be a challenge for the production system of Company A. Nevertheless, some of the recent changes, made along this investigation seem to address this connection between production and delivery.

In this type of investigation when there is a close interaction between the researcher and representatives of the company, and a long-term relationship between the company and the research institution, it is hard to define the boundaries of the research impact. However, it is worth to acknowledge the importance of the engagement of a company team in this implementation process. In addition, this investigation has benefited from the in-depth discussions carried out in workshops and meetings, in an attempt to change the mindset of some managers.

The opportunity of such a close interaction with the practice brings benefits both for the company and for the production of new theoretical knowledge. This type of opportunity was strongly supported by the positioning of this investigation as design science research.

One important contribution of this thesis is the understanding of the production system context, which resulted in the adaptation in practices and concepts to this environment. The set of planning and control processes that form the final version of the model, using some countermeasures, is an acknowledgement of the need to follow some gradual steps for changing a production system from a segregated production phases to an integrated approach.

As a researcher from outside of the company, it was impossible to interfere in every process perceived as problematic. Therefore, there was a need to describe and discuss what have been perceived in order to share this idea with the company and understand the limitations or opportunities of this analysis. An agent from outside the environment is likely to have a different view of the problems and this is an important point for carrying out an action-research in order to engage practitioners to the theoretical problem.

9.1 SUGGESTIONS FOR FURTHER RESEARCH

This research raised some topics to be addressed in future studies:

- Refine the model using empirical data from the role proposed for the Logistics Department, addressing how it might affect the production system as a whole, in terms of WIP and lead-time control
- Adapt the model for production systems using modular components, addressing the capabilities of this modular system to attend customer needs.
- Extend the investigation over the requirements for developing ETO production planning and control systems, through empirical studies to analyse their applicability in different contexts. Also to further develop the set of requirements proposed.
- Refine the model for companies less vertical integrated, such as the case light steel frame.

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