MASTER

Improving workflow in lean construction

design for construction (DFC) as a solution for waste elimination in a Lean construction pilot project 'Sporen in Arnhem'

Boschker, R.H.

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MASTER THESIS

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FACULTY
Architecture, Building and Planning
Building Technology

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Technische Universiteit Eindhoven
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bam utiliteitsbouw

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Titel	: Improving workflow in Lean construction
Subtitle	: Design for construction (DFC) as a solution for waste elimination in a Lean construction pilot project 'Sporen in Arnhem'

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Preface

This research paper has been written as graduation paper for my master study 'Building Technology' at the University of Technology in Eindhoven. Building technology is, besides sustainable building objectives and integrated product development, related to efficiency in construction. The focus of this research shifts to the construction process in order to improve construction performance according to Lean thinking. Besides a theoretical part about the concepts of Lean construction, the research has a practical extension since it is performed in cooperation with BAM Utiliteitsbouw in Arnhem.

When I approximately a year ago find out about the concept of Lean and started to read the book "The machine that changed the world" by Womack and Jones, Lean immediately attracted my attention. The book explains the rise of Lean manufacturing in the automobile industry. Transferring this Lean approach to construction, Lean construction has been developed in order to improve the industry's performance. Since I experienced on-site construction processes myself during a part-time summer job, in my opinion Lean offers a great opportunity to improve construction performance in the nearby future. This research is an attempt to determine the advantages (and complications) of implementing the Lean approach in practise. During my internship at BAM I was able to explore the 'current state' of Lean construction in practise by investigating a Lean construction pilot project 'Sporen in Arnhem' (SIA).

Before commencing this work, I would like to express my gratitude to all the people who supported me during my research period, especially Wim van den Bouwhuijsen and Niels Scholten.
Wim van den Bouwhuijsen introduced me into the Lean community. Besides the continuous support during my research, he involved me in various Lean seminars hosted by 'Arpa Lea(r)n Instituut' and the 'Lean Construction Network - Nederland' (LCN-NL). Visiting these seminars, I noticed that Lean is widely adopted in various businesses in the Netherlands, especially the adoption of Lean in the Dutch construction industry was of my interest.
I would like to thank Niels Scholten and all the other helpful colleagues from BAM for their support during my internship at BAM Utiliteitsbouw in Arnhem. BAM provided me the opportunity to expand my research in practice by investigating a Lean pilot project 'Sporen in Arnhem'. BAM granted me the opportunity to experience the Lean construction approach in practise by joining a Lean kick-off meeting and a Lean planning session in the early stages of a new Lean construction project (Groot Hungerink) executed by BAM. Alongside writing this thesis, these interviews, seminars and Lean meetings have extended my horizon about Lean thinking within the current state of the construction industry.

René Boschker

October 2013

Abstract

Construction contractors are facing continuous decline in profit margins and increased competition in construction projects. For this reason contractors are continuing to search ways for eliminating waste and increasing profit. Working according to the Lean philosophy is regarded as an effective method for reducing, if not completely eliminating non-value adding work. This knowledge reflected on a specific selected case study gives rise to the following research question for this master thesis: *How can waste according to Lean construction be identified and eliminated in the selected case study 'Sporen in Arnhem' in order to improve workflow?* The purpose of this research is to improve workflow according to Lean thinking in the selected case study: a Lean construction pilot project 'Sporen in Arnhem'.

The theoretical framework reveals what the existing knowledge of Lean construction is about. The gathered knowledge is used to develop a workflow model (framework) in order to identify waste in construction projects according to Lean thinking. Field research is performed in cooperation with BAM Utiliteitsbouw Arnhem to investigate the current state of Lean construction in practice. To enhance comparisons between the conceptual arguments and empirical data the project 'Sporen in Arnhem' is selected since it explicitly adopts Lean construction techniques.
By analysing identical construction processes within the scope of the project, wasteful activities according to Lean thinking will be identified. This Lean assessment is performed applying two research approaches:

- Qualitative research: Evaluation of the implemented Lean techniques subtracted from documents and interviews, focussing on the realization of the entire railway station.
- Quantitative research: Measuring the workflow of three identical construction processes, focussing on the so called 'standard elements' within the platform roofs. This comparative data analysis is performed using the developed workflow model as database in which the metrics from the available Lean planning schedules are used.

In both approaches a set of 'parameters of efficiency in construction' is used as manual to evaluate the effects of Lean construction. These parameters are distilled from a broader research 'Lean Construction Management (LCM) and efficiency in the building process'.

Although it is difficult to draw measurable conclusions associated with the effects of the implemented Lean techniques on the selected parameters, it can be concluded that the Lean planning sessions and the use of prefabricated components have the most (direct) impact regarding the on-site production performance. Lead times have been reduced drastically by removing buffers in planning and transferring time-consuming work to off-site facilities. It needs to be addressed that for both Lean techniques the underlying Lean approach implemented already in the tender phase has been crucial. The case study of SIA approves that implementing Lean thinking improves construction supply chain performance by stimulating cooperation, mutual responsibilities and joint objectives between general contractors, co-makers and sub-contractors already in the early stages of a project.
Literature revealed that reducing on-site material handling and lead times through proper workflow management are the most important aspects for eliminating waste in a construction process. The developed workflow model has been useful for identifying wasteful activities requiring much input of material, time and effort (labour and equipment). The assembly of the sub-construction and aluminium panels (ceiling) is identified as the most wasteful type of activity, mainly caused by the complex working conditions on-site and the lack of standardization. Both the quantitative and the qualitative research determined this work as bottleneck in the on-site construction process within the research scope.

In order to improve workflow, the wasteful craft work associated with the assembly of the ceiling will be eliminated (or at least reduced) from the process by redesigning the current process in which it is achieved. Following the 'product strategy' and applying the concept of 'design for construction' (DFC), an alternative Lean design is developed whereby all the sub-construction material and panels are integrated in prefab ceiling-elements. This Lean design, using pro-active Lean techniques, results in a significant reduction of resources (material, time and effort) without misdealing the architectural quality of the end product. Applying the recommended Lean design will lead ultimately to more added value for the (end)customer, general contractor and co-makers.

Key words:
Lean construction, Lean assessment, workflow model, comparative analysis, Lean design, Design for construction

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"The world we have created is a product of our thinking; it cannot be changed without changing our thinking."

Albert Einstein

1. Introduction

1.1 Problem scope

The construction industry is a project based production system, where the opportunities for repetition are limited. It is a 'low volume, high variety' environment in which workforce, equipment and materials must be taken to the site where the finished product has to be assembled (Errasti et al., 2009). The construction process is fragmented because construction projects usually require contributions from suppliers to co-makers with specialist skills that span a broad range of construction and manufacturing disciplines (Peter Simonsson et al., 2012). The level of complexity that arises as a consequence of these operational characteristics may explain the perceived inefficiencies and management difficulties that are frequently associated with construction projects. Empirical data indicates that construction costs increase exponentially with the increasing degree of complexity and scale of a project (Li et al., 2008). In recent years some authors have modelled the building process and identified potential savings of 25% by reducing non value activities.(Li et al., 2008; Errasti et al., 2009).

With the continuous decline in profit margins and increased competition in construction projects, construction contractors are continuing to search ways of eliminating waste and increasing profit. Although numerous approaches have been developed to improve efficiency and effectiveness of construction processes, Lean construction techniques offer the promise to minimize, if not completely eliminate, non value-adding work. Since the 1990's, the construction research community has been analysing the possibility of applying the principles of Lean production to construction (O. Salem et al., 2005). Although the promotion of Lean construction has been highly visible in countries such as the USA, UK and Denmark, critical sounds are rarely heard (Jørgensen and Emmitt, 2008; Meiling et al., 2012). This research is an attempt to measure the effectiveness of Lean construction in practice.

1.2 Purpose

The purpose of this research is to improve workflow in construction according to Lean thinking in a specific selected case study. The research focuses on a Lean construction pilot project called 'Sporen in Arnhem' (see appendix A1 and A2). By analysing different identical construction processes within the scope of the project, wasteful activities (cost drivers) according to Lean thinking will be identified. A solution will be recommended in order to improve workflow by eliminating waste in the on-site construction process. Although this solution is just one of the possible solutions and only theoretical since the project has been completed already, the way of Lean thinking, the endless search for perfection, should be an eye-opener for all construction participants in future projects.

1.3 Research questions

The literature has revealed that general contractors and co-makers (subcontractors included) work within a project based system and that savings might be achieved by reducing non-value activities in the total value stream. This knowledge, reflected on a specific selected case study (a Lean pilot project), gives rise to the following research question:

How can waste according to Lean construction be identified and eliminated in the selected case study 'Sporen in Arnhem' in order to improve workflow?

In order to answer this research question, five sub questions are formulated:

1. *What is Lean management?*
2. *What is Lean construction?*
3. *How can Lean thinking improve workflow in construction?*
4. *Which methods can be used for Lean assessment in construction projects?*
5. *What type of activity in the case study project can be identified as the most potential for waste elimination?*

1.4 Research model

In figure 1.1 the research model is visualized. The structure of the research is divided into four major parts: theoretical framework, field research, conclusions and recommendations. The numbers refer to the chapter numbers.

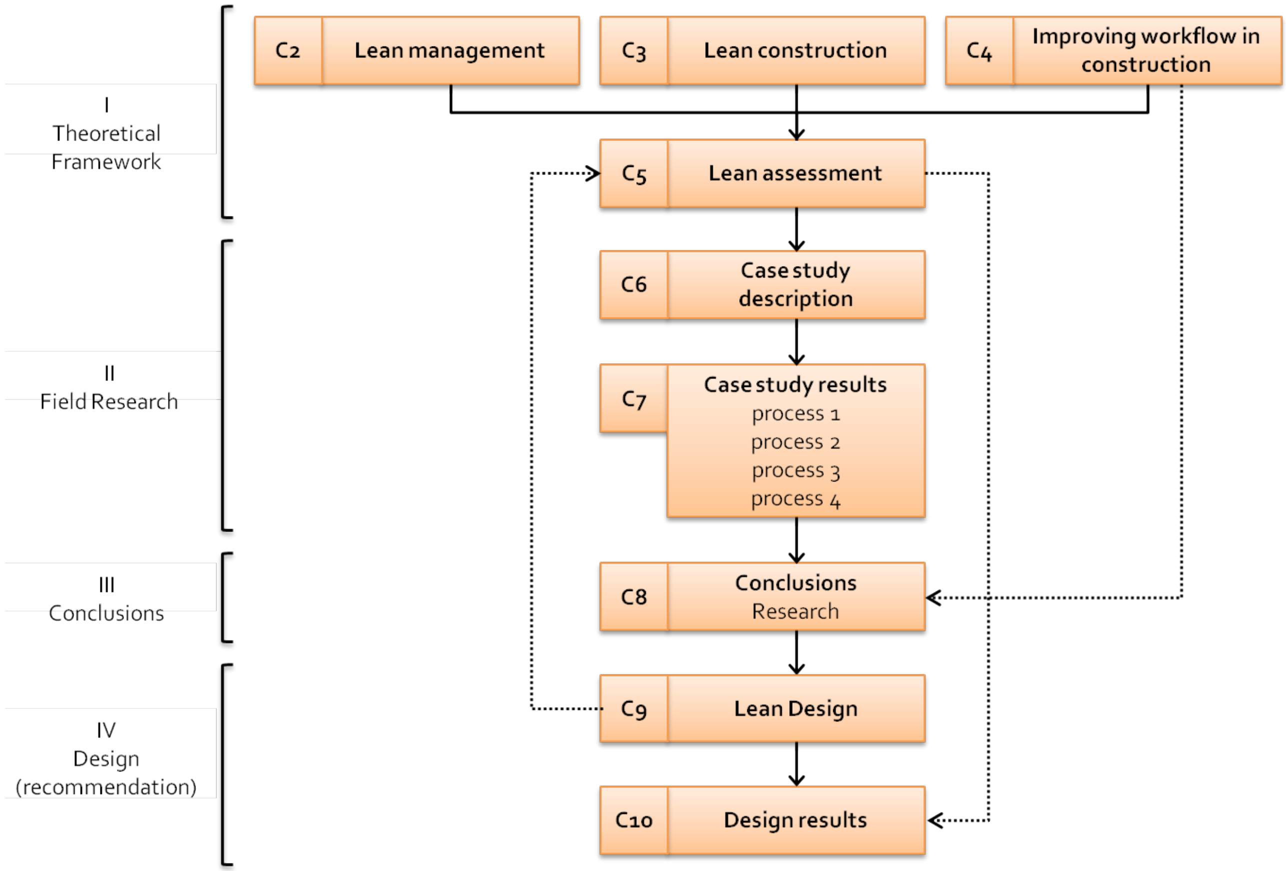


Figure 1.1 Research model

1.5 Research method

The research is executed in four general steps. Each step is described beneath.

I: THEORETICAL FRAMEWORK

The literature reveals what the existing knowledge of Lean construction is about. The gathered knowledge is used to develop a workflow model (framework) in order to identify waste according the Lean philosophy in construction projects.

First, the principles and origin of Lean thinking will be introduced along with the concept of value and waste (chapter 2). Second, the transfer of Lean management from manufacturing environments (processes) to the construction industry (projects) will be explained. The definition of Lean construction will be presented along with various Lean construction techniques (chapter 3). Third, the main aspects of workflow will be revealed as well as two strategies how to improve workflow with Lean construction (chapter 4). Finally, a model will be presented in order to measure workflow data in practise (chapter 5).

II: FIELD RESEARCH

In order to evaluate the literature review in practice, field research is performed. To enhance comparisons between the conceptual arguments and empirical data, it is important to select a critical case that explicitly adopts Lean construction techniques. For this reason the project 'Sporen in Arnhem' (SIA) is selected what is seen

as a Lean construction pilot project. The scope within this project is the realization of the railway station (chapter 6), executed by BAM Utility
The field research is split in a qualitative and quantitative approach. The qualitative research is focuses on the effect of implemented Lean techniques within the case study. The quantitative research focuses on a comparative analysis between three identical construction processes (platform roof) using the developed workflow model. The Lean planning schedules are applied as data source since they contain the most accurate information and are justified as most reliable concerning the workflow metrics. The workflow model shows the use of recourses and time needed during construction. By comparing these processes it is more evident to identify wasteful activities in the selected on-site construction process.

III: CONCLUSIONS
In this part the research question will be answered. By analysing the results of the qualitative and quantitative research, conclusions can be drawn how waste can be identified and which type of activity has the most potential for waste elimination within the research scope of the case study.
In order to improve workflow, a conceptual solution will be recommended in what way the identified waste can be eliminated from the on-site construction process. The application and elaboration of the recommended (design) solution will be the challenge of the next part (part IV: Design).

IV: DESIGN
The root cause of waste in the case study is carefully reviewed. The recommended design solution will be worked out in detail using various Lean techniques (implementations). As a consequence of the re-design, the workflow will be improved which ultimately creates more value for both the client and the general contractor.

1.6 Research material

In table 1.2 the research material and its application is described concerning literature review, data analysis and interviews.

Method	Source	Application
Literature review	Scientific articles (see references)	Chapter 1/2/3/4/5/9
Data analysis	Calculations	Chapter 6/7
	Work reports	Chapter 5/6/7
	(Sub) Contracts	Chapter 5/6/7
	Planning schedules	Chapter 5/6/7
	Drawings	Chapter 6/9
Interviews	Tender manager (BAM)	Chapter 6/7
	Chief foreman (BAM)	Chapter 6/7
	Preparation engineers (BAM)	Chapter 6/7
	Planning engineers (BAM)	Chapter 6/7
	Project manager Co-maker (Sorba)	Chapter 6/7

***Table 1.2** Research material*

I. THEORETICAL FRAMEWORK

II. FIELD RESEARCH

III. CONCLUSIONS

IV. DESIGN

"One of the most noteworthy accomplishments in keeping the price of Ford product low is the gradual shortening of the production cycle. The longer an article is in the process of manufacture and the more it is moved about, the greater is its ultimate cost."

Henry Ford, 1926

2. Lean management

In this chapter the origin and principles of Lean management in the automobile industry will be explained. The following sub question is answered: ***What is Lean management?***

2.1 The concept of Lean

Lean is seen as a successful management philosophy to lead and manage an organization. Essentially, it is 'doing more with less' by employing 'Lean thinking' in an organization. It is based on one clear basic definition: all activities within an organization that directly contribute to that where the customer is willing to pay for is value. Everything else is seen as 'waste', whereby sometimes waste is a necessary evil. The aim is to create more added value for the customer by focusing on quality of both the product or service as well as the process by which this is achieved.

Lean operating principles began in manufacturing environments and are known by a variety of synonyms: Lean Manufacturing, Lean Production, Toyota Production Systems (TPS), etc. It is commonly believed that Lean started in Japan (Toyota), but Henry Ford had been using parts of Lean as early as the 1920's, as evidenced by the following quote:

"One of the most noteworthy accomplishments in keeping the price of Ford product low is the gradual shortening of the production cycle. The longer an article is in the process of manufacture and the more it is moved about, the greater is its ultimate cost." Henry Ford, 1926

The National Institute of Standards and Technology manufacturing Extension Partnership's Lean Network developed a definition of Lean (Jerry Kilpatrick, 2003): Lean principles

"A systematic approach to identifying and eliminating waste through continuous improvement flowing the product at the pull of the customer in pursuit of perfection."

Today many large manufacturers are demanding that suppliers adopt Lean practices. Lean organizations are able to be more responsive to market trends, deliver products and services faster, and provide products and services less expansively than their non-Lean counterparts. Lean crosses all industry boundaries, addresses all organisational functions, and impacts the entire system, improving supply chain to customer base.

2.2 The origin of Lean manufacturing

The Americans invented the term 'Lean' in the 1980's to explain the fundamentals of the Toyota Production System (TPS) which is seen as the origin of Lean production today. The steady growth of Toyota, from a small company to the world's largest auto maker, has focused attention on how it has achieved this success. In the book 'The Machine That Changed the World' (1990) James P. Womack, Daniel Roos, and Daniel T. Jones described the evolution of Lean manufacturing practices led by Toyota in the automobile industry.

The automobile industry has come a long way since the days of craft production. The craft producer used highly skilled workers and simple but flexible tools to make exactly what the customer wanted in one product at a time. Goods produced by the craft method where too expensive for most people to afford. Mass production was developed at the beginning of the twentieth century as an alternative production method.

Figure 2.1 *Smooth workflow through the assembly line at a Ford factory in 1913*

It was Henry Ford who really understands the drawbacks of craft production. The key to mass production was not the moving assembly line. Rather it was the complete and consistent interchangeability of parts and the simplicity of attaching them together. These were the manufacturing innovations that made the assembly line possible. Taken together, interchangeability, simplicity and ease of attachment gave Ford tremendous advantages over his competition. Mass-producers began to use narrowly skilled professionals to design products made by unskilled workers tending expensive, single purpose machines. These machines turned out standardized products in very high volume. So the mass-producer added many buffers (supplies, workers, space) to ensure smooth production. The consumer got a cheaper product but the variety of products decreased drastically.

Inspired by Ford's mass-production facilities, Toyota developed a new way of producing cars. They saw the possibilities of mass-production in Japan but they had to rethink the system since the Japanese car market was too small and divers for the huge scale of mass production. Additionally the mentality of the workforce was different. Their new way of production, assembly and delivery of cars and managing workforce was known as the Toyota Production System (TPS). It forms the foundation of what we now know as Lean (Daniel T. Jones & James P. Womack, Daniel Roos, 2007)

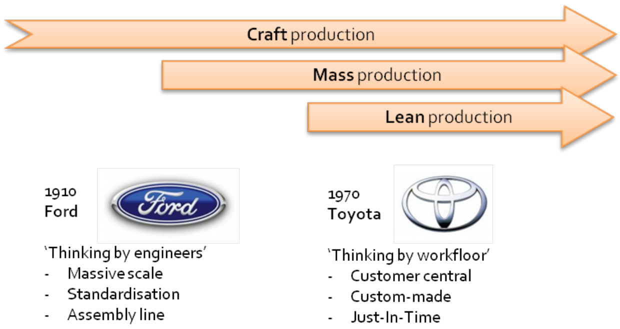


Figure 2.2 The Origin of Lean manufacturing

Lean producers led by Toyota emerged today as global leaders in the automobile industry. The Lean producer combines the advantages of both systems while avoiding the high cost of craft production and the rigidity of mass production. Lean producers employ teams of multi skilled workers at all levels of the organization and use highly flexible, increasingly automated machine to produce volumes of products in enormous variety.

The most striking difference between mass production and Lean production lies in their ultimate objectives. Mass-producers set limited goals for themselves. This translates into an acceptable number of defect, a maximum acceptable level of inventories and a narrow range of standardized products. To better, they argue, would cost too much or exceed inherent human capabilities.

Lean producers, set their sight explicitly on perfection: continually declining costs, zero defects, zero inventories, and endless product variety. No Lean producer may have achieved perfection and none ever will. But the endless quest or perfection, on the part of Lean producers, continues to generate surprising results.

2.3 Lean principles

The concept "Lean production" was established by Womack et al. (1990) as they present five production principles, see figure 2.3. The long process of Lean was thoroughly described in the book The Machine That Changed the World (1990) by James P. Womack, Daniel Roos, and Daniel T. Jones later on in the book Lean Thinking (1996). The five principles resulted from a five-year benchmarking study conducted at Massachusetts Institute of Technology (MIT), regarding car production all over the world:

1. **Specify the value for the customer** - Determine the value of a product or service from the customer's perspective.
2. **Improve the value stream** - Identify and visualize the value stream and eliminate waste in the process.
3. **Create a continuous flow** - Work in a continuous flow with shorter lead times with only the remaining value-added steps.
4. **Establish Pull Production** - Switch to a demand-driven production system: produce only at the customer's request: pull instead of push. Delivery should be only on order.
5. **Seek for perfection** - Continuous improvement of the product and process.

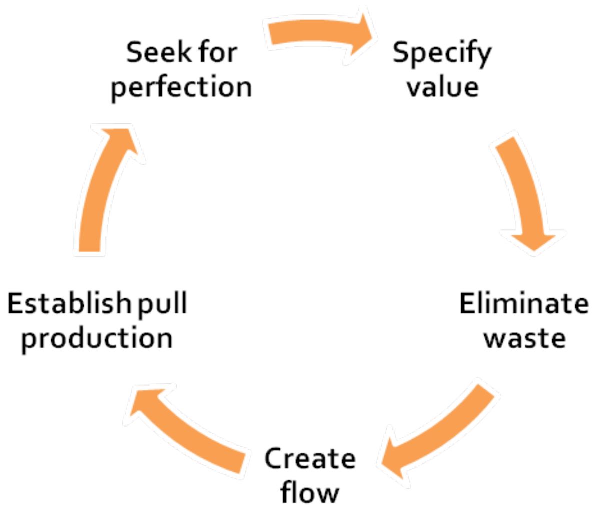


Figure 2.3 The five Lean principles within the learning process of continuous improvement.

2.4 Value and waste in the Lean philosophy

Lean manufacturing involves never ending efforts to eliminate or reduce 'muda' (Japanese for waste or any activity that consumes resources without adding value) in design, manufacturing, distribution, and customer service processes. The theory of Lean production states that every process and operation consists out of three types of activity (Jørgensen and Emmitt, 2008):

1. **Value adding activities**
2. **Necessary non-value adding activities** (necessary waste)
3. **Unnecessary non-value adding activities** (pure waste)

In the Lean terminology value is understood very narrowly, as consisting only of what the end customer perceives as representing value to the customer (type 1: value adding activities). Anything that does not directly add to this value is regarded waste. Consequently any process is wasteful, so it is appropriate to distinguish between waste that cannot be avoided but should be reduced as much as possible (type 2: necessary waste), and waste that in principle is not required for delivering the value requested (type 3: pure waste) which should be eliminated. Many organizations aim to optimise the value adding work to increase their profit, while organizations implementing Lean thinking are focusing on the elimination of wasteful work.

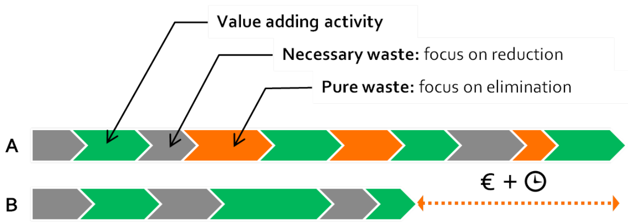


Figure 2.3 Time and money will be saved by shortening of the production cycle (schematically)

	Type	Examples in manufacturing	Examples in construction
	1. Overproduction	Making more than is immediately required.	Completing operations earlier than necessary, e.g. painting of walls in rooms that are not completed
	2. Waiting	Waiting for parts, information, instructions and equipment.	Blueprints are not finished when on-site operations need them
	3. Transport	Moving people, products and information.	Inappropriate distances between storage, workplace offices on site owing to little logistic planning
	4. Over-processing	Tighter tolerances or use of higher quality in materials than necessary.	Including more functions within the product than the customer wants
	5. Inventory	Storing parts, pieces, and documentation ahead of requirements	Unnecessary large storage of materials and components on site
	6. Motion	Bending, turning, reaching and lifting	Inappropriate work conditions, e.g. unnecessarily heavy and high lifts
	7. Defects	scrap and incorrect documentation	Rework of operations and construction material affected by climate
	8. Unused employee creativity	Under utilizing capabilities	Not considering on-site experiences from earlier projects in new projects

Table 2.4 Examples of the different types of waste according the Lean philosophy (Gerth et al., 2013).

In the Lean literature waste is commonly divided into eight subtypes, see table 2.4 (Gerth et al., 2013). Waste types 1–5 are mainly addressed at the production management level, which in the case of construction includes project manager, design engineer and site manager. Types 6 and 7 are mostly addressed at the operational level, e.g. by craftsmen, but controlled by supervisors such as foremen. Waste type 8 is addressed at both levels. All the eight types of waste can occur at any organizational level, however, the root cause for each type can be traced to either management or operational activities for each level.

In order to eliminate waste, Lean companies utilize many tools or so called Lean techniques. Successful practitioners recognize that, although most of these may be implemented as stand-alone programs, few have significant impact when used alone.

2.5 Conclusions

What is Lean management? Lean management is seen as a superior way of how we deliver products and services. Lean management principles began in manufacturing environments and are known by a variety of synonyms: Lean Manufacturing, Lean Production, Toyota Production Systems (TPS) etc. Organizations which have implemented Lean management principles are able to be more responsive to market trends, deliver products and services faster, and provide products and services less expansively than their non-Lean counterparts.

The National Institute of Standards and Technology manufacturing Extension Partnership's Lean Network developed a definition of Lean: *"A systematic approach to identifying and eliminating waste through continuous improvement flowing the product at the pull of the customer in pursuit of perfection."*

According to the pursuit of perfection, the concept 'Lean production' presents five production principles for continuous improvement:

1. Specify value for the customer
2. Improve the value stream by waste elimination
3. Create a continuous workflow
4. Establish Pull production
5. Seek for perfection.

Lean manufacturing involves never ending efforts to eliminate or reduce 'waste' (any activity that consumes resources without adding value) in design, manufacturing, distribution, and customer service processes. The theory of Lean production states that every process and operation consists out of three components:

- Value adding activities
- Necessary non-value adding activities (necessary waste)
- Unnecessary non-value adding activities (pure waste)

>> Since manufacturing plants and construction sites are different in many ways, Lean management theories and practices do not fully fit the construction industry. The differences in implementing Lean thinking between manufacturing industries and construction will be explained in the next chapter.

3. Lean construction

In this chapter the transferring of Lean manufacturing to construction environments is investigated. Due to the differences in manufacturing and construction industries, Lean principles and Lean techniques acquire adjustments for adoption in construction projects. Therefore the following sub question will be answered: ***What is Lean construction?***

3.1 Construction industry performance

Construction is commonly characterized as a 'backward industry', one that fails to innovate in comparison to other sectors (Gong et al., 2011; Höök and Stehn, 2005). While other sectors modernized through the introduction of interchangeable parts, then assembly lines, and then automation, construction retained its craft method of operation. As a result of that it fell further and further behind the rest of the manufacturing industry in terms of productivity, quality, and therefore value for money. (Winch, 2003)

Manufacturing companies have made many significant improvements in both productivity and management efficiency over the last century. This progress has not been matched in the construction industry, which is still related with a variety of long-standing problems like time and schedule overruns, poor health and safety conditions as well as low quality and productivity. The total cost of a construction project typically exist of three major components (Li et al., 2008; Errasti et al., 2009):

- About approximately 75% is spent on labour, material, plant and equipment;
- Around 12% is wasted due to rework incurred by design errors and construction mistakes;
- About 13% is used to cover management costs (payment to project management team), overheads and profits of the contracting firms.

In other words, there is up to 25% of waste in the project cost.

Construction is an industry sector of great diversity in technology, complexity, value proposition, organization and performance (Pasquire, 2012). It can be divided into broad sub-sectors in a variety of ways depending on the nature of the commissioning client; the nature of the function being delivered by the structure; the size and scale of the work; the point in the life cycle or the skills required to achieve the desired structure. In other terms, the commissioning client may be the public sector, a commercial organization or a domestic householder.

Manufacturing plants and construction sites are different in many ways that might explain why Lean production theories and practices do not fully fit the construction industry. Construction and manufacturing differ significantly in the physical features of the end product. Construction industry has three features that distinguish it from manufacturing (Salem et al., 2006; Ballard and Arbulu, 2004)):

- **On-site production** - Construction is site position manufacturing in which the product cannot be moved after assembly like car and air plane manufacturing. The contractor must ensure that all components assembled on site meet high-quality standards that are greatly influenced by specific site conditions.
- **One-of-a-kind projects** - Normally manufacturing takes advantage of specialized equipment to make standardized units, allowing only a limited level of customization by retailers. In construction, customers play a key role throughout the project cycle. Under guidance from the designer, customers define their product explicitly through the bid package or contract. The owner or the owner's representative can modify the requirements and details of the contract by addenda (before bids are opened) or change orders (once the bid is closed).
- **Complexity (temporary multi-organization and regulatory intervention)** - In manufacturing, many components from different subassemblies can be easily managed because suppliers are selected early in the design phase. With repetition, this supply network eventually becomes manageable and optimized. In contrast, in construction the completion of activities is highly interrelated and complicated. Being an on-site production, the installation of those subassemblies is constrained by the interacting and overlapping activities of different contractors, making it more difficult to meet a fixed schedule.

3.2 Implementing Lean in a construction context

Lean is highly interpretive and there is no shared definition of understanding of what is meant by Lean, Lean production, and Lean construction. Although the promotion of Lean construction has been highly visible in countries such as the USA, UK and Denmark, critical sounds are rarely heard (Jørgensen and Emmitt, 2008). The failure to recognize the potentially dark side of Lean in the construction debate should be a cause for concern: the danger is that both researchers and practitioners are misled by an overly optimistic literature.

Lean construction is a "way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value". (Koskela, 2002)

When considering the transfer of Lean production (processes) to construction (projects) it is necessary to consider the main characteristics of organisational concepts. Organisational concepts that become management fashions could become de-coupled from their original meanings as they are diffused, interpreted, translated, adopted worldwide. This phenomenon has had significant impact on the diffusion of Lean production. Adopting Lean principles in construction can be seen as an investment in the future of the project, which will give benefits and a solid return on investment.

Customer value in construction

An important implication of applying the Lean philosophy to construction is the understanding of waste and value. A main principle is to consider all downstream operations as customers, while value is defined only as perceived by the final customer ("ultimate customer"). The original concept of delivering value to a specific single end customer is highly problematic when considering the built product in a whole-life context with different owners and users (Jørgensen and Emmitt, 2008). From a practical perspective, questions of systematically enhancing value and eliminating waste become increasingly more complex the further one moves from production activities into the field of architectural design.

3.3 Lean construction techniques

Many authors highlight the importance of improving the construction supply chain collaboration and performance in order to achieve both short-term business objectives as well as long-term competitive advantage. Lean thinking is an approach that has been adopted in many different industrial settings to improve the supply chain performance. Recently it has been adopted by the construction industry (e.e. Lean construction) as a means of supply chain improvement. An investigation of important aspects and core elements of Lean construction seems pertinent in order to increase the understanding of what Lean construction really is about. The literature review presented below discusses how various techniques of Lean construction can be grouped into six core elements (Eriksson, 2010; Salem et al., 2006; Höök and Stehn, 2008 ;Jerry Kilpatrick, 2003).

1) Waste reduction

The most important core element of Lean construction is waste reduction. A central aspect of waste reduction is housekeeping, that is, keeping the construction site well organized, clean and tidy. Workers should therefore be encouraged to clean the job site once an activity has been completed.

A related aspect, crucial for waste reduction in Lean construction, is efficient transportation and stockholding of material, often termed just-in-time (JIT) delivery. From a JIT perspective inventories are not valuable and should be regarded as waste. Through JIT, contractors strive to receive smaller batches of material to the site when they need it in order to reduce stockholding and double-handling of material.

Another aspect of waste reduction is information technology. Joint IT tools or Building Information Modelling (BIM) allow detection and correction of most errors prior to production. Joint IT tools, enhancing integration among supply chain actors and their tasks, therefore increase the chance of cost and schedule success.

A fourth central aspect of waste reduction is off-site manufacturing of components and units. Prefabrication has many advantages similar to manufacturing industries, such as reducing material waste, shortening construction duration, improving work environment, etcetera. Hence, increased prefabrication makes Lean construction more similar to Lean production in manufacturing industries.

2) Process focus in production planning

Approaching production management through a focus on processes and flow of processes is a core element of Lean construction. The last planner system (LPS) is a key aspect that enhances efficient production planning and controlling. Last planners are the people accountable for the completion of individual operational assignments. Each planner prepares weekly work plans to control the workflow, and if assignments are not completed on time, they must determine the root cause and develop an action plan to prevent future failures.

It is important that each individual takes immediate action regarding their own work (i.e. self-control) to prevent defects at the source, hindering them to flow through the process. This aspect should be adopted in all activities during the whole buying process. Traditionally, contractors are used to being controlled by the client, which reduce their incentive to perform self-control satisfactorily. Nor do design consultants perform self-control satisfactorily due to lack of time. Empowering all co-workers to control their own work is therefore decisive.

A third aspect that enhances the focus on the schedule and production plans is to establish project milestones. By clarifying the importance of production milestones and making them explicit to everyone, the project participants will feel more involved in the execution of the project.

3) Customer focus

Increasing the value for the customer is a core element of Lean construction. Therefore, contractors and suppliers must understand the need of the customer: they have to supply what the customer needs, not what the customer asks for. Customer satisfaction is dependent on both the end product and the process during in which it is achieved (see also Systems Engineering). Early involvement of contractors and integration of design and construction in Concurrent Engineering (CE) is therefore highly important. Concurrent Engineering is a technique of using cross-functional teams (rather than sequential departmental assignments) to develop and bring new products to the market. It increases the contractors' understanding of the needs of the customer and improves teamwork and joint problem-solving, resulting in significant time savings.

Second, relying on competitive bidding is not efficient when procuring customized products in Lean construction. Focusing only on the lowest price will increase self-protecting attitudes among contractors rather than aiming for customer satisfaction. A limited bid invitation of trustworthy contractors should be coupled with a bid evaluation based on soft parameters in order to select capable partners to satisfy the customer's requirements.

4) Continuous improvement

A long-term perspective on continuous improvements (called Kaizen in the Toyota Production System) is important in Lean construction in order to reduce waste and increase the efficiency of the construction process over time. Long-term contracts (e.g. framework agreements) are therefore an important aspects, reducing the traditional short-term focus on cost reduction and promote lasting improvements. By working together on a series of projects the transfer of knowledge and experiences among supply chain actors and from one project to another is facilitated.

Measuring performance against pre-set targets is an important aspect of continuous improvements. Control and measurements of different kinds of performance indicators are vital in order to determine if performance is improving. Subsequently the reasons for satisfactory or unsatisfactory performance should be analysed in order to decide on potential improvement actions.

Additionally, staff and workers should be encouraged to initiate ideas and improved solutions to solve problems encountered on site. It is crucial that suggestions from workers are taken seriously in order to enhance their commitment to continuous improvements.

Although knowledge sharing and joint learning among people from different trades and disciplines is important in order to enhance continuous improvements in Lean construction, it is seldom realized due to lack of suitable methods. Such learning can be obtained by the establishment of quality circles, giving project staff opportunities to participate in the improvement process. These groups meet periodically to exchange knowledge and experience in order to jointly propose ideas for critical work-related problems.

The understanding of the Lean concept and its prerequisites must be improved by the project partners in order to increase their willingness and ability to contribute to continuous improvements. Therefore, relevant training is a precondition for effective Lean implementation.

5) Cooperative relationships

Cooperative relationships among the supply chain actors (often referred to as partnering) are an important element of Lean construction, facilitating the integration of different actors' competence and efforts in joint problem-solving. Since traditional procurement and governance forms are often criticized for producing waste, long lead times, and adversarial relationships, they need to be changed into a Lean contracting approach.

Since subcontracting can account for most of the project value and project activities are totally interrelated, a harmonization between main contractors and subcontractors is important for partnering and for Lean construction. Accordingly, it is crucial to involve key subcontractors in a broad partnering team, allowing all important actors to contribute to the joint objectives.

Earlier research has, however, found practical difficulties when trying to involve the wider supply chain in Lean construction initiatives.

Central to the establishment of such a cohesive partnering team is the achievement of good communication, integration, and coordination, which is facilitated by various collaborative tools, such as joint objectives, joint project office, facilitator, and teambuilding.

It is important that all parties benefit from improved performance resulting from the implementation of Lean construction. Fair and equitable rewards are especially vital for building trust and cooperation among construction supply chain actors. Hence, an incentive-based compensation form including gain share/pain share arrangements, which increase the actors' commitment to contributing to the joint objectives, is an important measure in cooperative relationships.

6) Systems perspective

Another core element of Lean construction is to adopt a systems perspective aiming to increase the overall efficiency of Lean construction projects instead of sub-optimizations. A reliable workflow in the general system is more critical than individual activity speed or cost. Considering the whole buying process and making coherent procurement decisions is an important aspect for supporting the general process.

In addition, by minimizing the number of steps, parts and linkages, the construction process will be simplified. Lean construction cannot be achieved by considering construction, design, and operation in isolation. Therefore a rearrangement of the contractual boundaries among the parties is required. Accordingly, large scope contracts are desirable instead of dividing a project into small pieces, involving many different supply chain actors during short periods of time. Value Stream Mapping (VSM) is considered as a useful tool for identifying bottlenecks in supply chain.

A systems perspective is also helpful in terms of the end result of the process. In order to obtain properly balanced objectives (e.g. cost, schedule, and quality), each project objective should receive a suitable amount of attention, relative to its importance, during the whole project process. Focusing on the formulated objectives by the customer, Systems Engineering (SE) is a helpful method in an interdisciplinary field of engineering that focuses on how to design and manage complex engineering projects over their life cycles. It is also important that the specified objectives and values of the project are made explicit to all supply chain actors.

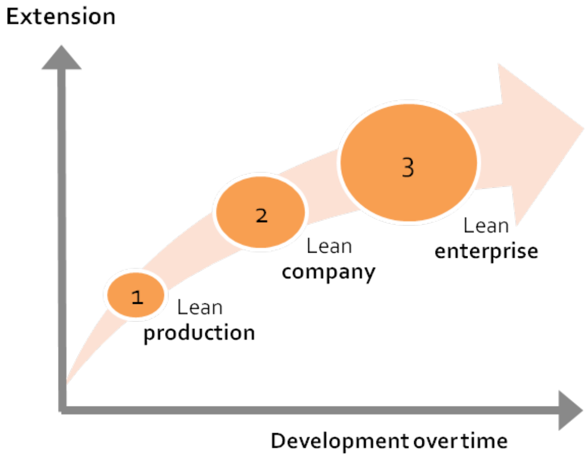


Figure 3.1 The evolution process adopting Lean principles and techniques within an organization

3.4 Three stages of Lean

According to Green and May (2005), implementations of Lean construction techniques can be divided into three different stages. These stages have an increasing degree of sophistication. To become a 'Lean enterprise' in the end, a organization should adopt all the three stages (Eriksson, 2010):

Stage 1: Focus on waste elimination for a technical and operational perspective

The responsibilities and focus are tied to managers rather than individual workers. Essential parts of this stage are: elimination of needless movements, cutting out unnecessary costs, optimizing workflow and sharing the benefits from improved performance. The Lean aspects related to this stage can be adopted in any construction project striving for operational efficiency.

Stage 2: Focus on eliminating adversarial relationships and enhancing cooperative relationships and teamwork among supply chain actors.

The essential parts are cooperation, long-term framework agreements, workshops and facilitator. Lean stage 2 does not go much beyond the concept of partnering since it is about eliminating waste derived from sub-optimizations and adversarial relationships through increased integration and collaboration.

Stage 3: Focus on a structural change of project governance (the most sophisticated stage). It's essential parts are: information technology, prefabrication, last planner system, bottom up activities and emphasis on individuals, a rethink of design and construction,

Lean concepts (objectives)		Lean techniques (methods)	Stage		
1.	Waste reduction	• Housekeeping	1		
		• JIT-deleveries	1		
		• Joint IT tools			3
		• Pre-fabrication			3
2.	Process focus	• Last Planner System (LPS)			3
		• Self-control			3
		• Milestones	1		
3.	Customer focus	• Concurrent Engineering (CE)			3
		• Limited bid invitation		2	3
		• Soft parameters		2	3
4.	Continuous improvement	• Long-term contracts		2	3
		• Performance indicators	1		
		• Special interest groups (SIG)			3
		• Training			3
		• Suggestions from workers			3
5.	Cooperative relationships	• Broad partnering team		2	
		• collaborative tools		2	
		• Gain/pain share	1		
6.	System perspective	• Coherent procurement decisions			3
		• Large scale contracts			3
		• Systems Engineering (SE)			3

***Table 3.2** Lean techniques divided in six core concepts of Lean construction (framework for qualitative field research)*

decreased competitive forces, long-term contracts, training at all staff levels, and a systems perspective of both processes and the product. Only when striving to achieve stage 3, a radical change from other types of project governance is required.

3.5 Conclusions

What is Lean construction? Lean construction is a way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value. In order to measure the degree of Lean construction, the effective utilization of the following three elements should be adopted in the framework:

- Materials
- Time / Lead time
- Effort

Construction has a much lower production performance compared to the rest of the manufacturing industry in terms of productivity, quality, and therefore value for money. Some authors have researched that there is about 25% of waste in construction projects. Lean construction is seen as a solution for eliminating this waste in order to improve the production performance. The difficulty is that the concept of Lean is highly interpretive and there is no shared understanding of what is meant by Lean management, Lean production, and Lean construction.

When considering the transfer of Lean production (processes) to Lean construction (projects) it is necessary to consider the main characteristics of their organizational concepts. Construction industry has three other features that distinguish it from manufacturing:

1. On-site production
2. One-of-a-kind projects
3. Complexity (temporary multi-organization and regulatory intervention)

Although these operational differences, Lean manufacturing and Lean construction techniques share many common goals. Many authors highlight the importance of improving the construction supply chain collaboration and performance in order to achieve both short-term business objectives as well as long-term competitive advantage.

Since the interpretation of Lean is highly variable, exceeding all boundaries, organizations and management levels, in this research Lean construction will be explained by following the concepts and techniques subtracted from literature, as presented in table 3.2. This table will be used as 'framework' for translating the Lean thinking concepts in practical terms. Although most of these Lean techniques may be implemented as stand-alone program, few have significant impact when used alone. Implementing a specific set of techniques will result in significant improvements on various Lean concepts.

>> In the next chapter the implementation of the Lean techniques as formulated in table 3.2, will be explained by following two strategies in order to improve workflow. In chapter seven. The implementation and effects of these Lean techniques will be reviewed in practice by investigating a Lean construction case study.

4. Improving workflow in construction

This chapter explains the importance of a proper workflow in construction. Additionally, two strategies for improving workflow in construction will be revealed adopting a specific set of Lean techniques. The following sub question will be answered: ***How can Lean thinking improve workflow in construction?***

4.1 Understanding workflow in construction

To improve productivity in construction industry, one of the most important aspects is reducing on-site material handling and lead times through proper workflow management (Peter Simonsson et al., 2012).

Achieving the right workflow in construction is a core principle of Lean construction. According to Womack and Jones (2003), workflow refers to the movement of materials, information and resources through a system. A flow is composed of transformations, inspections, moving and waiting. To create a smooth flow of work, the availability of materials, information and resources must be controlled during the whole production process (Sarker et al., 2012; Peter Simonsson et al., 2012; Errasti et al., 2009).

In comparison with the smooth (serial) workflow in manufacturing environments, for example the use of assembly lines in the automobile, it is more difficult for construction industry to define value-adding production steps. This is perhaps more evident in civil construction projects as value is often viewed differently by different stakeholders and participants. Root cause is the unique nature of most on-site construction projects. A random construction process is not standardized and needs to be re-developed each time, from that the contractors focus is not to plan and optimize the on-site building process. It is a 'low volume, high variety' environment in which workforce, equipment and materials must be taken to the site where the finished product has to be assembled (Errasti et al., 2009).

4.2 Two strategies for improving workflow

As mentioned in before, there is up to 25% of waste in construction costs. For improving workflow in construction there seems to be two different strategies (Peter Simonsson et al., 2012 Sven Bartelsen, 2004; Höök and Stehn, 2005): to reduce the complexity to a level where the principles from the ordered world of manufacturing can be used, or to develop new methods for the management and control of the construction process as a complex system. In other words, to develop either the product or the process. In practice the product strategy, means to transfer more and more parts of the construction work into off-site fabrication, and thereby make the site work an assembly only. The process strategy aims to develop the on-site construction process in its own right.

Decisions made early, affects how to be built and therefore affects the workflow on-site. Such factors as location, type and shape, material choice and detail design all affect the flow of work. Hence, to achieve workflow at the construction site, the design and planning phase needs to be controlled and managed from a constructability perspective. Adams (1989) stated that the key to success is the early design stage where knowledge from all vital actors is gathered to create constructability for a specific project. Wong et al. (2004) states that design decisions

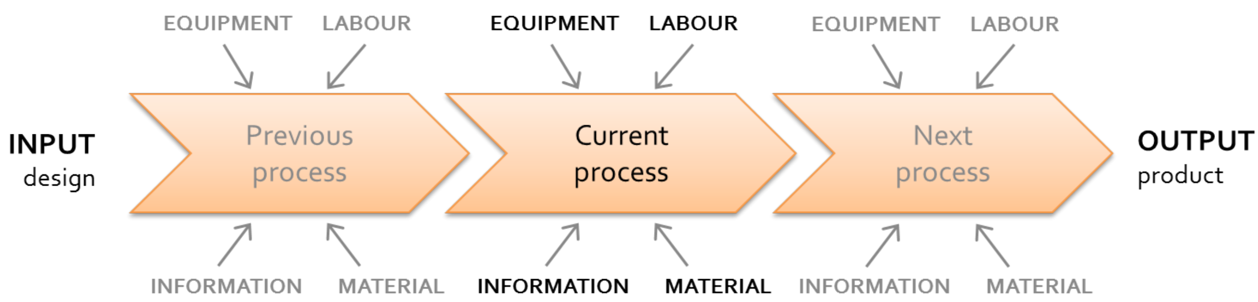


***Figure 4.1** Simplification of workflow*

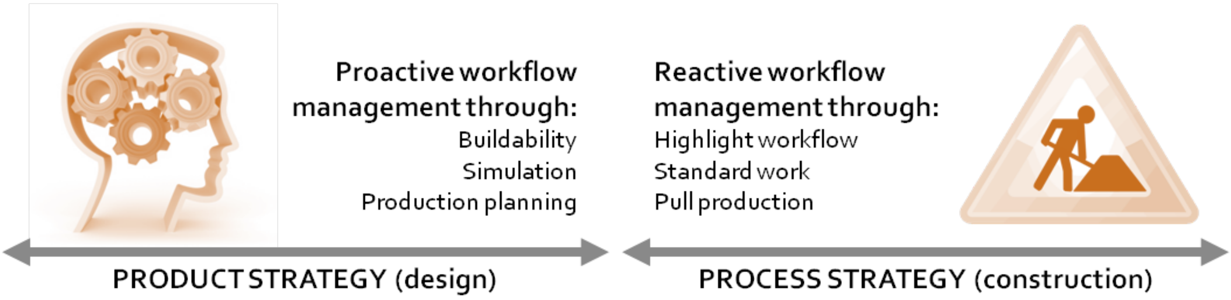


Figure 4.2 Two strategies for improving workflow in construction

affect how a building is to be built and determine the types as well as level of resources to be involved in the conversion process, and that designers often lack the knowledge and the incentive to make the right decisions.

Consequently, it is possible to work with workflow at both the early stages of a construction project using the so called proactive workflow methods (product strategy) and during the project execution at the construction site using so called reactive workflow methods (process strategy) (Peter Simonsson et al., 2012; Sven Bartelsen, 2004; Höök and Stehn, 2005)):

- **Product Strategy (Proactive method)** - Aims at removing hindrances to production workflow in the design phase. Common methods are e.g. improved constructability and proper production planning. Another useful method for proactive workflow management is simulation using for example 4D planning with BIM software.
- **Process Strategy (Reactive method)** - Aims at removing hindrances in the production phase so that even workflow is achieve at the construction site. Common methods are e.g. planning for pull production like Lean planning methods and standardizing work tasks. Another useful method for reactive workflow management is to highlight workflow by value stream mapping.

1) Product strategy: Developing construction into assembly

This strategy is based on recognizing that not every production resulting in a building is construction. Some cases, for example prefabricated standardized houses, are fabrications which have much similarities to the manufacturing industry. But also the manufacturing of components, materials and systems becomes more and more developed. Structural steel and concrete slabs are almost always prefabricated, the envelope is often so as well, and recently we have seen approached towards prefabricated HVAC-piping. Also the construction materials turn more and more from being basic materials as timber, bricks and cement into being components or systems with a much higher degree of prefabrication, making the process at the construction site more and more an assembly process than actual work of craft, and industrial thinking about new issues such as the management of tolerances comes into focus.

The product strategy, also promoted by Lichtenberg (2002) with the 'SlimBouwen' concept, becomes more and more common as can be seen from the steady growth of the supply industries and the development of their products into systems. Even though this strategy may seem to increase complexity as the products become more complex and the depth of the supply chain grows, it is in its nature a reduction in the total project complexity. The project may still be a one-of-a-kind product, but as

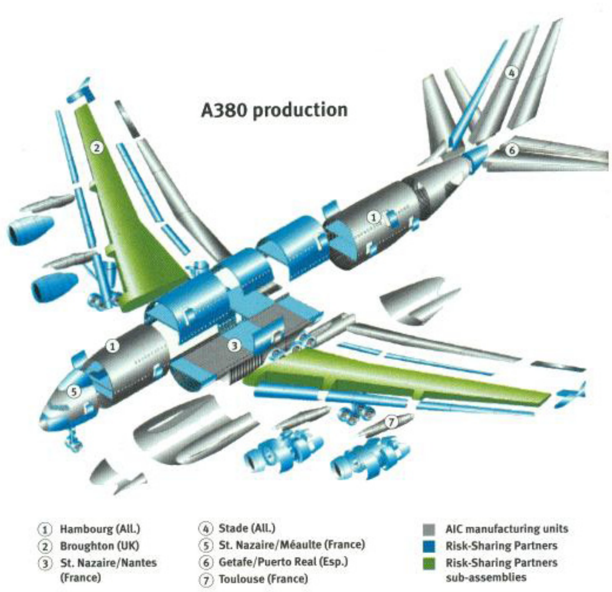


Figure 4.3 The Airbus A380 is composed of prefabricated modules manufactured by different partners (co-makers)

it is more and more composed of industrialized modules manufactured in ordered and controlled environments where manufacturing management principles can be applied, the complexity of the construction process is reduced substantially (Sven Bartelsen, 2004).

2) Process strategy: Improving reliable schedule forecasting

Project managers in construction participate in a multi disciplinary process riddled with technical and social pressure. For the project management it is important to understand the relationships between planning, organizing, leading and controlling a process. Overall, these four tasks facilitate the structuring and execution of work. In this manner, scheduling is an important process that network tasks in order to communicate what should happen in future to create a smooth workflow.
The most readily applicable method for improving workflow is pull production. Pull means that no upstream actor should produce anything until the customer downstream asks for it (Womack and Jones, 2003). In construction, the most recognized and applied tool to generate pull is the four-tired Last Planner System (LPS) of production control (Peter Simonsson et al., 2012; Christine A. Slivon et al., 2010):

1. **Master planning** (milestone planning)
2. **Phase scheduling** (make-ready planning)
3. **Look-ahead planning** (weekly planning)
4. **Commitment planning** (daily stand-up sessions in the field)

Using these four levels of planning, management can structure work using the most recent information and provide reliable workflow with pull techniques and active conflict resolution. Overall, controlling uncertainty can provide more reliable schedule forecasting and project control. Since the unknowns for Design-Build (DB) projects are unavoidable, the four-tiered planning approach of the Last Planner System (LPS) may provide the only viable option (Timothy Gannon, Peter Feng, William Sitzabe, 2012).

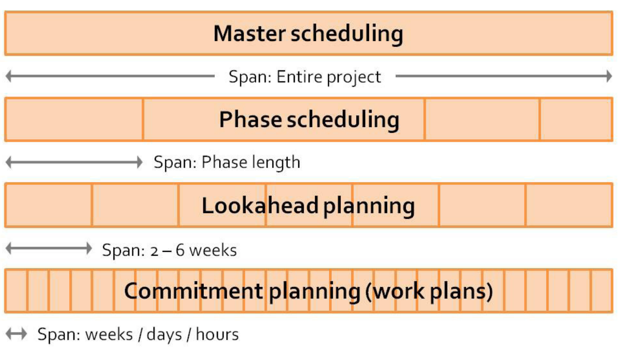


Figure 4.4 The four-tired planning approach of the Last-Planner-System (LPS)

Planning must begin with incomplete knowledge of the future. Each work's ability to proceed depends on the reliable fulfilment of prior and concurrent promises (and external conditions). The Last Planner System orchestrates a continuous renegotiation of these promises to keep the work flowing so workers should never wait for work.

Balancing the financial investments and risks of a facility project against the progression of completed work is a key management mechanism for the project management. General contractors are committed to show a plan to accomplish work and receive compensation through an initial schedule. However, if the initial schedule fails as a suitable baseline because of change, change should be integrated into project management fort both sides of the contract. Together the government and contractors can work to pull scheduling into place rather than push.

Another approach to minimize wasteful activities is to standardize work tasks (Timothy Gannon, Peter Feng, William Sitzabe, 2012). The execution of work tasks varies from construction site to construction site and from worker to worker. Work is standardized to systemize operations and materials so that human motion between operations and needed resources is used in the best known order and hence most efficiently. With process standardization, the manufacturing process becomes more solid, leading to operational excellence, continuous improvement and elimination of non-value-adding activities.

4.3 Learning from manufacturing industries

Learning from manufacturing industries is a useful approach for improving the productivity of the construction industry and to solve problems arising from construction processes. For example, total quality management (TQM), supply chain management (SCM) and Lean manufacturing are now familiar management concepts in the construction industry (Li et al., 2008).

A good example is the assembly process of an IKEA product. As the world's largest (and arguably most successful) furniture retailer, the IKEA Group and its methods have been studied by many researchers from several perspectives and its smart logistics system, revolutionary strategy and management system have inspired other industry sectors. The essence of the IKEA spirit is 'offering a wide range of well-designed, functional home furnishing products at prices that are so low that as many people as possible will be able to afford them'. It became famous for the fact that the customers have to assemble many of the products by themselves. During the process of assembling a piece of IKEA furniture, there are no design errors and construction problems as the design is checked in a 3D environment and the assembling process is guided by a set of 3D easy-to-read instructions.

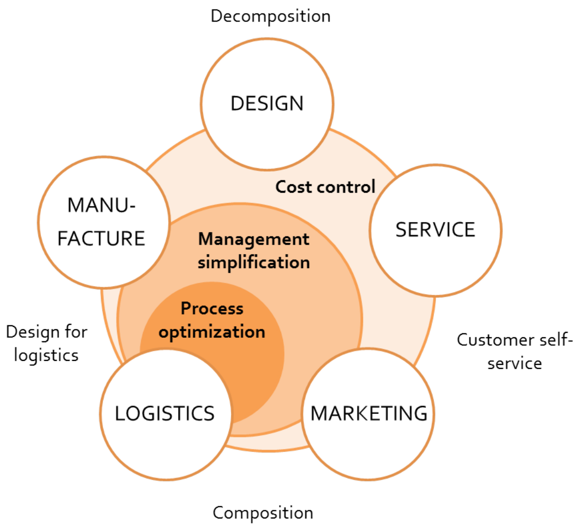


***Figure 4.5** The IKEA 'business model'.*

In the manufacturing industry, the decomposition and assembly of a product are two basic activities that determine its cost. To do this, IKEA extends the traditional principle of 'Design for manufacturability' (DFM) to 'Design for logistics' (DFL), by considering not only the function and manufacturability of the product, but also the convenience of packaging, transporting and assembling the product. In this way there is no need to have any additional management personnel to supervise or manage the assembling process. This is reducing management costs to a minimum. A construction process, especially when prefabricated components are extensively used, has similarity with the assembly process of an item of IKEA furniture.

4.4 Co-maker as critical success-factor

Since a huge proportion of work in construction projects is conducted by subcontractors and in a higher evolvement by so called co-makers, the non-performance of any (sub) contracting firm can be one of the root causes for project failure. Despite that, these sub-contractors are still commonly seen by the main contractor as a mechanism to save costs, redistribute workload and streamline in-house manpower (Ng and Tang, 2010; Chan et al., 2004). The performance of sub-contracting firms is far from satisfactory. Besides that, sub-contractors are notorious for their high rate of bankruptcy and poor output standard. This is totally undesirable when sub-contractors are regarded as the specialists in their trades.

The problem is that the sub-contracting team is reassembled each time, and it is difficult to build up a trust and enduring relationship between the main contractor and sub-contractors. Some sub-contractors may therefore try to cut corners in order to recoup their profit under a fierce competition. The ultimate sufferers would be the main contractor, clients and end-users.
Lean project delivery is seen as a solution because it includes several ways of reducing the inherent risk of a large, complex construction project: iterative planning, public commitment, and an Integrated Form of Agreement (IFOA) (Christine A. Slivon et al., 2010; Becker et al., 2012) Traditional forms of contract in the construction industry attempts to minimize risk by one party. The IFOA is an innovation which enables participants to work together to minimize total risk and to share the remaining risk

***Figure 4.6** Improving cooperation in sub-contracting teams by Lean thinking will reduce much waste occurred in the 'grey areas' between project participants.*

equal to the co-makers, from the start to delivery.
The most important success factors for working with sub-contractors and co-makers, are timely completion, profit, programme/planning, cash flow, as well as management level leadership (Ng and Tang, 2010). These critical success factors should the general contractor taking in mind by choosing a party as co-maker or sub-contractor.

4.5 Conclusions

How can Lean thinking improve workflow in construction? To answer this question, first the aspects of workflow will be explained.

In order to improve the productivity in Lean construction, the most important aspects are reducing on-site material handling and reducing lead times through proper workflow management. Proper workflow management can be achieved by efficient use of time and effort. The effort needed in the conversion process can be expressed in direct operational costs and indirect management costs.

Operational costs can be translated in the utilization of workforce (man hours) and equipment (rental prices) on-site, aiming to transform material into adequate output requested by the customer. Management costs are less specific since they contain several overhead costs. Both costs will be adopted in the workflow model (data framework):

- Direct operational costs (labour and equipment)
- Indirect management costs

To create a smooth workflow the availability of materials, information and resources must be controlled during the whole production process. In this way many disruptions during construction will be eliminated so that workers never have to wait for work or have to repair construction errors. As a result of reduced lead times, both operational costs as well as management costs will be saved.

For improving workflow in construction there seems to be two different strategies:

- Product strategy - Using the so called proactive workflow methods in the early design stage. Within the product strategy, design for constructability and prefabrication are mentioned as solutions for process improvement by transforming construction into an assembly system.
- Process strategy - Using the so called reactive workflow method during the execution at the construction site. The process strategy focuses on more reliable planning schedule methods by promoting the use of the Last Planner System (LPS) and standardization of work tasks.

In both strategies co-makers are seen as a critical success factor for project success. Because a huge proportion of work in construction projects is conducted by co-makers and subcontractors, the non-performance of any (sub) contracting firms can be one of the root causes for project failure.

Learning from manufacturing industries is a useful approach for improving the productivity of the construction industry and to solve problems arising from construction processes. In the manufacturing industry, the decomposition and assembly of a product are two basic activities that determine its cost.
Design decisions affect how a building is to be built and determine the types as well as level of resources to be involved in the conversion process. Architects often lack the knowledge and the incentive to make the right decisions.

>> In the next chapter a model will be presented to measure workflow in construction. Using this model, data can be compared between different construction processes in order to improve workflow in a construction project.

5. Lean assessment - from theory to practise

The literature in previous chapters explained what Lean construction is about. In order to compare the theoretical aspects of Lean construction in practice, the following sub question is answered: ***Which methods can be used for Lean assessment in construction projects?***

5.1 Parameters of efficiency in construction

As starting point for Lean assessment of the case study, a list with 'Parameters of efficiency in construction' will be applied as manual for evaluating the effects of Lean construction (see appendix A4). This instrument is distilled from a current research called 'Lean Construction management (LCM) and efficiency in the Building process' by W. Van den Bouwhuijsen en G. Maas (see appendix A3). The purpose of the research is to determine the parameters of efficiency in construction and to compare efficiency between (Lean) construction projects. These parameters concern the information flow from designers to contractors and from contractors to subcontractors and suppliers, both seen from the viewpoint of the general contractor. Since the list is too extensive for the purpose of this research, only the most valuable and comparable parameters are used for assessment of the case study project 'Sporen in Arnhem' (see table 5.1).

	Parameter	category #
1.	Bid price (euro)	C1
2.	Client demands	C4/C5
3.	Tender/Design phase	C11
4.	Co-makers performance	C14/C15
5.	Volumes/quantities (number)	C17
6.	Lead time (days; hours)	C20
7.	Operational cost (euro)	C20
8.	Construction site costs (euro)	C23/24
9.	Deliveries/logistics	C31
10.	Instructions/training	C33

Table 5.1 *Selected 'parameters of efficiency in construction' distilled from a broader research by Van den Bouwhuijsen.*

5.2 Developing a workflow model

As citated by Koskela (2002) in paragraph 3.2, Lean construction is a way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value. Reducing lead time and on-site material handling is one of the most important aspects that determine the construction costs (see paragraph 4.1). By reducing lead time, both operational and management costs will be reduced.

Allowing the site management to show the flow of materials, labour, equipment and information can improve the performance of construction (see paragraph 4.1). A standardized flow of, for example, materials makes it possible for the site management to plan ahead rather than "extinguish fires" (solve urgent matters). For this, site management must be trained to differentiate between value adding and wasteful activities in order to eliminate waste from the construction process. By analysing the workflow, the on-site management is able to understand the potential effect of improving the current workflow. Schematically visualizing the traditional workflow for identifying potential waste, is rarely enough for changing traditional practices (Peter Simonsson et al., 2012). But, with the inclusion of easy to understand and calculable metrics for lead time and operational costs, the potential savings in future workflow can be estimated.

Application

Using the selected parameters of efficiency as manual (see table 5.1), a model is developed for investigating workflow metrics in more detail. The purpose of this model is to (re)calculate and compare various workflow quantities (see figure 5.2). A framework attached to this model will be utilized as 'data base' for this case study (see appendix B11).

The following aspects extracted from literature are adopted in this model concerning the flow of work in construction projects:

- **Lead time:** the time needed to produce adequate output
- **Inventory:** the needed materials; the stock level
- **Effort**: the production costs connecting the transformation of input into output.

Related aspects for analysing the workflow in order to reduce lead times and material handling on site are:

- **Value-adding activities:** Primary activities what contributes direct to that what the customer is asking for.
- **Non-value adding activities:** Secondary activities which are necessary for completing the value-adding activities. These type of activities should be reduced as much as.
- **Labour utilization:** Type of activities which are highly depending on labour effort. These type of activities

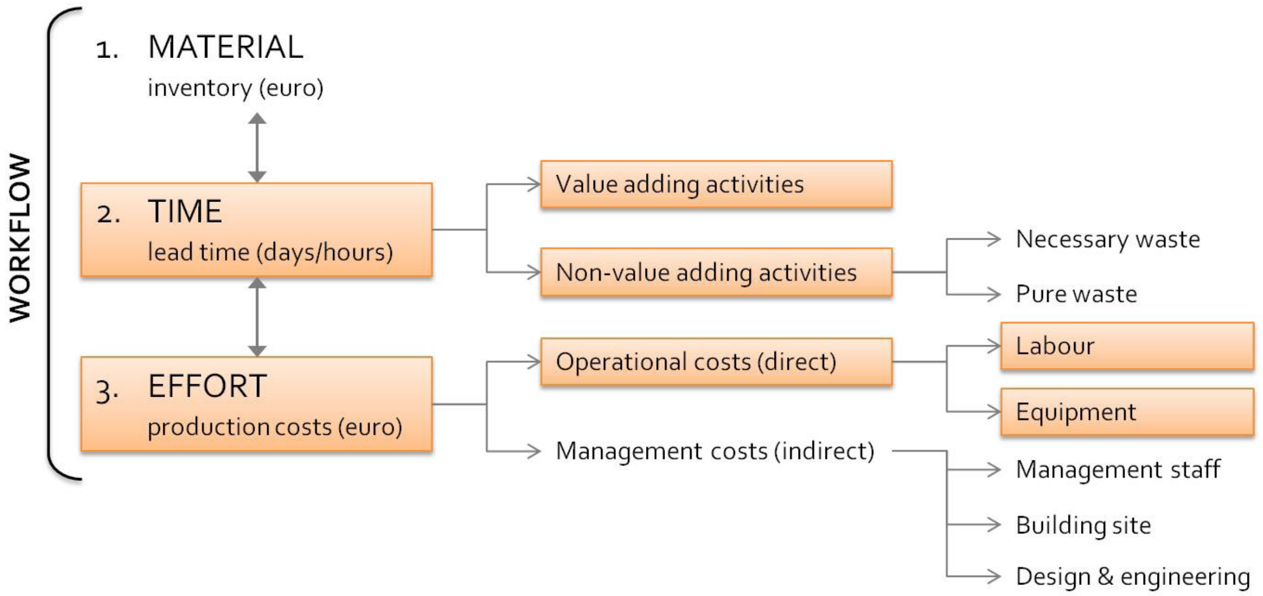


Figure 5.2 The workflow model developed out of the literature review (the metrics formulated in orange will be subtracted from the Lean planning schedules)

are highly influenced by manpower and therefore less reliable.

- **Equipment utilization:** Type of activities where most of the costs are determined by equipment utilization.

Data source

The metrics of total cost, total duration and activity count allow us to analyze data from the initial schedules versus the subsequent schedule updates (Timothy Gannon et al., 2012). These metrics illustrate the forecasting shortfalls in the activity based scheduling currently used in public sector construction management. The growth in these metrics indicates that uncertainty in the beginning of the project is unavoidable. Although creating a baseline early may establish an indicator of project plan and scope, the encountered modifications can quickly out date the current planning. Since change happens, it should be incorporated progressively in the planning schedules (Timothy Gannon et al., 2012). Therefore Lean planning schedules are the most appropiated schedules to use as source for workflow metrics.

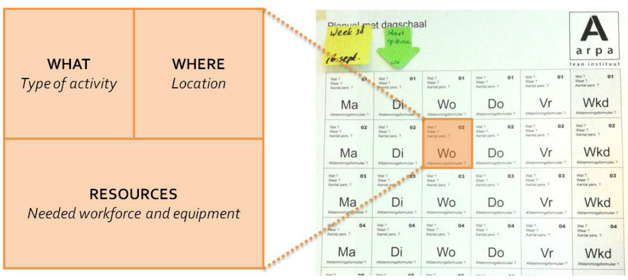


Figure 5.3 Co-makers schedule their own work simultaneously using post-its on giant posters. The post-its presenting lead time and effort (use of workforce and equipment).

5.4 Conclusions

Which methods can be used for Lean assessment in construction projects?

For Lean assessment of a critical selected case study, two research approaches can be used:

- **Evaluation of implemented organisational Lean techniques (qualitative research)** - Investigating the implemented Lean approach by evaluating the use of organisational concepts compared to the formulated Lean construction techniques (see table 3.2). To enhance comparisons between the conceptual arguments and empirical data, it is important to select a critical case that explicitly adopts Lean construction techniques.
- **Assessment of current workflow (quantitative research)** - Analysing the recourses needed during execution using the developed workflow model (see figure 5.2). With the inclusion of easy to understand and calculable metrics for lead time and operational costs, the metrics can be compared.

In both approaches a specific selected serie of 'parameters of efficiency in construction' (table 5.1) is used as manual for evaluating the effects of Lean construction in the selected case study.

I. THEORETICAL FRAMEWORK

II. FIELD RESEARCH

III. CONCLUSIONS

IV. DESIGN

"The most dangerous kind of waste is the waste we do not recognize."

Shigeo Shingo

6. Case study description

6.1 Field research approach

Now the theory about Lean construction and how to improve and measure workflow is well-known, these aspects will be tested in practice. Field research will be performed using (parts of) the Lean construction pilot project 'Sporen in Arnhem'. As concluded from the theoretical framework in the previous chapter, two approaches for Lean assessment will be used:

- **Qualitative research** - Evaluation of the implemented Lean techniques subtracted from documents and interviews. This research focuses on the implementation of organisational concepts associated with the execution of the railway station (focus 1, see figure 6.1).
- **Quantitative research** - Measuring the workflow of three identical construction processes of the so called 'standard elements' defined within the project 'Sporen in Arnhem' (focus 2 and 3, see figure 6.1). This comparative data analysis is performed using the developed workflow model as database in which metrics from the available Lean planning schedules are used (step 96, 190 and 290). These Lean planning schedules are considered as the most reliable approach of reality due work is tuned between all involved co-makers short before production starts. Although these documents are the most detailed and updated production schemes available, tolerances will certainly exist. When the needed data is not sufficient or (partly) unavailable, it is recalculated or interpreted in the most appropriate way.

In the next paragraphs the case study project 'Sporen in Arnhem' will be introduced.

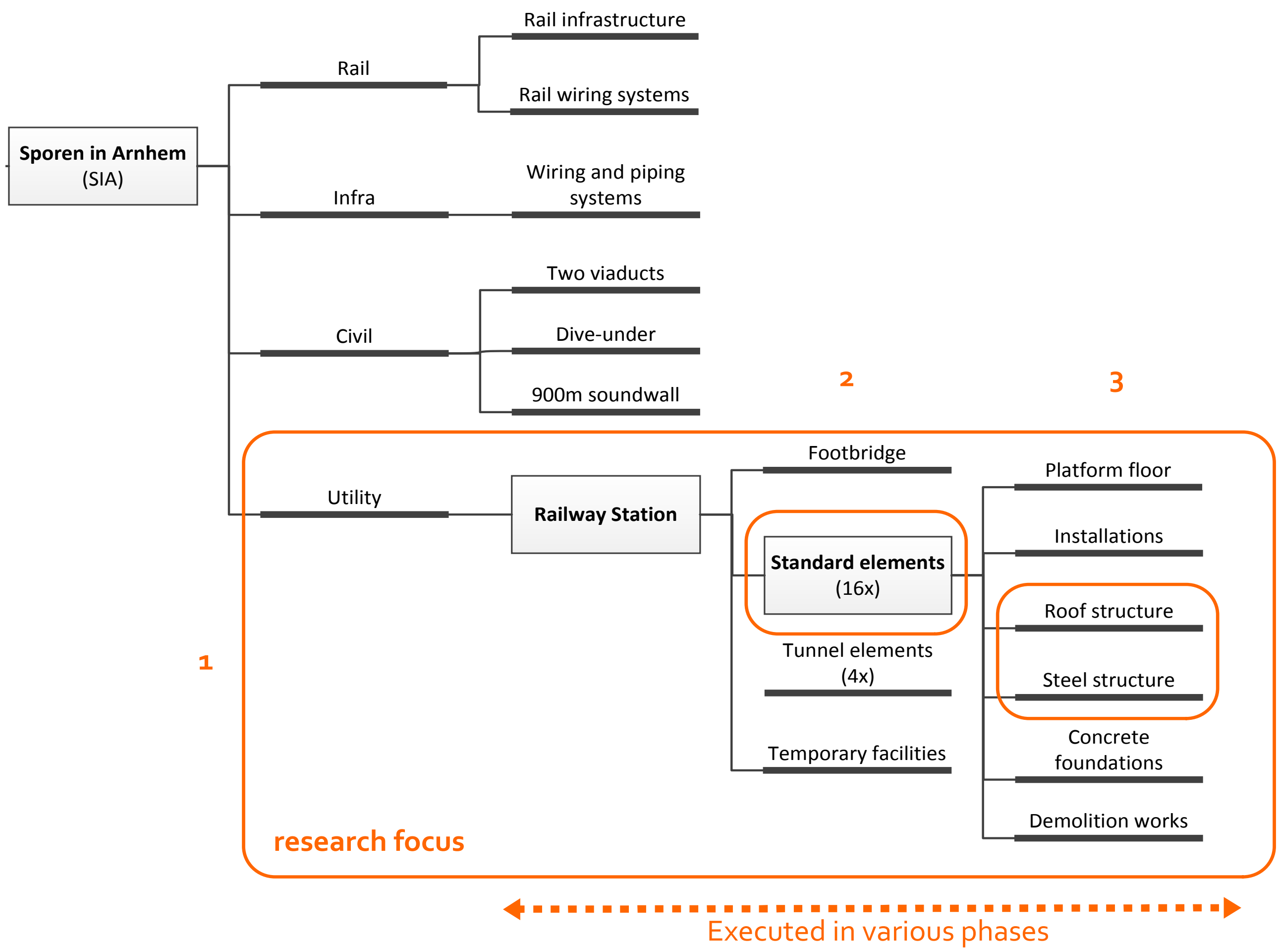


Figure 6.1 Overview of the research focus within the case study project 'Sporen in Arnhem'
1) Focus qualitative research
2) Focus quantitative research
3) Focus quantitative research: application of the workflow model determining lead time and operational costs

6.1 Project description: 'Sporen in Arnhem' (SIA)

General information SIA

Scope	: Replacement of the former railway station together with all the surrounding civil- and rail infrastructure.
Location	: Arnhem (the Netherlands)
Client	: ProRail (a company responsible for the Dutch railway infrastructure)
Architect	: UNStudio (Ben van Berkel)
Contractor Combination	: BAM/DuraVermeer
Disciplines	: Civil, Infra, Rail, Utility
Bid price	: € 110,6 Million
Extra work	: € 45 Million
Total price	: € 146,6 Million
Building period	: 29 months (in 5 general steps)
Completion	: April 2012

Figure 6.2 *Artist impression of the new railway station in Arnhem*

Masterplan

The project 'Sporen in Arnhem' (SIA) is one of the two major projects within the masterplan 'Arnhem Centraal' concerning the redevelopment of the railway station area in Arnhem (see appendix A5). SIA is completed in April 2012 and contained the replacement of the former railway station together with the rail infrastructure. The second major project is the development of the new public transport terminal 'Openbaar Vervoer Terminal' (OVT). This project is divided into two phases, the first is completed in 2011, the second will be ready in 2015.

The railway station 'Arnhem Centraal' is one of the key stations in the Netherlands (besides Amsterdam, Breda, Den Haag, Leiden, Rotterdam en Utrecht) which will be improved by the NS (Dutch railways) and the Dutch government into so called 'World Stations' with international appearance (www.ns.nl/wat-doen-wij/wereldstations) . Due to the arrival of the High Speed Line the new stations will compete in functional and architectural way with other International railway stations in Europe. These key stations will be functioning as dynamic city portals with a high architectural expression and much room for retail.

Scope of SIA

The scope of the project 'Sporen in Arnhem' contains the complete replacement of the rail infrastructure together with the replacement of the former platforms and the realization of a new fourth platform. Due to the arrival of the High Speed Line (HSL) the former railway station was not sufficient anymore. Aim of the project is to increase the capacity, reliability and availability of the rail tracks in Arnhem (www.arnhemcentraal.nu). A significant increase of capacity was needed: from 4 to 6 Intercity's per hour, from 30.000 to 52.000 passengers a day together with higher punctuality and a significant increase of cargo trains. With the realization of SIA ProRail is responding on the expected growth of travelers in the future.

Disciplines

Due to the project SIA is characterized by a combination of disciplines the tender is gained in a joint-venture of several construction companies (BAM Rail, BAM Civiel, BAM Infratechniek, BAM Utiliteitsbouw, Dura Vermeer Beton- en Waterbouw BV and Dura Vermeer Railinfra BV). These companies have to work together in orther to complete the project within the limited time. This complexity causes that the client ProRail has demanded a close alliance of several construction companies/ disciplines. Each of these companies is responsible for their own scope within the project SIA (see figure 6.1):

- **Civil** - The replacement of two viaducts, realization of a dive-under and the realization of a 900 meter sound wall on the North-side of the station.
- **Infra** - Complete replacement of all the wiring and piping systems.
- **Rail** - Complete replacement of the entire railway infrastructure around the station, including the wiring and safety systems.
- **Utility** - Replacement of the three train platforms (platform 1, 2 and 3) including roofs. Replacement of the traveller bridge which connects the platforms to the street on the North side. And the realization of a new fourth platform on the North side of the station.

6.2 Scope qualitative research: Railway station

Technical information

Scope	: Replacement of the railway station
Discipline	: Utility
Gen. contractor	: BAM Utility
Co-makers	: Van Dalen (demolition works)
	: Buiting (steel works),
	: Spie (installations)
	: Sorba (roofing)
Surface	: 16.000 m2
Bid price	: € 24.289.000 *(installations included)*
Turnover	: € xx.xxx.xxx (+60%) *(confidential)*
Profit	: € x.xxx.xxx (>10%) *(confidential)*
Completion	: September 2011

Figure 6.3 *Artist impression of the foodbridge (out of research scope) and platforms*

Railway station description

The railway station within project SIA exists out of new roof constructions on all the four platforms together with a footbridge. This footbridge runs over all the platforms and connecting them with the Northern entrance of the station. On the other side passengers can enter and leave the platforms by a passenger tunnel. This tunnel, containing much room for retail, will connect the platforms to the Public Terminal.

The complete structure of the platform roofs and footbridge is made out of steel. The facades are completed in glass. Aluminium composite panels and cold bended glass is applied for covering the roofs. The architectural shape is complex: large parts of the design is vaulted and no single column is straight.

Railway station elements

In a more technical way the replacement of the railway station within the project ´Sporen in Arnhem´ consists out of three different subsystems considering the work for BAM Utility:

Demolition works

Demolition of the platforms one, two and three and the new realization of a fourth platform on the North side.

Realization of platform roofs -

Realization of the platform construction on all the four platforms. This can be divided into three separate building objects (see figure 6.6):

1. ***Tunnel elements:*** the platform above the new platform tunnel
2. ***Footbridge elements:*** the platform connected to the bridge and above the stairs and elevators
3. **Standard elements:** the intermediate platform

Passenger food bridge

A footbridge starting from the first platform above al the four platforms, including stairs and elevators and a second new entrance on the North side of the station to the Amsterdamseweg.

Out-of-service periods

The entire project of SIA is executed in five general phases (see appendix A7). Four of these phases (step 96, step 190, step 290 and step 390) are so called 'out-of-service periods' (see table 6.5). In these periods rail traffic has been canceled temporary for a specific number of tracks. These periods have been rock-solid since they are planned far in advance.

In first attempt is examined to plan the construction work in a single large out-of-service-period (OSP), a so called 'big bang' in combination with various little OSP (see appendix A6). In order to acquire sufficient support, this idea is further elaborated during a number of workshops. A total of nine external parties (ProRail Infraprojecten, ProRail Capaciteitsmanagement, ProRail Railverkeersleiding, NS Reizigers, Railion, Syntus, NedTrain and the municipality of Arnhem) had to come to an agreement.

The initially idea of one 'big bang' has not succeeded. The Dutch railways Travellers and Syntus (a regional railway company) have argued that a total blocking of the Arnhem station for long periods is not negotiable because the logistical consequences. Because the high number of travellers at Arnhem Station insoluble bottlenecks will arise:

- Size of alternative transport by bus - First, the necessary numbers of buses are not available. Second, facilities for bus stops nearby Arnhem station are inadequate and impossible to realize. Third, intensity of the bus transport leads to bottlenecks in the supply and delivery routes.
- Overload at railway stations near Arnhem (where temporary train turn facilities will be realized).
- Insufficient room for equipment storage on-site.

This partly use of Arnhem station together with the preconditions of the rail users have led to the plan phasing 2011, in which all the building steps are executed in five phases (four out-of-service periods). For more detailed information see appendix A6 and A7. All the out-of-service periods are consciously planned during summer holidays to avoid much inconvenience for commutes.

Figure 6.4 Situation during step 250

Phase	Out-of-service Period	Period (start-end date)		Duration	Building steps
1 (blue)	I	25-7-2010	23-8-2010	20 days (summer 2010)	90, 92, 95, **96**, 100
2 (orange)	II	9-10-2010	25-10-2010	17 days (autumn break 2010)	180, 185, **190**, 200
3 (violet)	-	25-10-2010	24-7-2011	196 days (2010/2011)	**250**
4 (yellow)	III	24-7-2011	29-8-2011	37 days (summer 2011)	285, **290**, 300
5 (green)	IV	29-8-2011	26-9-2011	29 days (summer 2011)	**390**, 400

Table 6.5 Overview of the five different building phases (Execution in fat numbers is the scope of the Utility discipline)

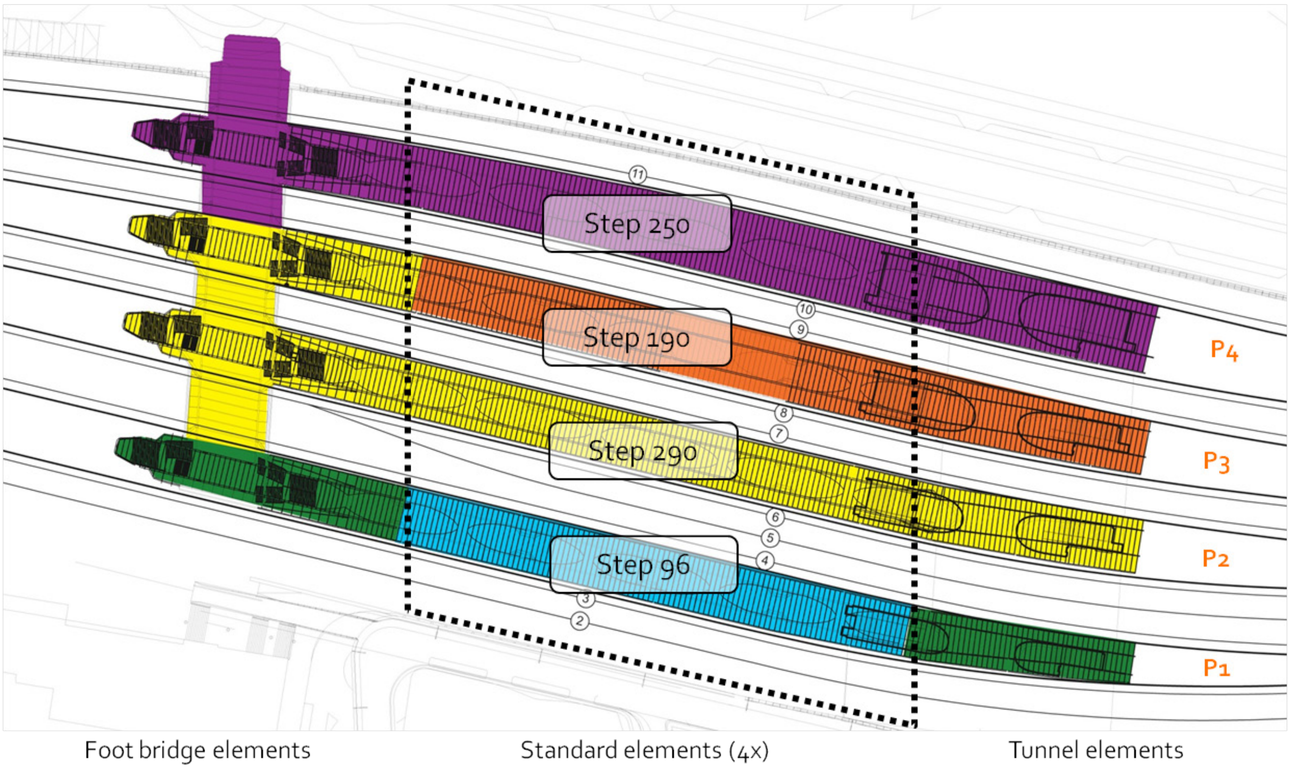


Table 6.6 Scope of the quantitative research (Standard elements)

6.3 Scope quantitative research: Standard elements

The quantitative data research focuses only on the construction processes of the platforms within the project SIA (see figure 6.1, focus 2). A more elaborated research is performed using the developed workflow model focussing on the completion of the roof structure only (see figure 6.1, focus three). The metrics associated with the workflow are subtracted from the available Lean planning schedules of step 96, 190 and 290.

The choice for the 'standard elements' as research object is based on three aspects:

1. **Identical objects** - The platforms are the most practical research objects to measure since they are identical in a technical way and therefore easy comparable.
2. **Build in four different periods** - Since the platforms are build in four different time periods, their construction processes can be seen as four identical minor case studies.
3. **Technical complexity** - Although most of the problems occurred during the execution of the footbridge (mentioned by foreman E. Willemsen and several planning engineers), the platforms are the most practical research objects in means of time, effort en reliability. By investigating the execution of the complete railway station (demolition works, the replacement of the platforms and footbridge and realization of several temporary constructions) the needed work and the complexity of the gathered information will grow exponentially. Furthermore the footbridge is too complicated in a technical way resulting in inappropriate data measurement and comparability (recommended by various BAM planning engineers). By solving one question, ten new questions will arise.

For using the most reliable data in field research, some implications are constantly taken in account by the choice for data analysis: the availability (proper documentation), comparability (common items; apples with apples) and complexity (influenced by many hidden/external factors) of the gathered information.

7. Case study results

In this chapter the following sub question is answered: ***What type of activity in the case study project can be identified as the most potential for waste elimination?***

A comparative analysis between the 'standard elements' of four (sub) case studies (step 96, 190, 250, 290) is completed using the selected 'parameters of efficiency in construction' (see table 5.1 / appendix A4)
Further research is performed by using the workflow model described in chapter five in which the metrics of the Lean planning schedules are used. The workflow model is only applied for step 96, 190 and 290 since no Lean planning of step 250 is available (realization of new platform without limitation by an out-of-service period). The use of the workflow model is used for measuring lead time (paragraph 7.6) and operational costs (paragraph 7.7).

The following parameters will be reviewed in this chapter. The paragraph numbers are in between brackets:

1. **Bid price** (7.1)
2. **Client demand** (7.2)
3. **Tender/Design phase** (7.3)
4. **Co-makers performance** (7.4)
5. **Volumes** (7.5)
6. **Lead time** (workflow model) (7.6)
7. **Operational costs** (workflow model) (7.7)
8. **Construction site costs** (7.8)
9. **Deliveries/logistics** (7.9)
10. **Instructions/training** (7.10)

All the data is gained by investigating plenty of documents, ranging from early contract documents to detailed Lean planning schedules. Only the most relevant or typical files are included in the attachment (appendices) of this report. Alongside the data analysis, interviews have taken place to get more inside information for making the right assumptions.

7.1 Bid price

The bid price of the platforms containing the standard elements and the tunnel elements are presented in figure 7.1. The bid price of the footbridge elements are separated in calculations. In order to distinguish the bid price of the standard- and tunnel elements, the mean line of step 96 with only standard elements is showed. The extreme peaks of the roof installations in step 250 and step 290 are probably caused by the integration of the installations trough the entire building because these costs are not seen in the footbridge elements (see appendix A13).

Most of the costs are determined by the roof structure and site costs as seen in the two peak of the line in figure 7.1. The roof contains work of the co-makers Sorba (plating) and Spie (installations). Although these bid price costs are not very accurate since they contain both direct (e.g. material, labour) and indirect costs (e.g. management, job site), the work of Sorba and secondly the building site cost could have the most economical potential for cost reduction.

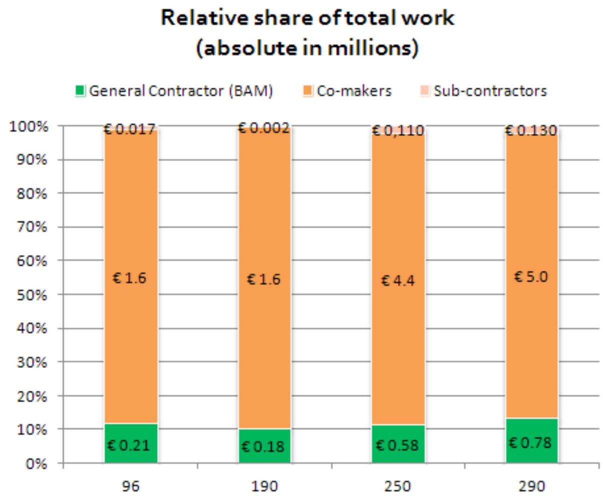


Figure 7.2 Relative share of total work within utility discipline per phase.

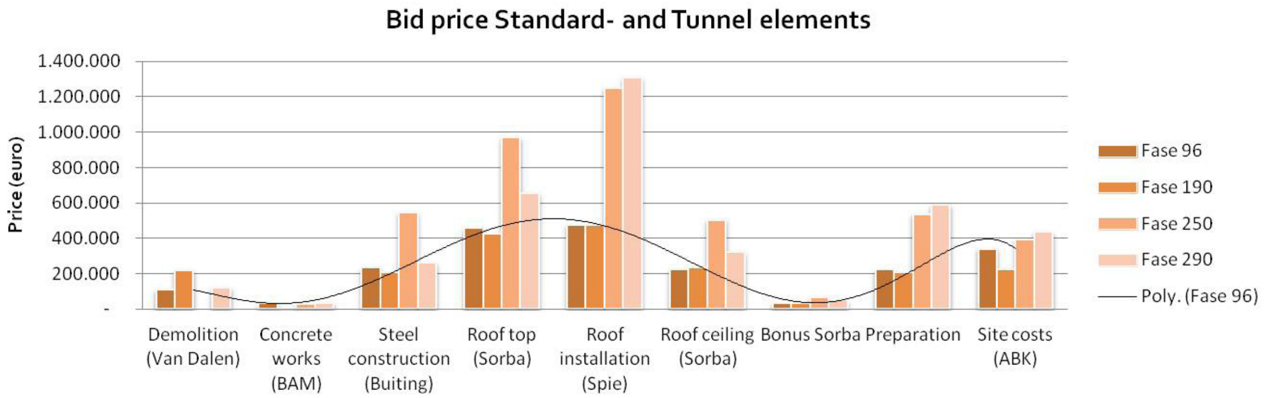


Figure 7.1 Bid price of Standard- and Tunnel elements per type of expense

As seen in figure 7.2, a significant share of work is conducted by co-makers over all the four building phases (see appendix A14), highlighting the importance of proper collaboration already at the start of a project.

7.2 Client demands

Considering the value for the customer according to the Lean philosophy, the client attaches extreme high value on timely completion of the projects phases. Exceeding the out-of-service periods is highly problematic for the intensive train traffic. To prevent delays in completion, the client has formulated high penalty/bonus regulations within the contract, in agreement with the general contractor combination (GCC). This should ensure that the GCC works properly and finish the five phases within the available time.

The penalties for each out-of-service period which the client can be place by the GCC are formulated in table 7.3, with a maximum of one million euro in total. Exceeding the deadline will cost the GGC 5000 or 2000 euro per day depending on the phase plus a fee for every 15 minutes of delay. If the building steps are accomplished at the stated deadlines the GCC can claim bonuses. By exceeding these deadlines by exactly 4.00 AM, the general contractor combination is not able to claim the bonuses, despite the exceeding's are caused by other parties.

As seen in figure 7.4, the GCC has increased its profit by deserved bonuses for meeting the customers demand to accomplish the phasing steps in time (see appendix A16). The bonus part for the Utility discipline is 22,6%, related to the share of the total project costs (civil, infra, rail, utility). If you look to timely completion, in this case the maximum bonus compared to the deserved bonuses of the phases, phase 400 (90%) has the best score, followed by phase 300 (72%), phase 100 (56%) and phase 200 (42%). The bonus regulations have some changes comparing to the formulated regulations in table 7.3. Some bonuses are divided into various subtopics for exclusions of external causes for the GCC. The payments are calculated minus several little penalties.

If you compare the total bonus (1.500.000) with the gained bonus (991.250) the gained bonus is 66 percent. This means that there is room for improvements (34%) by increasing the building speed by all the disciplines. Although on-time completion is heavily depended on the work performed by the rail discipline (stated by Erik Willemsen), increasing the building speed can result an extra income of 113.000 euro (22,6% of the remaining 500.000 euro) for the utility discipline. Unfortunately this is only a theoretical bonus since the scope of this research (standard elements) has marginal impact on overall timely completion. Improvements have therefore no direct impact on the bonus regulations.

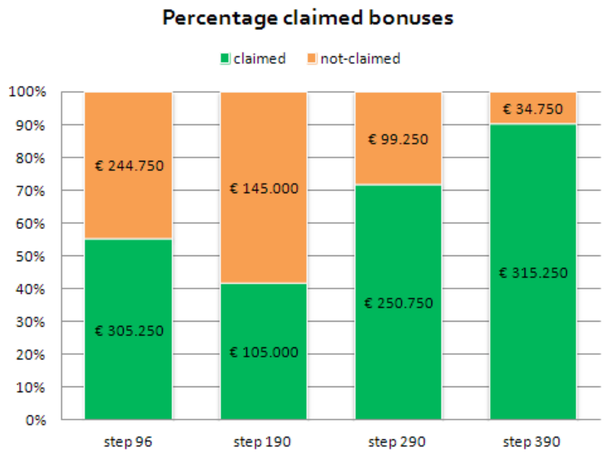


Figure 7.4 Claimed bonusses by the general contractor combination (all disciplines)

Phasing	Penalties (-) Deadline exceeding per day + exceeding per 15 minutes	Bonuses (+) Deadline accomplished + earlier completion per 15 minutes
Step 100 (23-08-2010 at 4.00 AM)	5000 + 1500 euro	450.000 + 750 euro
Step 200 (25-10-2010 at 4.00 AM)	2000 + 500 euro	150.000 + 750 euro
Step 300 (29-08-2011 at 4.00 AM)	2000 + 500 euro	250.000 + 750 euro
Step 400 (26-09-2011 at 4.00 AM)	2000 + 500 euro	250.000 + 750 euro
Maximum penalty/bonus	1.000.000 euro overall penalty	400.000 euro for earlier completion

Table 7.3 Overview of and penalty- and bonus regulations between the client and general contractor combination of SIA

7.3 Tender and Design phase

The critical paths for the replacement of the station platforms and the realization of a new fourth platform are the planned periods that rail traffic is out-of-service. These periods are rock solid and are requested very accurate in advanced by the general contractor combination.

In order to participate in the joint-venture it was necessary for BAM Utility to work very close with several co-makers to complete the project within the given time. This was already clear at the beginning (see figure 7.2). From the tender phase it is assumed that prefabrication is one of the solutions to minimize the risk of delays in these out-of-service periods. Since the project is tendered in a Design-Build contract and the (semi governmental) client demanded to work with 'System Engineering' in the initial phase, the GCC is free to initiate modifications in order to improve quality in both the product and the process (See appendix A8).

BAM Utility assumed that as much as possible should be mounted on the building site. The construction of the platform roofs is suitable for prefabrication and is already discussed in the tender phase with various co-makers. Consultations have taken place per discipline but also with all disciplines together. During these meetings, together with the architect UN Studio and the client ProRail, they agreed to work on this option. The constructive design was at that moment in progress but was not calculated for execution with prefabricated components. Adjustments would causes delay in the tender phase so further elaboration was taken place by the contractor.

7.4 Co-makers performance

As described in literature, co-makers are the critical factor for project success. In order to succeed the project on time BAM Utility wanted to organize and realize the project in a new way by implementing the 'Lean thinking' approach (see appendix A9). The GC has formulated one common goal for all the construction partners involved (co-makers and sub-contractors): *"Achieving optimal results through a well coordinated process."*

The Lean thinking approach is seen as a crucial policy decision. All the partners should operate as one team to improve workflow. Aiming for a faster realization the margins will be higher for all parties. Additionally a higher quality of the delivered product is ensured, creating more value for the customer. The GC expected that all the parties implement this approach in their processes. To introduce and adopt the same vision for the entire team, several in company trainings by Arpa (a Dutch Lean organization) have been implemented where all the involved project managers, job engineers and construction foreman expected to be present.

All the partners with their own speciality (see figure 7.6) share ownership for the planning and delivery at different stages of the project. To achieve this, mutual trust and open communication during the entire process is crucial. The success off the cooperation is therefore not temporary but continues with the ultimate goal of a long-term partnership. By a high degree of cooperation and being open to suggestions from others, a strategic alliance stimulates the success of the project SIA.

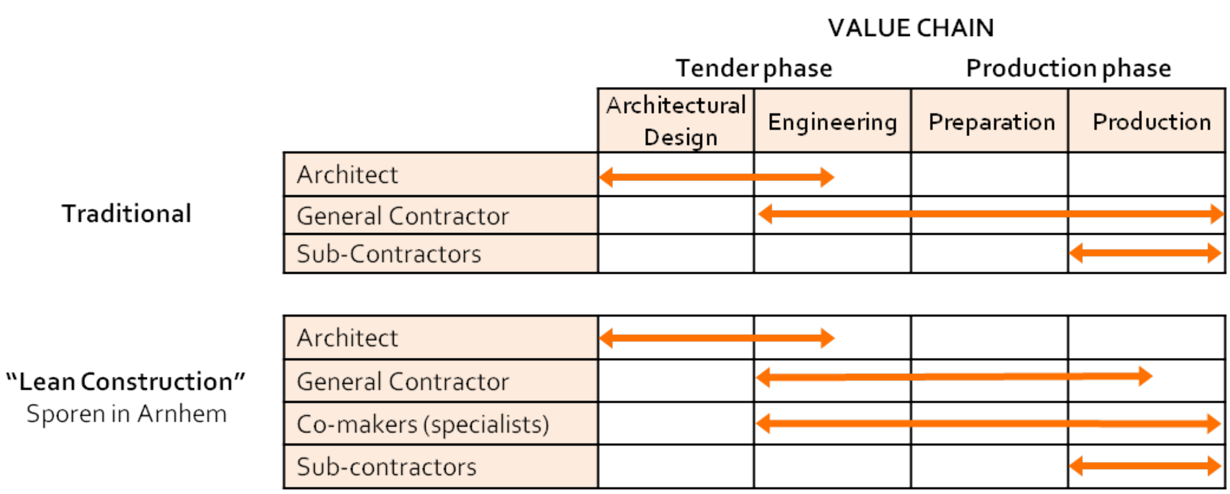


***Figure 7.5** Improvement of construction supply chain collaboration in the Lean project 'Sporen in Arnhem': implementing knowledge from co-makers already in the tender phase.*

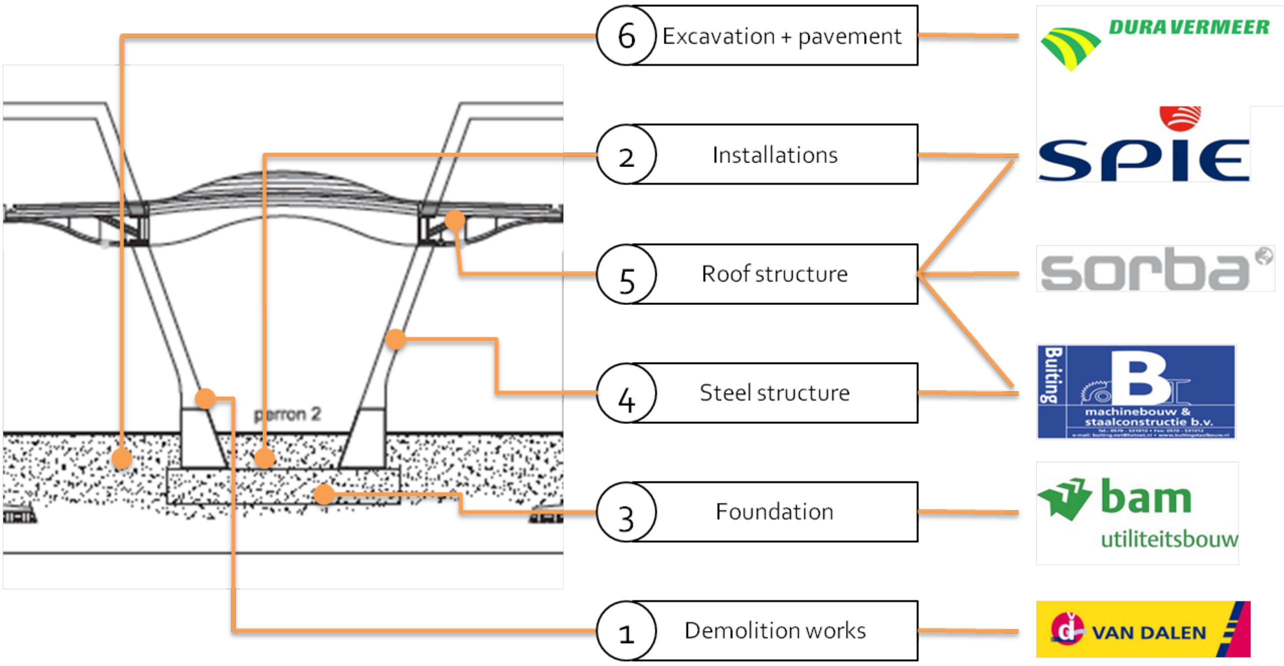


Figure 7.6 Mutual cooperation and involvement between co-makers considering the standard elements.

The GC set high standards for the input of all the partners. This Lean approach with the high standard has great consequences on site. The most important rules are here formulated, for more detailed information see appendix A9 and A10).

- Mutual cooperation and involvement. One solid team, everyone is important on the field and together we help each other to achieve the planning.
- Clear responsibilities for each player on the team. Everyone should always know their responsibilities and consistently fulfil their agreements.
- Anything today, we do today and not tomorrow. The realization of the project is only possible when everyone is constant pro-active.
- The knowledge of the performers should be implemented at an early stage in the process, at plan elaboration and planning (see appendix A10)
- In planning all time buffers should be removed. A tight schedule leads to a more efficient construction process, a good delivery and a higher customer satisfaction.
- Select reliable subcontractors. When you work with sub-contractors, the assuming party involved in the project from the beginning and think this party as a full partner in the process.
- All materials just-in-time on the construction site. Proper alignment with suppliers is essential for a reliable process; There are no stocks held on the construction site.

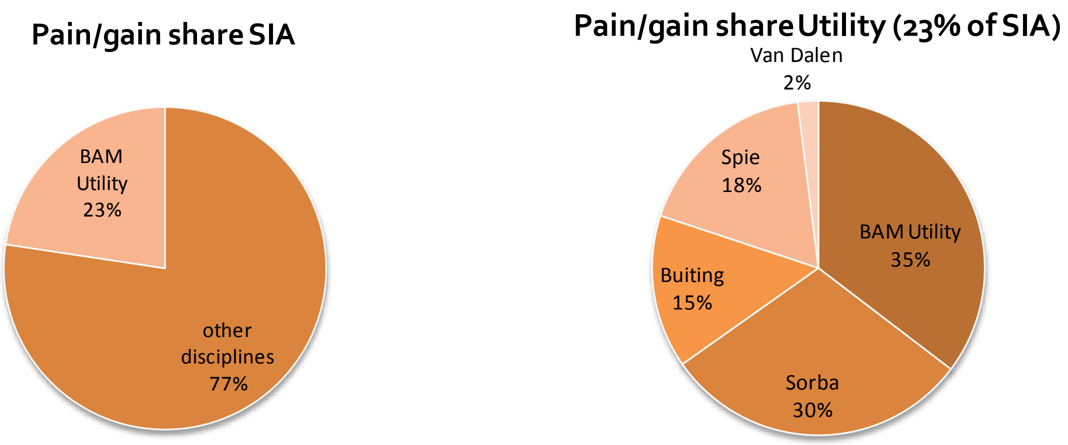


Figure 7.7 Pain/Gain share: left for all disiplines (SIA), right only utility discipline

The gained bonuses for the utility discipline are subdivided by the different co-makers (see figure 7.7). The percentages are determined by the share of the construction costs. It is obvious that Sorba (finishing), Buiting (steel structure) and Spie (installations) have a large share of the total budget. This is illustrative for the shared commitment to the project.

Joint IT-tools

Another implemented aspect is the use of a communication platform for all project participants. The current practice is that the GC is responsible for process planning, control and coordination. However, there are often inconsistencies and conflicts in the project information generated by the various co-makers involved. All the work is visualized in 2D with the development of a so called 'strip book' (see figure 7.8) generated out of the Lean planning.
Although the development of the strip book acquired much effort, it has been an effective communication platform for simplifying overview for the project management.

7.5 Volumes

All the four periods, in a range from 17 to 196 days, have various construction volumes. The justification for taking the standard elements as research object is based on the fact that they are identical in physical terms, additionally they are constructed all in different periods. Since they contain marginal differences in volumes as seen figure 7.10 (appendix A12), the factor volume has no significant impact on the other resources. Consequently the results of the comparisons of workflow will become more reliable.

All the platforms build in the four phases have identical steel structure volume of five V-formed columns elements. The volumes of the roof structure as seen presents little differences since the width of the platforms are variable. The resources needed for on-site construction of the plating material are negligible as they are intercepted in the prefab wings (see figure 7.9)

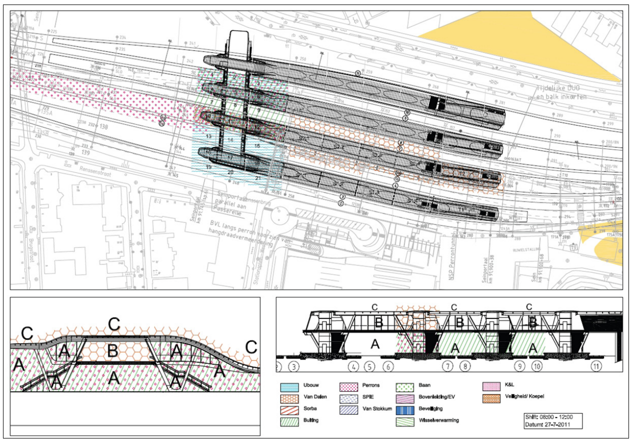


Figure 7.8 Visual 'strip book' attached to the Lean planning

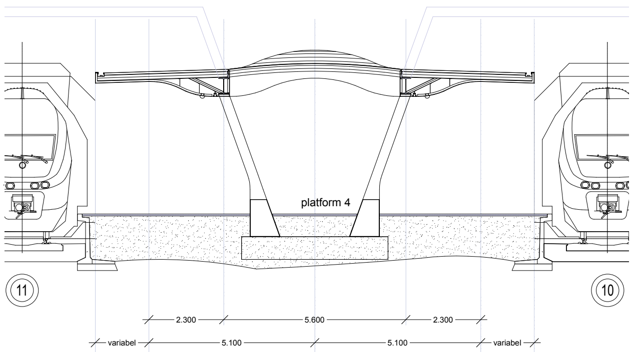


Figure 7.9 Cross secton of the standard elements

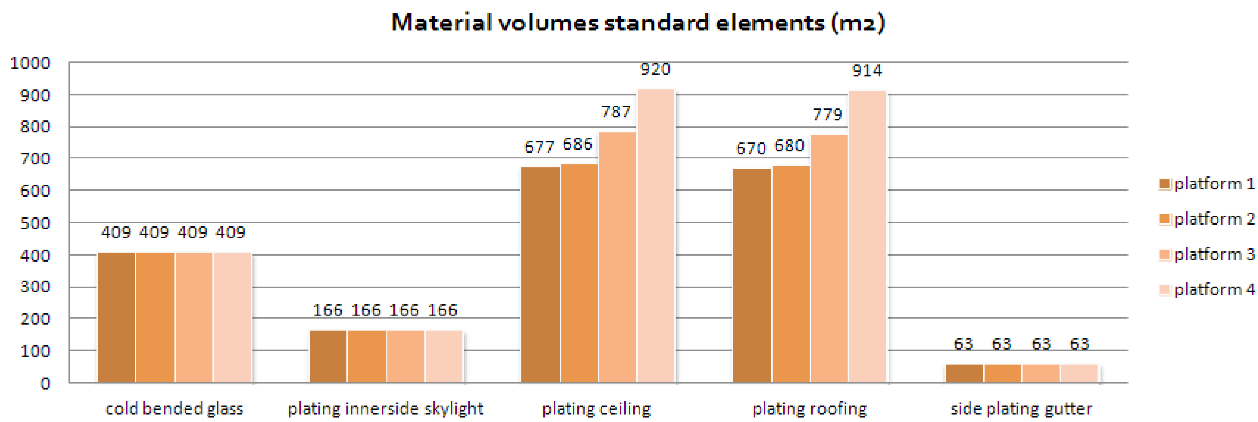


Figure 7.10 Material volumes of the standard elements

7.6 Lead times (using the workflow model)

The out-of-service periods, as mentioned before, are rock solid and cannot be extended. By not succeeding the (critical) construction parts within these periods, the construction partners taking high financial risks. To get the job done within the given time, some parts of the foundation consoles (see figure 7.22) and parts of the roof structure (see figure 7.17) are prefabricated. The roof components are manufactured in advance by a Co-maker (Buiting Staalbouw) which was responsible for the steel structure. Not only the extreme time pressure played a major role for the choice of prefabrication, also the complex architectural shape of the building was an important aspect. The design by UN Studio exists out of many curved parts which had to be implemented and connected. To avoid finding mistakes during execution, the roof is partly prefabricated so that only assembly would be necessary on site.

Production planning versus Lean planning

Since time is the most important aspect, lead times are planned more narrowly in subsequent planning schedules. In the project SIA the technique of the Last Planner System is used together with Lean project delivery. The most elaborated planning, the commitment planning according to the Last Planner System (LPS), is scheduled during Lean planning sessions.

- **Contract schemes** - The contract schemes show a master planning of every phase. Milestones for completion are set and core activities are planned to explain the payments by the client.
- **Production planning** - The contract schemes are more elaborated within the production planning schedules (See appendix B4;B5;B6;B7). Not only core activities are planned and calculated, also secondary and more detailed tasks are scheduled, causing a significant increase of total activities. Production planning schedules are dictated by the GC and are planned far in advance, without knowing the latest information.
- **Lean planning** - During Lean planning sessions (See appendix B1;B2;B3) input of all parties is required. First goal is to remove buffers in planning through concurrent planning. All parties plan their own activities with a specific colour post-it on giant boards with milestones. All the work is planned using pull production: they post their planned activity when the needed previous activity is ready. To ensure a proper workflow, work is planned in time-blocks of two hours. During the planning sessions the parties are able to consult each other in order to ensure that their activities can be done without disruptions. These negotiations causes that parties have a broader project view what increases the cooperation, trust and team spirit. In fact they simulate the real construction process by plan their actions together.

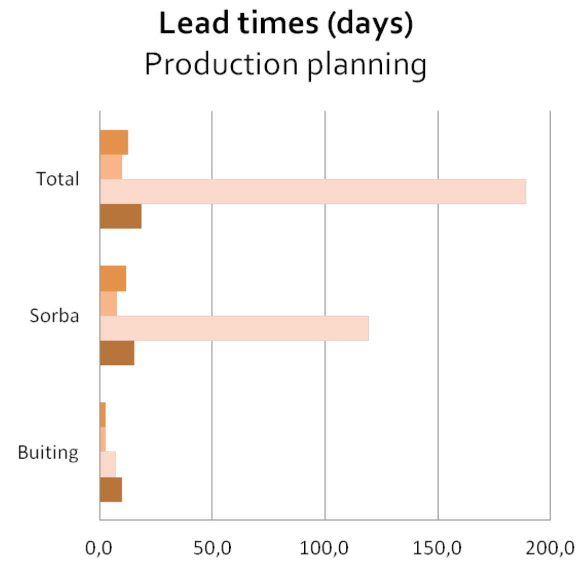
At Lean planning sessions, participants make commitments in public. They stake their reputation on their ability to deliver on their promises. This underlying interest or concern is fundamental to the success of the system as cited in the literature review (Christine A. Slivon et al., 2010). As project team members strive to fulfil their commitments, they build trust with one another and improve their chances of success. As their promises

Figure 7.11 Simultaneous planning during Lean planning sessions involving all co-makers and sub-contractors (example from project 'Groot Hungerink', BAM Utility)

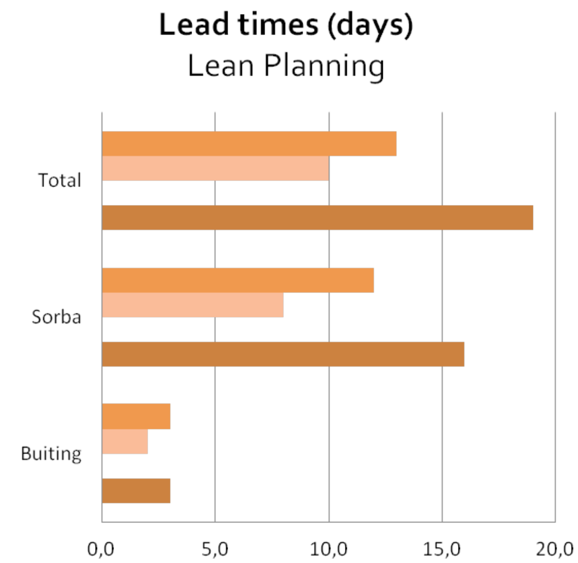
become more reliable, the Last Planner System reduces risk by making workflow more predictable. This is of main importance working under extreme time pressure during out-of-service periods. This predictability reduces both duration and cost by reducing the amount of time workers wait for work.

Figure 7.12 shows that the lead time (end date – start date) in production planning of step 250 is much longer than the others. This could be explained by the reason that step 250 (realization of the new platform) has no interference with an out-of-service period and is therefore not limited by time. This work can be done without working in shifts (8 hours a day in step 250 vs. 20 to 24 hours a day in step 96 and 290). For the same reason the Lean planning session for this phase is also skipped by the building team what can be seen by the gaps in the diagram. A BAM planning engineer explained that several co-makers didn't need a Lean planning for this step because they 'learned from previous phases and therefore know the tips and trics', for this they made a anonymous decision to skip the Lean planning method.

Figure 7.12 shows there is no significant difference of lead times between the production planning (imposed by the GC) and the Lean planning schedules. On the contrary, the Lean planning schedules where buffers should be eliminated, have a small increase of lead times.
The absolute advantage of the Lean planning method in means of reducing lead times cannot be concluded out of the data. This can be explained by the fact that the previous planning schedules have been planned already extreme critical. From the start is was clear that the general contractor combination had to work in shifts (3 shifts of 8 hours a day, 7 days a week) to deliver in time. Therefore negligible room was available to remove much buffers within the Lean schedules for this specific case.
On the other hand, the Lean planning sessions were indisputable necessary to tune all the work since various co-makers had to work in shifts seven days a week (see figure 7.21). For this fact the Lean planning schedules are superior over other generated planning schedules and can be regarded as a commitment planning for all team members.



	Buiting	Sorba	Total
PP - 96	2,5	12,0	12,5
PP - 190	2,5	7,7	9,9
PP - 250	7,3	119,3	189,3
PP - 290	10,2	15,5	18,6



	Buiting	Sorba	Total
LP - 96	3,0	12,0	13,0
LP - 190	2,0	8,0	10,0
LP - 250			
LP - 290	3,0	16,0	19,0

***Figure 7.12** Total lead times (associated with the construction of the platform roof) compared between production and Lean planning schedules. The high peak in the production planning and the non-existing Lean planning of step 250 is caused by the fact this phase is not limited by an out-of-service period.*

Value adding activities versus necessary waste

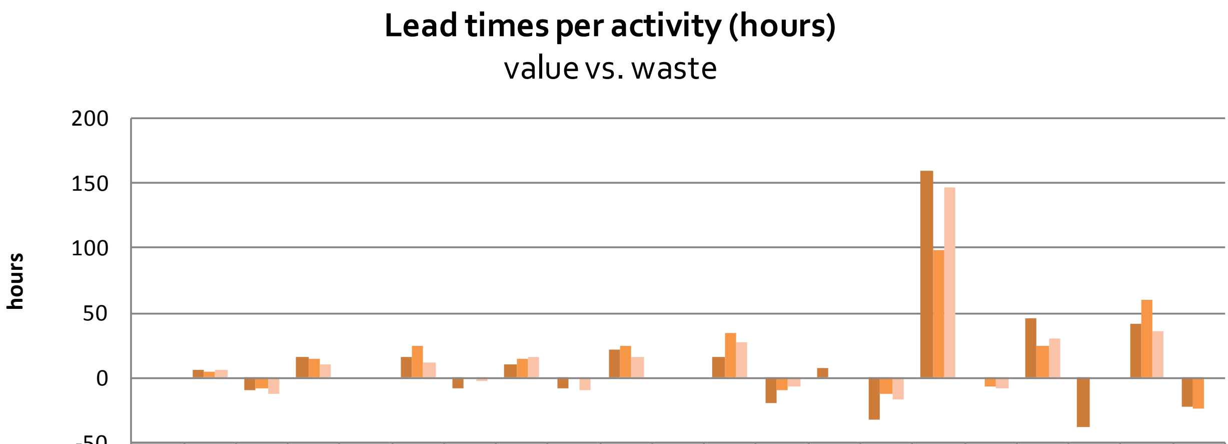
All the work on the platforms is done in six general steps executed by different parties. These steps are subdivided into various core activities (see appendix B8;B9;B10). Due to most time on site is consumed by the construction of the platform roof (see appendix B1), these activities are further investigated, considering the work of Buiting and Sorba. In figure 7.14 the lead times of all the type of activities are presented. The comparative analyses is performed subdividing all the type of activities into:

- Value adding activities (type 3.1-4.3) These activities can be seen as the work direct needed in the transformation process (see table 7.13). Since these activities are adopted in all planning schedules, they are directly comparable.
- Non-value adding activities (type a-k): These activities can be seen as contributory work and are therefore suggested as (necessary) waste. These activities are presenting little differences between the phases including transport of material and equipment, work preparation, assembly and dismantling of scaffolding and site cleaning.

For a complete overview of all the type of activities see appendix B11. It needs to be addressed that both activities contain undoubtedly 'pure' waste. Since pure waste is obviously not planned (documented), it will be interpreted in the most reasonable way. Figure 7.14 shows the lead times on-site per type of activity. It is evident that the most time consuming work is activity 4.1: the assembly of the sub-construction and aluminium panels.

Step	Type of Activity
1.	**Demolition works (Van Dalen)**
2.	**Foundation works (BAM Utility)**
3.	**Assembly of the steel structure (Buiting)**
3.1	Positioning anchors for column installation
3.2	Mounting columns (four elements in total)
3.3	Assembly of prefab wings
3.4	Assembly of roof beams
3.5	Welding of columns
3.6	Completing the assembly of the standard elements
3.7	Applying of anti-graffiti paint
4.	**Finishing of the roof elements (Sorba)**
4.1	Assembly of the sub-construction and mounting the aluminium panels
4.2	Lifting and placing the glass panels on top of the roof
4.3	Fixing the glasses (taping/kitten)
5.	**Installations works (Spie)**
6.	**Completion of the platform floors (DuraVermeer)**

Table 7.13 Type of value adding activities (codification)



	a	3.1	b	3.2	c	3.3	d	3.4	e	3.5	f	3.6	g	3.7	h	4.1	i	4.2	j	4.3	k
Step 96		6	-10	16		16	-8	10	-8	22		16	-20	8	-32	160		46	-38	42	-22
Step 190	0	4	-8	14		24		14		24		34	-10		-12	98	-6	24		60	-24
Step 290		6	-12	10		12	-2	16	-10	16		28	-6		-16	147	-8	30		36	

Figure 7.14 *Lead times per activity*

Traditional craft work versus prefabrication

The labour intensive assembly work of the sub-construction and aluminium plating is already in a high degree prefabricated off-site by integrating 57% (939/1655) of the volume in the prefab wings (see table 7.15). If you compare the assembled surfaces on-site versus off-site matched to the lead times, the differences in productivity (m2/hour) can be calculated, taking workforce as a constant factor (see appendix B15 for detailed calculations).

Table 7.15 shows the productivity in assembly of the sub construction and aluminium plating for both off-site (prefab wings) as well as on-site. The on-site productivity is divided into into 'top panels' and 'ceiling' since assembling the ceiling is much more problematic: all the assembly work has to be done above the head while manoeuvring with cherry pickers in the soil, second the ceiling includes assembly of many components for the sub-construction in contradiction with the top plating. Together with significant differences in plating volume (240 m2 top versus 476 m2 ceiling) a factor of 0,856 is calculated to split the manhours on-site for the top and ceiling (see appendix B14). These two facts causes that the productivity on-site for the top panels is much higher (see table 7.15).

The average productivity for the ceiling on-site is low (0,86 m2/manhour) compared to the pre-assembly in the wings (1,22 m2/manhour). This emphasizes much waste occurred in the complex on-site assembly (This is approved by the Sorba project manager as he stated that more than half of the time was consumed by manoeuvring with the cherry pickers over the soil). By transferring this particular work from the job-site to manufacturing plant, the average productivity can be upgraded by 49% (see table 7.15, productivity ceiling/wing factor 1,49). Additionally the lead time for on-site construction will drastically incline.

Figure 7.16 Activity type 4.1: Assembling the sub-construction and aluminium panels (conducted by co-maker Sorba).

	Volume (m2)				Labour (manhours)					Productivity (m2/manhour)			
	ON		OFF	total	ON			OFF	total	ON		OFF	factor
	top*	ceiling	wings		total	top* (14,4%)	ceiling (85,6%)	wings		top*	ceiling	wings	wing/ ceiling
Step 96	240	476	860	1.576	800	115	685	768	1.568	2,08	0,70	1,12	1,61
Step 190	240	476	879	1.595	490	71	419	768	1.258	3,40	1,13	1,14	1,01
Step 290	240	476	1.079	1.795	735	106	629	768	1.503	2,27	0,76	1,40	1,86
Mean	240	476	939	1.655	675	97	578	768	1.443	**2,58**	**0,86**	**1,22**	**1,49**

Table 7.15 *Quantities concerning assembly of sub-construction and alu. panels. (ON = on-site; OFF = off-site; *= without sub-construction)*

Table 7.17 Positioning the prefab 'wings' on the columns

7.7 Operational costs (using the workflow model)

The framework is used for determining the (direct) construction costs needed for the transformation of input (material) into output (product). The input is transformed by using the resources of labour and equipment.

Labour costs are determined by number of workers and the type of shift (day/night/weekend) for every two hours. The equipment costs are little more difficult due to the accuracy over time is much complicated. Equipment is mostly hired a day or in blocks of eight hours (without the high cost for a certificated machinist). The general equipment, for example the 40T railway crane is hired in common by the general contractor combination. Costs are therefore spread over longer periods. Specific equipment acquired by various co-makers is rented by the co-makers itself, for example the cherry pickers used for the mounting the sub-construction and aluminium plating by Sorba.

Looking to figure 7.17 you should expect a small decline in costs of labour (and in a lower degree in equipment) over the three steps in time since workers learn over time. This 'learning effect' together with some operational improvements applied during the various building steps should incline construction costs which is apparent in the labour and construction costs of Sorba in step 190 and the utilization of labour by Buiting in step 290.

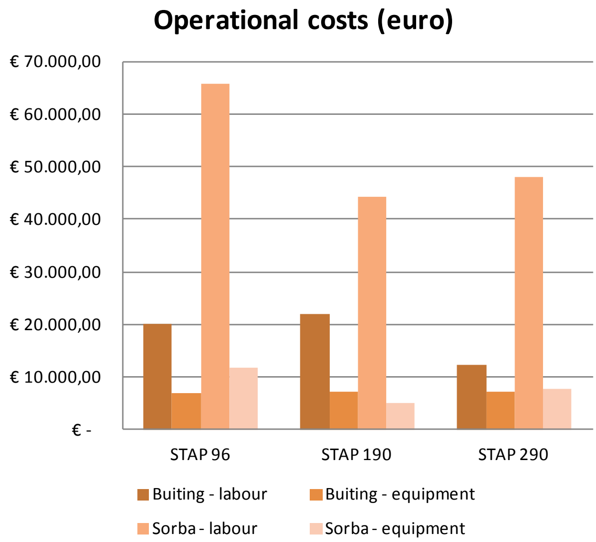


Table 7.18 Total operational costs of Buiting (steel structure) and Sorba (roof plating)

Workflow improvements

In step 96 Sorba used scaffolding suspended on roll-bars underneath the steel structure to 'fly' over the sand box and tunnel entrance near the stairway. The use of suspended scaffolding was not copied to the next phases since this method was not very successful. Adjustments needed for running the scaffolding over the platform where time consuming (assertion by project manager of Sorba). With the use of this suspended scaffolding together with the 'pilot' assembly process, the relative high labour and equipment cost in step 96 can be explained, see figure 7.17.

Table 7.19 In step 96 Sorba used suspended scaffolding on roll-bars which pointed out not very convenient.

In step 96 the prefab wing elements were assembled using a railway. In step 190 these elements were assembled using two auto cranes located on the construction site of the fourth new platform. The utilization of two cranes conflicted sometimes during assembly. This is improved during step 290 where the prefab wings were assembled using one railway crane in combination with temporary supporters to ensure stability during assembly. This fact could be a root cause for the decline in labour utilization in step 290 during the installation of the steel structure.

Working in shifts

Hourly wages (recalculations of Sorba wages) are determined in this research as follow (see appendix A12 and B12):

- **Day production** (a period of 12 hours from 6AM to 6 PM): 45 euro/hour
- **Night production** (a period of 12 hours from 6PM to 6AM): 50 euro/hour
- **Weekend production** (a period of 2x24 hours on Saturday and Sunday): 55 euro/hour

As seen in figure 7.20 the absolute number of hours decreases over time what can by explained by improved construction performance. The relative share of day production has a small decline what suggest that more work is performed during nights and weekends. Although these workforce hours are more expensive the team is forced to work during these hours since removing time-consuming buffers in planning is necessary for on time delivery. Reducing lead time by working 24/7 has been the main reason for implementing the Lean approach into this project.

Skilled workforce

Labour price in means of hourly wage is relative high compared with normal construction workers. The project manager of Sorba stated that working on complex projects like 'Sporen in Arnhem' safety is of highly importance. No temporary employees could work during this projects since experience (certification) is crucial, especially when work is done during day and night.
For this reason, moving the labour intensive work to off-site manufacturing environments through prefabrication will probably be economical beneficial. Besides a reduction of lead time on-site, hourly cost will reduce due to the fact that you can produce with less skilled (cheaper) workforce.

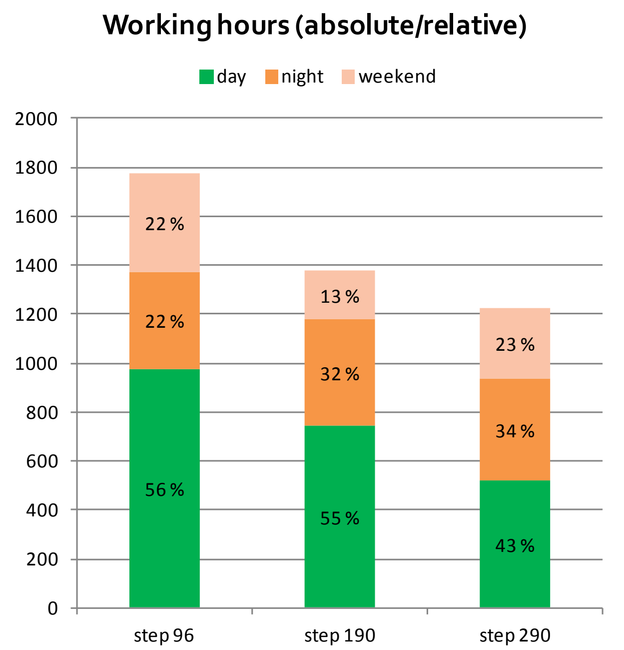


Figure 7.20 Significant reduction of working hours over a production volume of three caused by the 'learning effect'

Removing buffers in planning

Figures 7.21 represents the labour intensity per activity planned in the Lean planning schedules. As seen in all the phases, the production work of the sub-construction and plating is both absolute and relative mostly executed outside day-time hours. If the team members only would operate during day, the lead time would be doubled and therefore project success was completely out of the picture.

Figure 7.21 Relative working hours of three phases (absolute number in bars), much operating time is planned during night and in weekends in order to remove buffers.

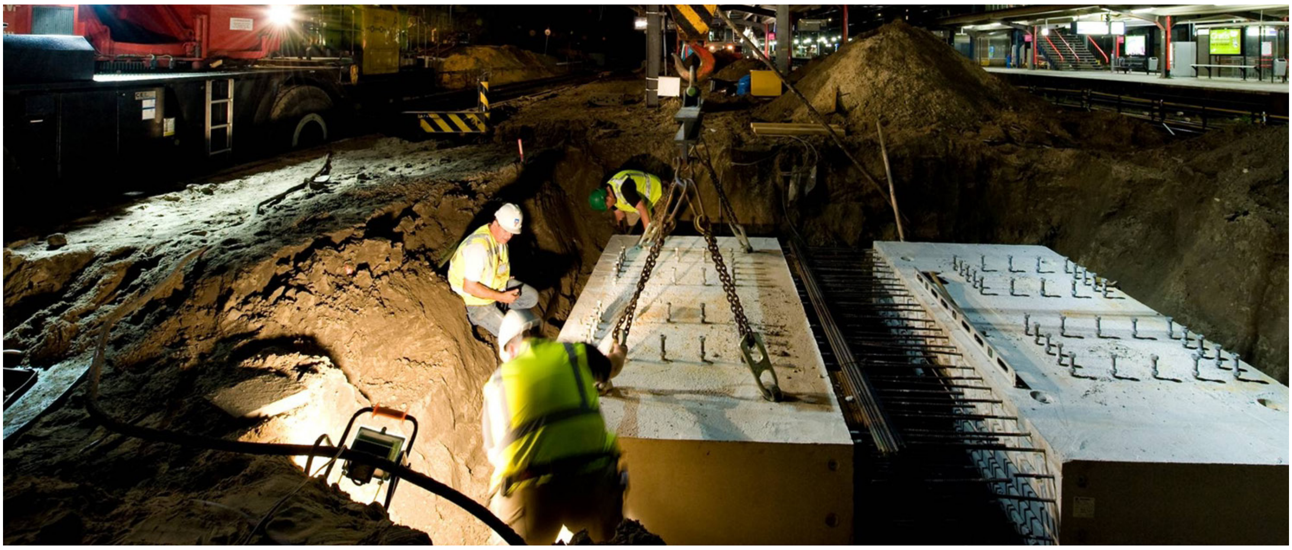


Figure 7.22 Much work is performed during night and weekend hours, like positioning the prefab foundation elements.

7.8 Construction site costs

Besides the direct costs for operation, construction contains indirect costs for the construction site. Within the workflow model the construction side costs are adopted in the indirect management costs containing:

- Management staff
- Building site
- Design and engineering

Since the costs for management staff and construction site are generally based on lead times, these costs are recalculated on a daily base in order to make proper comparisons (see figure 7.23). The costs for design is not relevant since the four platforms are identical and intercepted in one single design assignment.

Management staff

Costs for management staff are largely determined by the total duration of a project. The work for the project management (e.g. project manager, chief foreman, foreman, logistic engineers and job engineers, see appendix A15) commences far in advance before the on-site execution starts. For this reason reducing the on-site lead time will have no significant impact, although the cost for management staff contains the majority of the indirect costs. Despite the cost for management staff is to diverged for making costs estimations, reducing lead time will reduce stress from the project management since they had to be constant standby during day and night within the out-of-service periods (stated by E. Willemsen).

Site facilities

The costs for site facilities (e.g. site office, scaffolding, safety aspects, electra, transport) are highly depending on the lead time of on-site construction. Especially in this case study since the general contractor combination utilized an overcapacity of (transport) equipment to ensure proper workflow through just-in-time logistics (stated by E. Willemsen).

The building site costs (see appendix A15) differ from the four building steps because the amount of construction volume and building period is different. A reduction of lead time by improving workflow can save an average of ±4500 euro a day ((5082+3855+4500)/3) concerning the site facility costs (step 250 is excluded because the significant differences, caused by the much longer period of 196 days and construction volume).

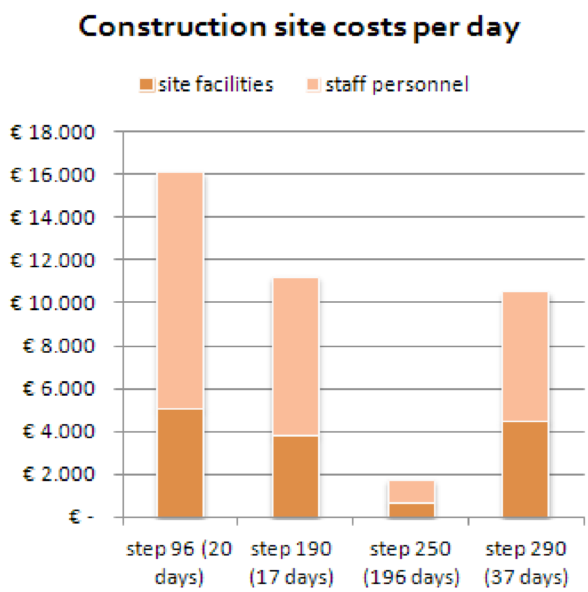


Figure 7.23 Construction site costs per day

7.9 Deliveries and logistics

Many of the transport of material (delivery and removal) and equipment is done by rail traffic, especially during the construction activities on the first and second platform (step 96, 290 and 390) where delivery and removal of material by road is impossible. On a shunting yard at the industrial area near the regional office of BAM the railway carriages are loaded with equipment and materials for transportation to the job-site.

Just-in-time (JIT) delivery is used since marginal room for storage is available on-site. Therefore the railway carriages are arranged to transport mostly prefabricated components. This logistic system has required much preparation time, especially when only one train per hour is permitted to enter and leave Arnhem Central.

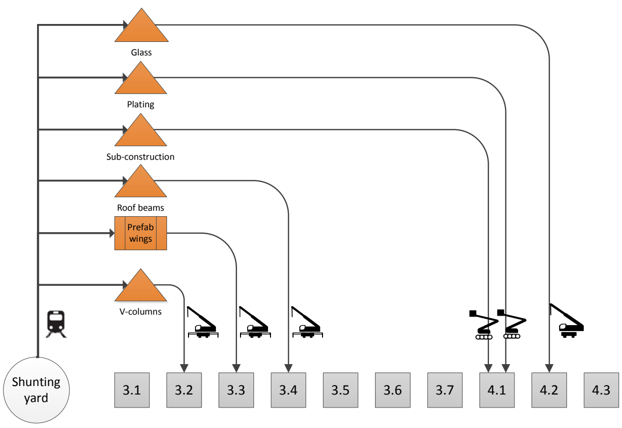


Figure 7.24 Overview of material input to the job-site associated with various process steps (blocks).

7.10 Instructions & Training

To ensure proper workflow on the job-site, the co-makers Buiting and Sorba decided to test the assembly method and detailing using a mock-up. The mock-up is build on the manufacturing plant of Buiting during the completion of the engineering phase. Preparation for the assembly method using a mock-up is usual for Sorba when they have to work on large scale projects like 'Sporen in Arnhem', especially when they have to operate under extreme time pressure (stated by R. Landeweert, projectmanager Sorba). During the construction of the mock-up all the details have been tested. Little adjustments where made to avoid complication during assembly on-site. An additional advantage is that the workforce is already 'trained' before real work starts.

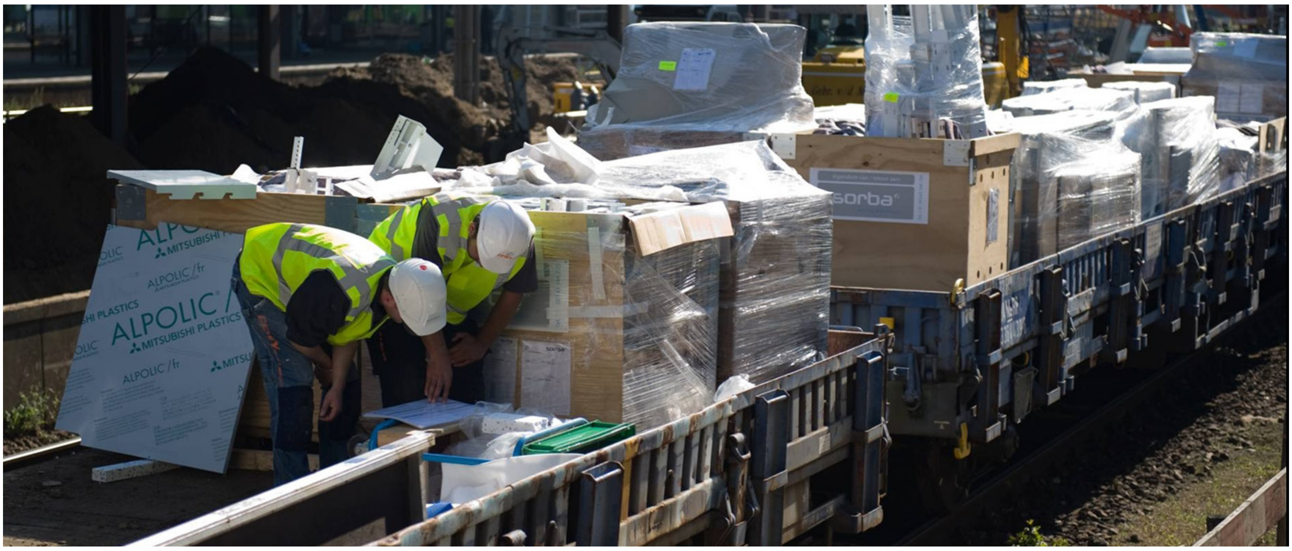


Figure 7.25 Just-in-time delivery using rail cargo.

		Implementation		Effects on parameters										
Lean concepts	**Implemented Lean techniques (application)**	**Tender phase**	**Execution phase**	**Bidprice (metrics)**	**Client demands**	**Tender/design phase**	**Co-makers perperformance**	**Volumes (metrics)**	**Lead time (metrics)**	**Operational costs (metrics)**	**Construction site costs (metrics)**	**Deliveries/logistics**	**Instruction/training**	**TOTAL effect of Lean technique**
1. Waste reduction	**Housekeeping**													
	JIT-deleveries (demanded by rail transport; no stocks on job-site)		x				+		+			+		3
	Joint IT tools (Lean planning stripbooks)		x				+							1
	Pre-fabrication (prefab wings and foundation consoles)	x				-/-		+	+	+	+	+		4
2. Process focus	**Last Planner System** (Lean planning sessions)		x				+		+		+	+		4
	Self control													
	Milestones (out-of-service periods)	x			+		+		+					3
3. Customer focus	**Concurrent Engineering** (CE)	x			+	+								2
	Limited bid invitation (selection of reliable Lean adopting sub-contractors)	x		-/-		+	+							1
	Soft parameters													
4. Continuous improvement	**Long-term contracts**													
	Performance indicators													
	Special interest groups (SIG)													
	Training (Lean sessions; mock-up wing)		x	-/-			+			+			+	2
	Suggestions (knowledge from co-makers)	x				+	+							2
5. Cooperative relationships	**Broad partnering team** (joint-venture contract)	x				+	+					+		3
	Collaborative tools (shared equipment and logistics)		x				+				+	+		3
	Gain/pain share (bonus regulations)	x			+		+							2
6. System perspective	**Coherent procurement decisions**													
	Large scale contracts (share of extra work)	x					+							1
	Systems Engineering (SE)	x			+	+								1
	TOTAL effect on parameter	9	5	-2	4	4	11	1	4	2	3	5	1	

***Table 7.26** Overview of the qualitative research findings considering the implemented Lean techniques. Techniques in grey can not be confirmed by the investigated documents.*

7.11 Conclusions

What type of activity in the case study project can be identified as the most potential for waste elimination?

If we look at the effects of the qualitative research (Implemented Lean techniques) and the quantitative research (metrics of the workflow model) on the various parameters, most parameters refer to one kind of activity as the most beneficial for waste elimination: the assembly of the sub-construction and aluminium panels within the roof structure conducted by co-maker Sorba (activity type 4.1).

Although the project team already focused on this particular work in the current stage, by the development of prefab 'wing elements' aiming for shorter lead times on-site, the quantitative research indicates that this type of activity is still the most potential for waste elimination.

Since pure waste symptoms are obviously not documented and therefore not directly measurable in the performed field research, the types of waste considering the assembly of the sub-construction and aluminium panels are interpreted in the most reasonable way. The causes of waste on site, formulated in table 7.28, will be the scope for improving workflow in this Lean construction project . A solution will be recommended in chapter nine for eliminating these types of waste.

Qualitative research

Although it is difficult to draw measurable conclusions associated with the effects of the implemented Lean techniques on the selected parameters, it can be concluded in general that from all implementations, the Lean planning sessions and the use of prefabricated components have the most direct impact on the on-site production performance (see figure 7.26).

Both techniques lead to a significant reduction of lead times during on-site construction. Due to the Lean planning sessions, involving all co-makers and sub-contractors, time buffer could be removed by tuning all the work accurately in shifts. The use of prefabricated wing-elements has also resulted in a significant reduction of lead time equally to the incline of on-site material handling. Additionally this prefabrication led to an incline in transport frequency to the job-site, which is highly vulnerable for delays because of the train logistics.

Although both Lean techniques may be the most effective considering the on-site execution, they could not have been implemented without several other Lean techniques implemented in advance during the early (design) stages of the project.

Many Lean techniques already implemented in the tender phase can be seen as preconditions for some Lean implementations during the execution phase. For example, in order to use prefabricated components composed by several co-makers, implementing knowledge from these participants in the early stages is demanded. Additionally a broad partnering team, systems engineering and joint IT tools such as BIM software are helpful underlying Lean techniques. This is an approval of the statement in literature that some Lean techniques may be implemented as stand-alone, the most impact can be achieved by implementing a specific set of co-operating Lean techniques.

As seen in figure 7.26, the majority of the Lean techniques are already implemented in the tender phase highlighting mutual responsibilities between project participants already in the early stages of a project. Additionally most implemented Lean techniques are affecting the parameter concerning the co-makers performance. These findings confirm the statements from literature that Lean thinking indeed improves construction supply chain performance, by stimulating mutual cooperation and involvement between project participants in the project 'Sporen in Arnhem'.

Quantitative research

Looking to the lead times adopted in the workflow model, the far most time consuming activity on-site is the assembly of the sub-construction and aluminium plating. Comparing the mean productivity assembling the prefab-wings off-site (1,22 m2/manhour) versus the traditional assembly of the ceiling on-site (0,86 m2/manhour), it can be concluded that off-site productivity is much more effective. Transferring this particular work from the job-site to manufacturing environments will reduce the lead time by an average of 49% for this particular work. This fact implicates much wasteful work on-site is associated with the complex on-site assembly of the sub-construction and aluminium plating.

Considering the effort within the workflow model, it can be divided into (direct) operational costs and (indirect) management costs.

The majority of the (direct) construction costs, determined by the utilization of the resources labour and equipment, are also related to the craft work of assembling the sub-construction and aluminium panels. This can be explained by the fact that this work contains high volumes of

material input. This on-site assembly work is complicated due to the poor physical circumstances: besides they have to assemble the components in the ceiling above the head, manoeuvring with cherry pickers in a large 'sand box'.
Transferring this labour intensive work to off-site manufacturing plants by using more prefabricated components will be economically beneficial for two reasons: due to a significant reduction of work on-site all remaining assembly work can be performed in cheaper day production hours; second, labour costs will incline since off-site production can be performed under more secured circumstances using less experienced (cheaper) workforce.

Besides the effort is affected by the direct costs for operation, construction contains indirect management costs. These site costs are highly depending on lead time of construction. Although the costs for 'staff' and 'design and engineering' are to diverged to draw proper conclusions, a reduction of lead time can save an average of ±4500 euros a day only on site facility costs.

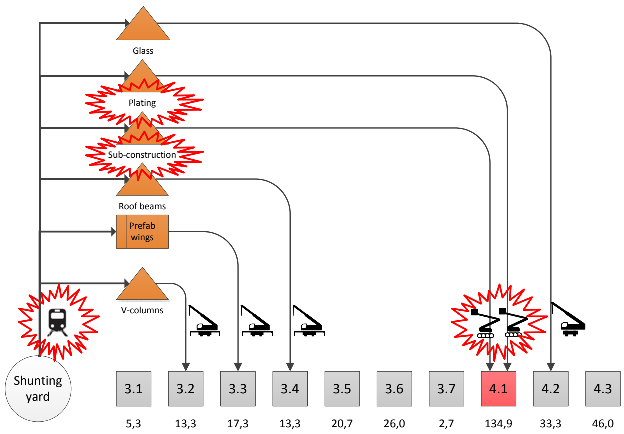


Table 7.27 Overview of combined results within the on-site production system, presenting the root causes of waste (the blocks represent the process steps, the numbers beneath the average lead time in hours).

Research response	**Most potential for waste elimination**	**Waste symptoms**	**Root cause of waste** (focus for improvement)
Quantitative research • Material • Time • Effort **Qualitative research** Implemented Lean techniques	Assembly of sub-construction and aluminium panels (especially the ceiling)	**Waiting** Complex and time consuming assembly operations on site. **Transport** Complex material delivery to the job-site. **Inventory** Large stock of materials and components needed on-site. **Motion** Unnecessary and time consuming movement on-site.	**Design** (variable) • Many components and parts have to be assembled on-site using craft work. • Many components and parts have to be delivered on-site. • Assembly of unwieldy materials above the head (ceiling panels). **Context** (non-variable) • The extreme time pressure leads to disruptions since co-makers have to work very closely. • Marginal working and storing space is available on-site. Material must be stored on the rail carriages. • Transport of material and components is limited by rail deliveries. **On-site management** (assumed as appropriate)

Table 7.28 Overview of identified (interpreted) waste symptoms associated with the assembly of the sub-construction and panels. In order to eliminate waste, the root causes of waste should be dissolved.

I. THEORETICAL FRAMEWORK
II. FIELD RESEARCH
III. CONCLUSIONS
IV. DESIGN

"Continuous improvement is not about the things you do well, that's work. Continuous improvement is about removing the things that get in the way of your work. The headaches, the things that slow you down, that's what continuous improvement is all about."

Bruce Hamilton

8. Conclusions

In this chapter the results of the literature review and the field research will be reviewed in order to answer the research question:

How can waste according to Lean construction be identified and eliminated in the selected case study 'Sporen in Arnhem' in order to improve workflow?

8.1 Research conclusions

Identifying waste

In order to identify waste in construction projects, a model is developed to measure workflow in practice. This model contains the three main elements of any kind of production process adopting the resources of material, time and effort. These resources are highly interrelated and can therefore not be seen independently. Although it can be difficult to measure generic steps in a construction process, the workflow model is useful by identifying wasteful activities requiring much time and effort (labour and equipment). Since wasteful activities can be seen as major cost drivers they should be eliminated out of the process.

The case study results confirm that it is not easy to formulate proper performance indicators to measure the effects of Lean construction. Although the implemented Lean techniques in the case study have a great impact on project performance, the metrics in the case study results indicates there is still much waste occurred during construction on-site.

Using the workflow model, the assembly of the sub-construction and aluminium panels (ceiling) is identified as the most potential for waste elimination. Both qualitative as well as the quantitative research implicated that this type of activity consumes significant lead time on-site, additionally subsequent work could not be started before finishing it. For this reason the assembly of the sub-construction and aluminium panels is determined as the bottleneck in the process. This wasteful and time-consuming work, mainly caused by the complex operational conditions, should be eliminated, or at least reduced be redesigning the process in which it is achieved.

Eliminating waste

Literature revealed that reducing on-site material handling and lead times through proper workflow management are the most important aspects for eliminating waste in a construction process.

Reflecting this knowledge to the identified waste associated with the assembly of the sub-construction and aluminium panels, the 'product strategy' promises to be the best solution for workflow improvements (see table 8.1). The use of so called proactive workflow methods already in the early design stage will result in major overall process improvement due to the intended 'standard elements' are multiplied 16 times (four in each platform) and possess much room for standardization.

8.2 Discussion

The benefits of the implementations of the Lean approach in the pilot project 'Sporen in Arnhem' were obvious: although the team (general contractor, co-makers and sub-contractors) had to work under extreme time pressure in complicated on-site conditions, the project was completed successfully within time gaining a profit of more than ten percent.

Most of the interviewees were very enthusiastic about the achieved results and associated the project success with the implementation of the Lean approach, especially the Lean planning sessions. The project manager of co-maker Sorba stated that, rather than the Lean planning schedules itself, short communication lines during the Lean planning sessions and later on during execution of the project was fundamental for the success. The success of the Lean planning sessions reveals that informal collaborative joint objectives and cooperation between the co-makers already in the early stages are of main importance, parallel to the formal construction performances.

Besides the application of the Lean planning sessions, field researched pointed out that prefabrication has played also a major role in on-time completion.

Both Lean techniques acquire involvement and knowledge from co-makers. This highlight the statement that co-makers are crucial for project success and proper production planning. Especially when future projects are often constructed in compact urban environments with limited time and less space inventories. In that perspective the case study project 'Sporen in Arnhem' exposes the advantages of Lean construction methods in challenging projects whereby mutual collaboration and on-time completion is crucial for project success.

8.2 Recommendation (Design)

In the seek for perfection led by Lean thinking, the construction process of the roof elements will be re-designed, providing an alternative preliminary design.

Within the product strategy 'design for constructability' and 'prefabrication' are the most effective solutions for workflow improvement. In addition to significant lead time and cost price reduction, management activities considering logistics will be simplified by the greater use of prefabricated components and standardized assembly methods. Ultimately, the added value for both the client as well as the construction partners will be increased.

Implications

There are certainly many solutions for waste elimination within the case study and in particular within the construction of the roof structure but only one solution will be worked out in detail in the next chapter.
If we follow the two strategies, the product strategy has the most practical advantages. Due to this research is performed in a 'reactive' way (the project has been completed already) waste symptoms could only be identified and interpreted by document analysis. Since design is eternal, in contradiction with expiring construction processes, it is more likely to make adjustments following the product strategy than the process strategy.

	DESIGN SPECIFICATIONS: Re-design of the roof structure		
Type of waste	**Objectives**	**Lean construction techniques (Product strategy)**	
		Concepts	**Preconditions** (examples)
• **Waiting -** Complex and time consuming assembly operations on site. • **Transport -** Complex material delivery to the job-site. • **Inventory -** Large stock of materials and components needed on-site. • **Motion -** Unnecessary and time consuming movement on-site	• **TIME:** A significant reduction of lead time on-site (only assembly). • **EFFORT:** A significant reduction of material handling on-site (standardization). • **MATERIAL**: A significant reduction of material input on-site (simplified logistics).	**Design for construction** • Prefabrication (more sophisticated elements including the ceiling components) **Design for logistics** • Just-in-time (JIT) delivery	• Concurrent engineering • Implementing knowledge from co-makers in early design stage • Broad partnering team • Joint IT tools for Lean design process (BIM) • Simulation with Lean planning sessions • Systems engineering

Table 8.1 *The formulated design specifications. Recommendations for the Lean design which will be elaborated in the next part.*

I. THEORETICAL FRAMEWORK

II. FIELD RESEARCH

III. CONCLUSIONS

IV. DESIGN

"Design affects how a building is to be built and determine the types as well as the level of resources to be involved in the conversion process. Architects often lack the knowledge and the incentive to make the right decisions."

F. Wong 2004

9. Lean design

This chapter will finally come up with a recommendation (solution) for workflow optimization. Part of the design, the so-called 'standard element', is re-designed according to the product strategy whereby only assembly on-site is required.

In the automobile industry Lean design focuses on manufacturability. Studies from MIT identified craft work in a mass automotive plant as a cause of waste, and not (as was claimed) a proof of the manufacturer's dedication to quality. From the standpoint of the Lean producer the existence of 'craftsmen' shows the failure of the manufacturer to design easy to assemble parts and then a failure to identify defects as soon as they appear (Crowley, 1998). Their advice: stamp out this craftsmanship from the process. Reflecting this on the construction industry, in this case to the craft work needed for assembling the sub-construction and aluminium panels, it can be concluded that Lean design is rarely applied since a significant amount of production is still achieved by craft work.

9.1 Design for construction

Design has a significant impact on the performance and profitability of a construction project. Therefore, decisions made during the design process should take in to consideration knowledge and experience from processes in (previously) projects, specifically from the production phase. Constructability means the capability of a construction project to be realized with optimal utilization of recourses (material, time, effort) (Gerth et al., 2013; Tam et al., 2007) The goal is that by using appropriate construction experiences in the design and engineering phases of a project facility, the operations on site will be more efficient.

Based on the concept of constructability, 'design for manufacturing and assembly' (DFMA) and the theory of waste, the method 'design for construction' (DFC) has been developed. The four-step model complements the conventional construction process, and consists of the following steps (Gerth et al., 2013):

1. **Specify customer values and similar previous projects**
2. **Identify on-site waste and cost drivers in (previous) projects**
3. **Develop criteria to evaluate constructability;**
4. **Evaluate constructability of the design**

1. Specify customer value (preconditions)

The theory of Lean production states that specific customer values should always be the foundation for improvements. In this case the general customer values are formulated according the demands of the client Prorail and the architect UN Studio (Ben van Berkel). Both parties represent the ultimate customer (travellers) in explicit demands in terms of process quality (realization) and product quality (design).

ProRail: Preserving proper construction performance (process quality) by:

- On time completion according the out-of-service periods to avoid extra inconvenience for travellers.
- Securing safety for travellers during construction.

Figure 9.1 Architectural appearance of the platform roof. The two light line are running the entire platform length

Table 9.2 Root causes of waste: a large number of parts has to be assembled on-site under poor cirumstances.

UN Studio: Preserving the architectural design (product quality) which are translated into three architectural demands:

- The complex form of the roof, curved in three directions, should be maintained.
- The large transparency (glasses) of the roof should be maintained without adding extra frames (joints).
- The plain assembly of plating, using only two main lines running along the ceilings, should be conserved as the only desirable longitude joints.

2. Identify on-site waste and cost drivers

The key focus of design for manufacturing and assembly (DFMA) is to reduce the production cost, mainly by reducing the number of parts, in order to reduce the number of assembly operations and the complexity in production management (Gerth et al., 2013). Consequently, the on-site construction will be more simple and efficient.

Essentially important problems to identify are those which cause waste at both operational level and project management level. By analysing where, why and how the problems occurred, each problem can be sorted into three categories of desired product characteristics (Gerth et al., 2013). The problems associated with the assembly of the sub-construction and panels are presented in table 9.3 and visualized in figure 9.2 and 9.4.

Category	Problem	Root cause
1. Components and part design	Unsafe movements because of unwieldy materials and components *(assembly of large ceiling panels above the head)*	• The complex architectural design contains a large number of sub-construction components and panels to assemble on-site (see figure 9.4). • Poor physical working conditions on-site with marginal time and working space available (see figure 9.2).
2. Production ease (constructability)	Many components and parts to assemble.	
	Complex and time consuming assembly operations.	
3. Production execution and management (operation and coordination)	Large stocks of materials and components.	

Table 9.3 Root cause of problems sorted by category of constructability

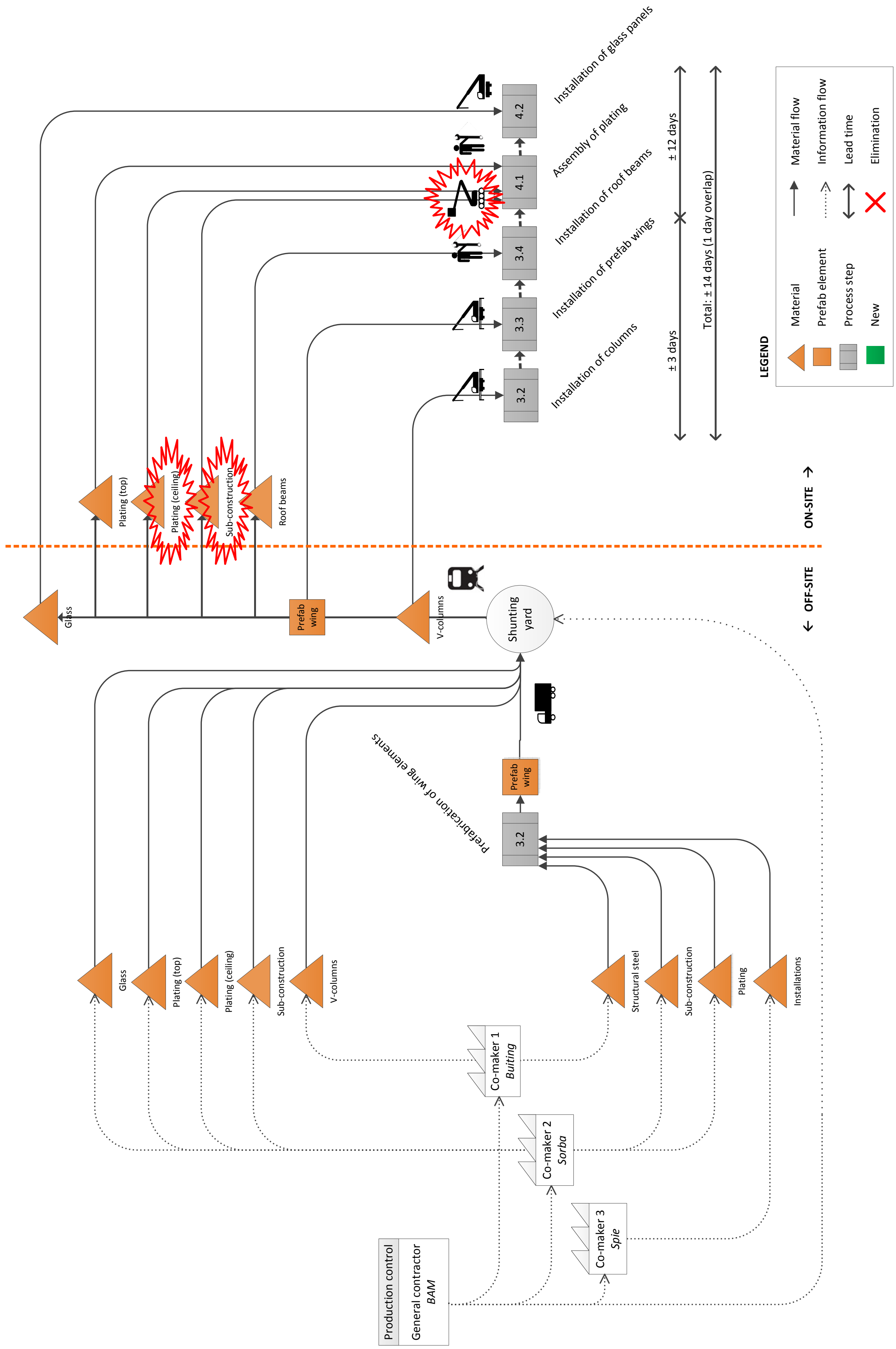


***Figure 9.4** Material flow 'current state'. The large number of material input and difficult assembly operations are root causes for waste associated with the assembly of the ceiling.*

3. Develop criteria for constructability (goals)

In order to evaluate how well desired product characteristic can be achieved without incurring unnecessary cost in production, some design criteria are formulated. The future design requires evaluation of the following three formulated product characteristics:

- **Architectural aspects (Product quality) -** The product quality, in this case the aesthetic design, shall be preserved by the architectural demands as formulated in the preconditions in paragraph 9.1.
- **Logistic aspects (Transport & Delivery)** - Since in some phases transport by road is impossible, all the logistic deliveries should be able for transportation by rail. Therefore the size of the prefabricated components is restricted by the maximum sizes of the rail transport carriages: 25,0 m in Length, 2,6m in width and 3,3 m in hight (www.gueterwagenkatalog.rail.dbschenker.de).
- **Assembly aspects (Standardization) -** Goal is to make the design highly standardized using highly prefabricated components in order to reduce wasteful craft work on-site. Consequently less expensive workforce and equipment is needed.

4. Evaluation of the design (Design analysis)

The primary structure of the platform roof consists of curved prefabricated columns in steel with on top of it a light weighted steel roof structure covered with aluminium composite plating. The cold bent glass plating are fixed on both sides and in cross direction clamped with kid joints to the aluminium composite plating.

Preliminary design (engineered by the architect)

The architect designed so called 'standard elements' for all the intermediate platform objects. The architect focuses mainly on the integrated product design, aiming to include drain facilities and electrical installations in an aesthetic way. Two continuous light lines are running the entire length of the platform roof (see figure 9.1). Alongside these light armatures, cable ducts are running over the entire roof length connecting the speakers and other technical facilities. These lines providing additionally an architectural solutions for looking the ceiling joint less. The mechanical engineering facilities like draining- and dry fire extinguish systems are completely integrated in the V-formed columns.

The standard elements are repeated 15 times: four elements in each platform, except for platform one which contain only three standardized elements due to a more curved platform following the tracks. Although the architect called these elements 'standard elements', its design lacks standardization. Much time and effort is needed on site to assemble all the different single parts. Since these standard elements are repeated fifteen times, there is much potential for standardization.

Final design (engineered by co-makers)

In a later stadium the preliminary design, focusing on product optimization, is more elaborated for process optimization. Concerning the preliminary design, Sorba was in first attempt not interested in the work of 'Sporen in Arnhem' as it was not able to deliver the (labour intensive) work on time. When Buiting suggested to prefabricate large parts of the standard elements, Sorba reconsidered and accepted the work. Reducing time consuming work on site was the basic assumption for the final design engineered through concurrent engineering by the co-makers Buiting (steel), Sorba (covering) and Spie (installations). This pro-active attitude of the co-makers was also acquired by the Lean approach implemented by the general contractor. As a consequence of this close collaboration a more elaborated design is developed containing large components (roof wings), pre-assembled on the plant of Buiting.

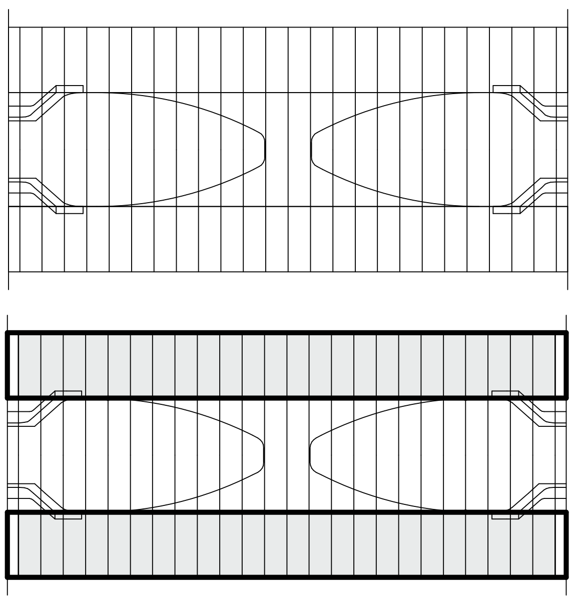


Figure 9.5 Preliminary design (on top) and final design (under) with prefabricated 'wings' in grey.

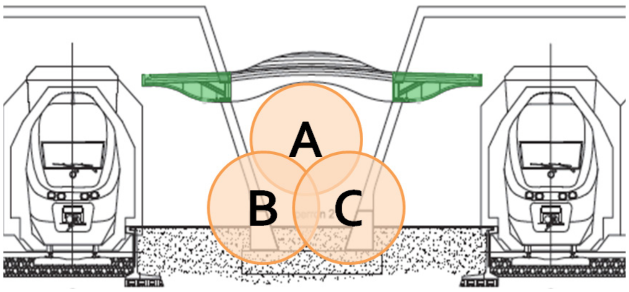
Figure 9.6 Typical scene showing the difficulties of operating in a giant sand-box with less work space. Co-maker (A) Sorba is finishing the ceiling, co-maker (B) Spie and co-maker (C) Dura Vermeer are working in the ground respectively on installations and the bedplate.

9.2 Design concept

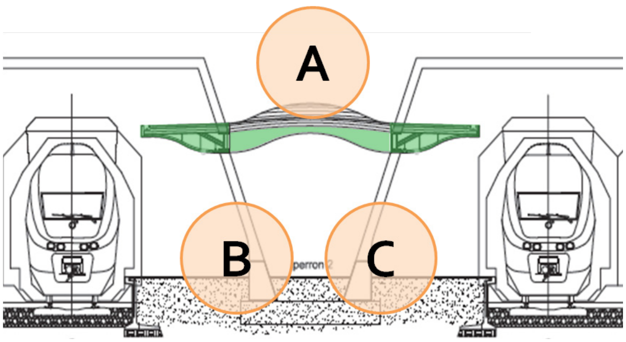
Objectives

The solution for workflow improvement is a redesign of the current process. The main objective is to reduce as much as possible complex craft work on-site associated with the assembly of the sub-construction and aluminium panels. This will be achieved by designing more elaborated prefab components. The use of prefabrication has been considered as one of the most effective waste minimization methods in the construction context.

In the 'improved state' the time-consuming on-site assembly work will be eliminated from the process using prefab roof elements in which all the ceiling parts are pre-assembled. By transferring the on-site craft work to manufacturing environments, the on-site assembly will be much easier and faster. In addition, all the remaining assembly work of the roof can be done from top of the roof creating a 'second work floor'. In this way the physical conditions in which the co-makers have to work will be much better resulting in significant improvements of workflow on-site.



CURRENT SITUATION



CONCEPT

Figure 9.7 The working conditions will be simplified according the new design concept (letters = co-makers, green = prefab elements).

Prefabrication

Prefabrication is defined as the transferring stage of construction activities from the field to an off-site production facility. Although the construction industry has been implementing prefabrication, it is continuously encountered difficulties (Tam et al., 2007; Ballard and Arbulu, 2004). The main reason is because of the high initial construction costs, time consuming in initial design development, limited site space in placing prefabricated building components, lack of experience, lack of demand in prefabricated components, water leakage problems and non-standardized design (Tam et al., 2007).

Looking to these difficulties, in the project 'Sporen in Arnhem', much of these difficulties can be seen as advantages for using prefab components. Since every design is time consuming, it should be designed properly by consulting all co-maker in an early stage. Secondly, the limited space acquire just-in-time deliveries, additionally the prefab components could be assembled direct from the rail transport without intermediate storage. The high initial cost will be earned back by reducing the overall lead times and saving much effort on-site. Finally, the standard element is multiplied 15 times, therefore it is economically profitable for prefabrication.

Prefabrication concepts

Based on the combined process and product optimization, four basic concepts are developed. The concepts are based on the cross sectional subdivision of the roof structure into various types of elements. Every concept has different options, see figure 9.8. Technically various options are possible but operating within the boundaries of the current architectural quality, logistic possibilities and assembly aspects, few options are satisfying. Only one option will be elaborated.

Concept 1: One element (Middle)

Concept one spans the total width of the platform roof and can be divided in four options.

Option 1.1 is one giant element mounted in between the columns. Option 1.2 is one giant element positioned on four columns in the centre the element.

Option 1.3 contain eight smaller parts mounted on two construction layers. Since these elements have to be positioned on a structural beam, the ceiling panels cannot be pre-assembled in this option without creating an extra longitudinal joint which is not desirable.

Option 1.4 is the traditional option with no prefabricated components at all. Within this option all parts (structural beams, roof beams, sub-construction elements, aluminium panels and glass panels) should be assembled on-site consuming much time and effort.

Only option 1.3 and 1.4 are possible by means of transportation since the sizes of the first two options are way too big (and heavy) for assembly and transportation.

Concept 2: Two elements (Side-Side)

In this concept the roof is divided into two large elements, with or without glass.

In options 2.1 and 2.2 the glass is cut in two pieces restricted by the size of the element. This results in a giant non-satisfactory joint in the sky-light.

In option 2.3 and 2.4 the beams and glass is mounted in a traditionally way afterwards. All the options are not possible due to the width of the elements (±5,5m) exceeds the rail transport limits.

Concept 3: Three elements (Side-Middle-Side)

In concept three, the roof contain three main parts. All options contain so called prefab 'wing' elements.

In option 3.1 the middle element is including the skylight. These glass panels could easily break during assembly: lifting these elements will create torsion by the lack of stability in its design.

In option 3.2 only the panels in the middle are prefabricated. Within option 3.3, which is the current (final) design, the middle part is completely assembled in a traditionally way. Only option 3.3 is possible for transportation.

Concept 4: Four elements (Side-Middle-Middle-Side)

This concept contains four main prefab elements. By dividing the middle part into two elements, the width of these elements will incline to 2,6m which makes them suitable for rail transport.

Both side-elements contain the structural beam. Both middle elements have to be assembled in between.

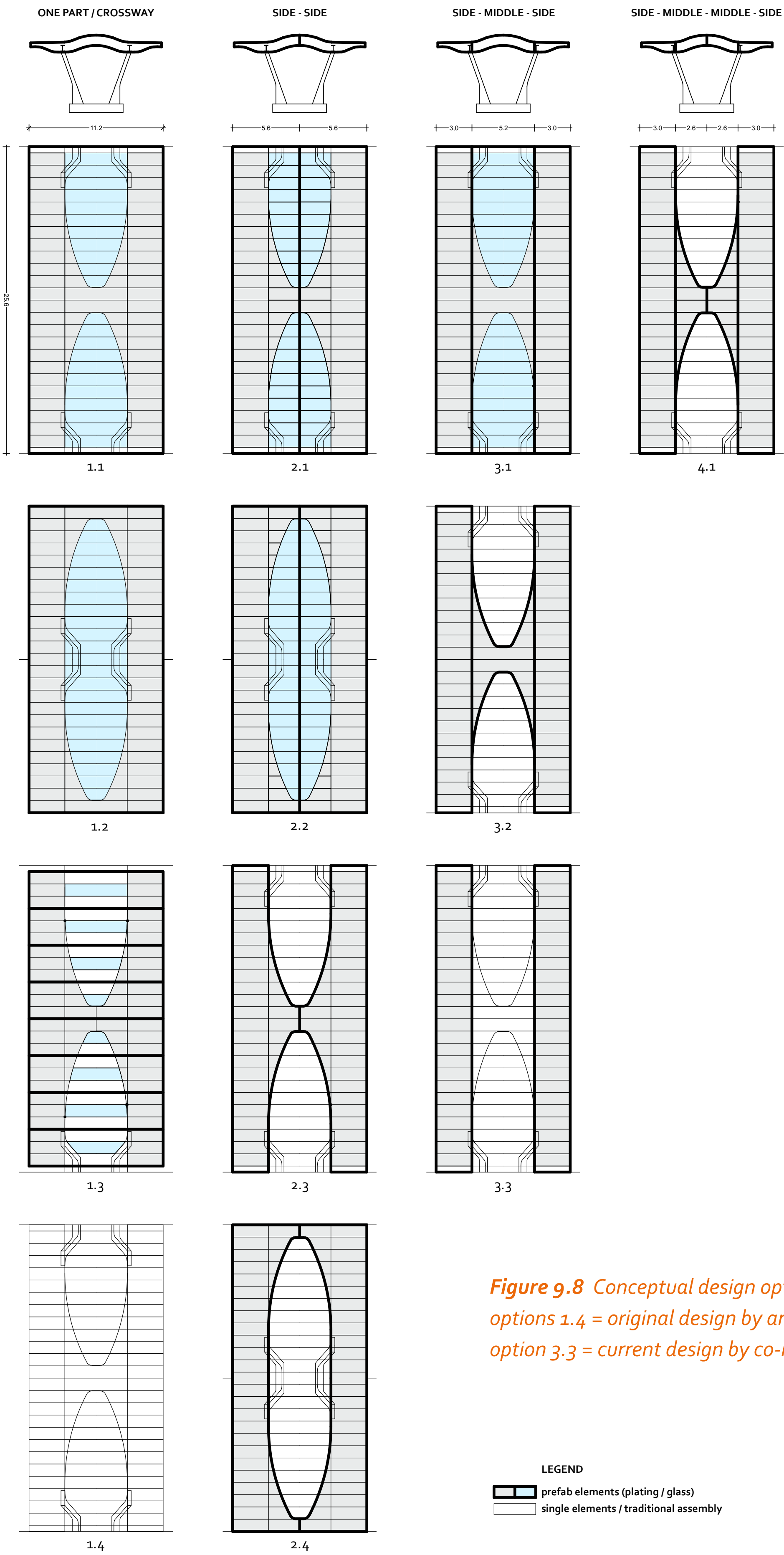


Figure 9.8 *Conceptual design options*
options 1.4 = original design by architect
option 3.3 = current design by co-makers

		Options	Architectural aspects	Logistic aspects	Assembly aspects	Total
Concept 1	*M*	**1.1**	+	-	+	-
		1.2	+	-	o	-
		1.3	+	+	o	+
		1.4 (original)	+	+	-	o
Concept 2:	*S-S*	**2.1**	-	-	+	-
		2.2	-	-	o	-
		2.3	+	-	o	-
		2.4	+	-	o	-
Concept 3	*S-M-S*	**3.1**	+	-	+	-
		3.2	+	-	+	-
		3.3 (current)	+	+	o	o
Concept 4	*S-M-M-S*	**4.1**	+	+	+	++

Table 9.9 *Evaluation overview according the developed constructability criteria.*
+ = good / possible
o = sufficient / possible
- = insufficient / impossible concerning logistics

After evaluation of all options according to the formulated constructability criteria (architectural quality, logistics and ease of assembly), concept four is determined as the best solution (see table 9.9) to work with. This option will be presented in more detail in the next paragraphs.

9.3 Technical design

Design complications

With the new design concept, various technical complications will arise associated with implementation of more elaborated prefab elements. To ensure ease of assembly together with integrated product design, various technical complications has to be solved:

- **Stability of the prefab elements (during lift) -** In the current design the structural beam is integrated in the 'wing-element' (side element), consequently the 'ceiling-element' (middle element) contain no structural body in the current design (see figure 9.11, current design). When moving the structural beam into the ceiling element, the wing element looses its structural strength acquired during lifting (see figure 9.11, primary concept). Attaching extra structural steel in this element is not the most economical solution considering the use of material. Consequently the structural beam (IPE500) will be 'split' in two structural beams. The new beam resulted in the choice for a honeycomb beam for two reasons: first, the maximum height of an UNP beam is 400mm which is not sufficient for gravity force compared to the current IPE500, second a honeycomb beam is more light weighted.

- **Transportation and assembly of the (prefab) elements on-site** - The honeycomb beams in both elements function as main structure for attaching the lifting devices, first for installing the elements on the rail carriage and second for installing the elements on the columns. All the joints are dimensioned loose to cope with tolerances during assembly. This is necessary for the two prefab elements and the roof beams. The joint between the wing- and ceiling element is 3cm and will be bolted before it will be covered with panels. After installing the ceiling- and wing elements, the roof beams have to be assembled in between. Brackets will be placed on the edges of the inner side plating near the skylight to avoid damaging during assembly.

- **Attachment of the ceiling components (sub-construction and plating material) -** In the current design the sub-construction and subsequently the aluminium panels are attached to the roof beams (see appendix C5 and C6) what results in time consuming craft work on-site. The new design will prevent this on-site assembly work since all the sub-construction and panels are pre-assembled in the ceiling-elements.

On the next pages the improved design will be presented. The purpose of the design is to show that the developed concept is suitable within the current architectural and technical boundaries, therefore it is not fully elaborated in detail. It can be seen as a preliminary design what has to be completed in detail by the various co-makers acquiring specific knowledge.

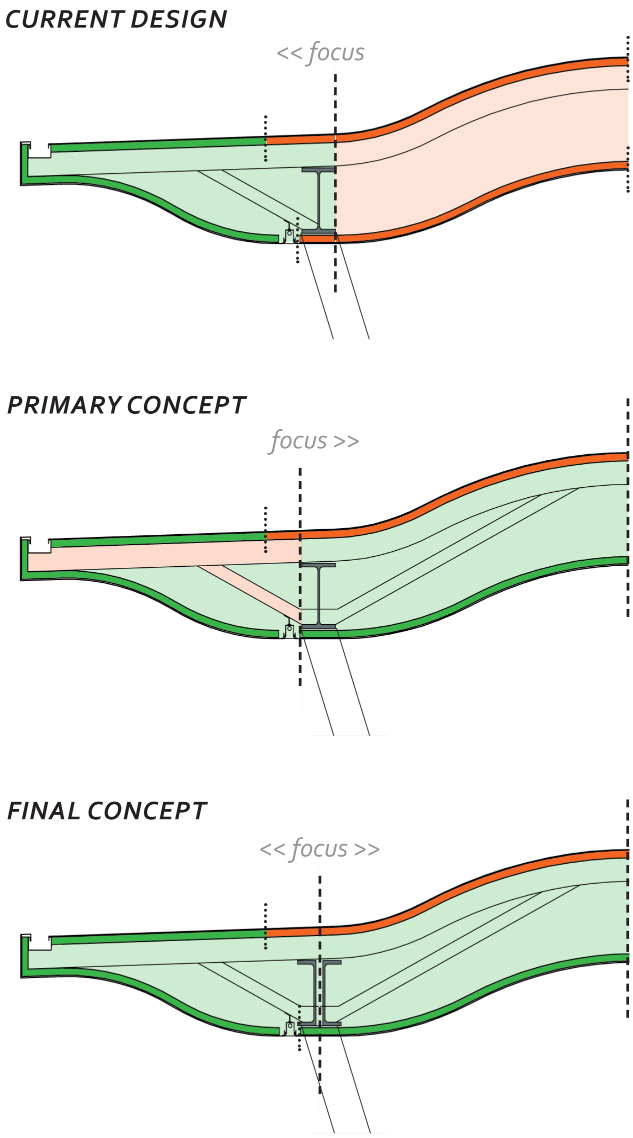
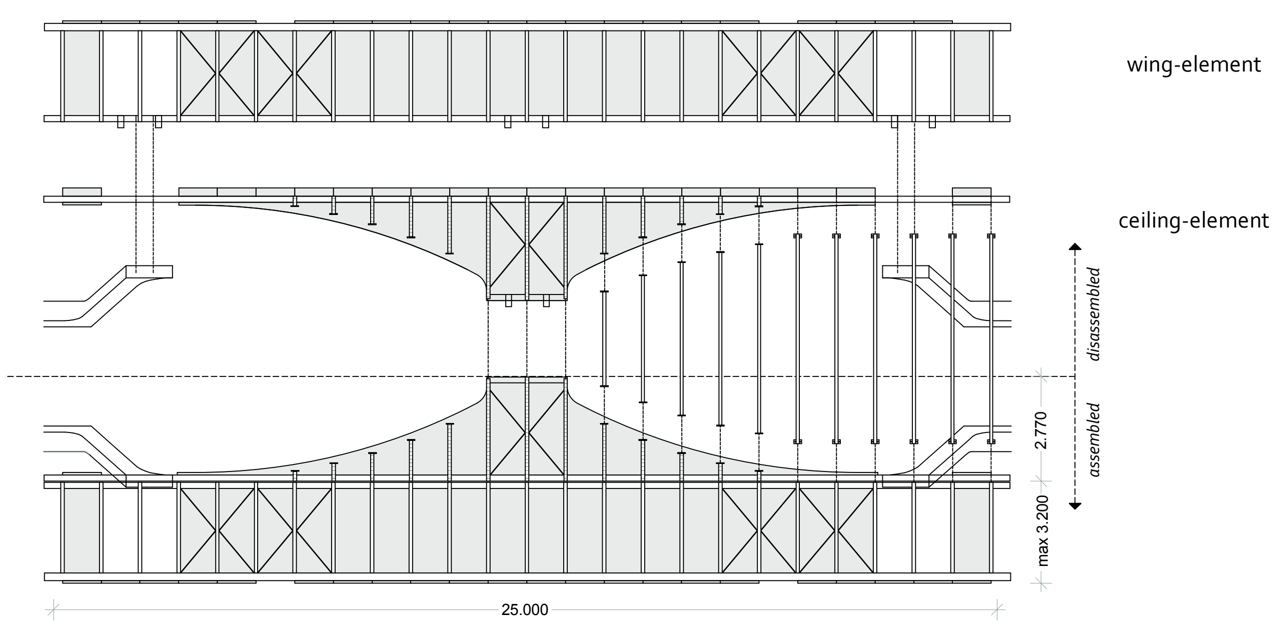


Figure 9.11 *Assembly concept*
Green: suitable for prefabrication
Orange: unsuitable for prefabrication (traditional assembly)

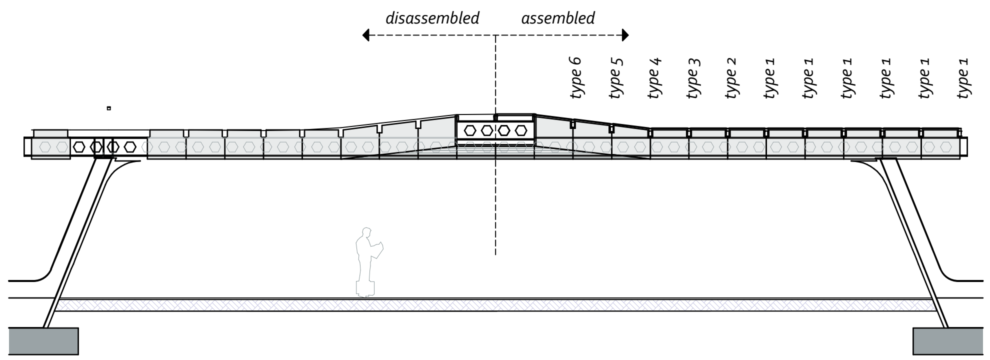
Complication	Current design	Improved design
Installation of the elements on-site 1) Prefab elements 2) Roof beams	1) Low accuracy: only on columns 2) No protection acquired.	1) High accuracy: two elements next to each other. A temporary assembly device is needed for proper installation and protection of the pre-assembled panels. 2) A temporary assembly device is needed to protect the pre-assembled panels.
Stiffness of the prefab elements (span of 25m)	The wing elements contain the structural beam (IPE500).	Both elements will contain a structural beam (honeycomb beam 500mm).
Attachment of the ceiling (sub-construction and panels)	Craft work is acquired to attach all single pieces to the roof beams in between the wing-elements on both sides.	Pre-assembled in the new developed ceiling-elements.

Table 9.10 *Overview of design complications: current versus improved design.*

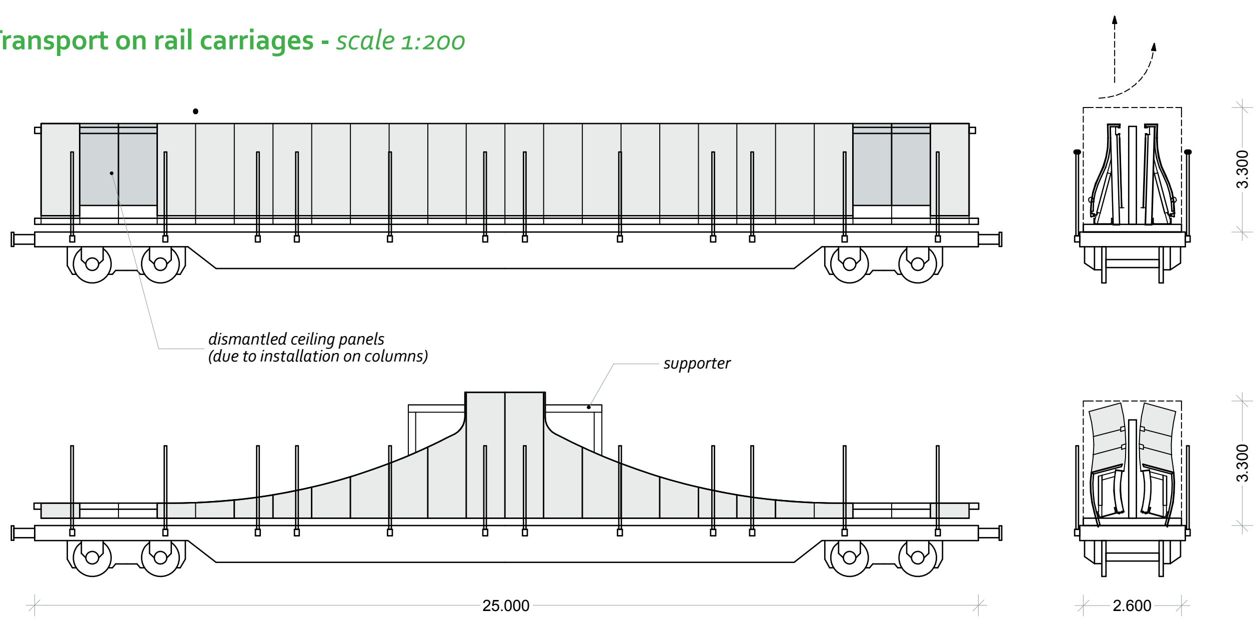
Roof plan (exploded) - *scale 1:200*



Section D - *scale 1:200*

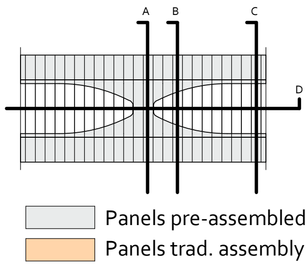


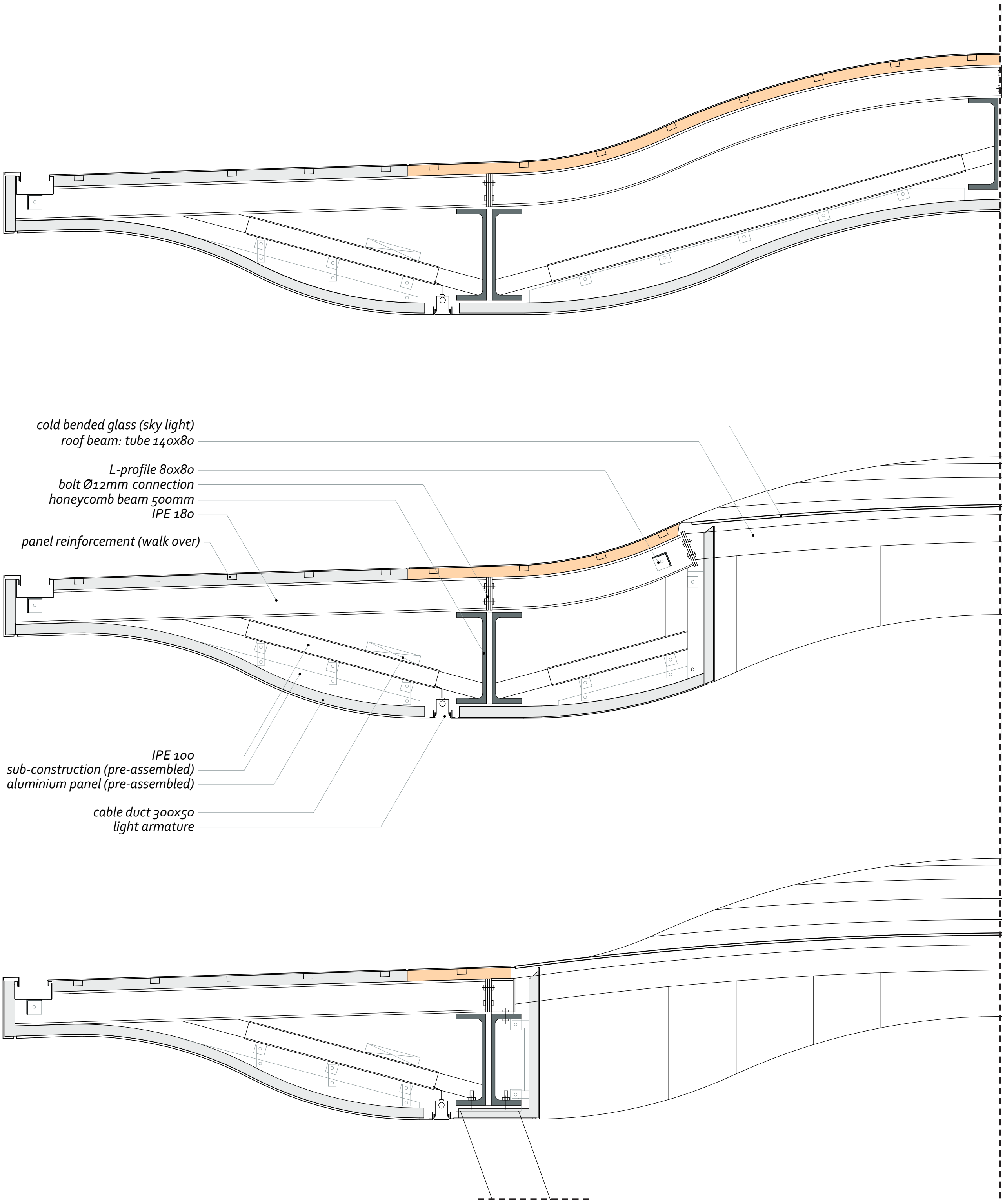
Transport on rail carriages - *scale 1:200*



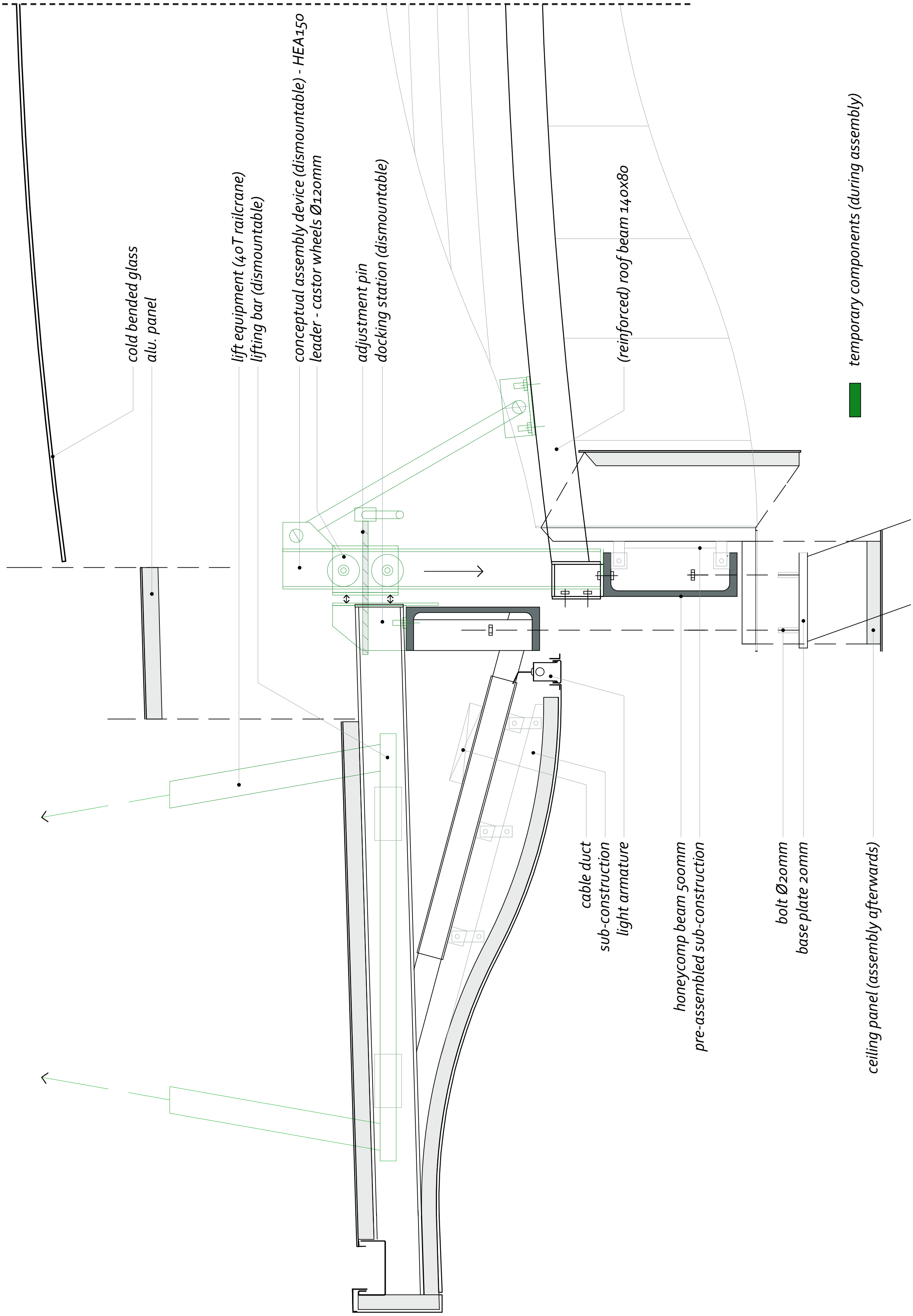
Sections A - B - C

scale outlined

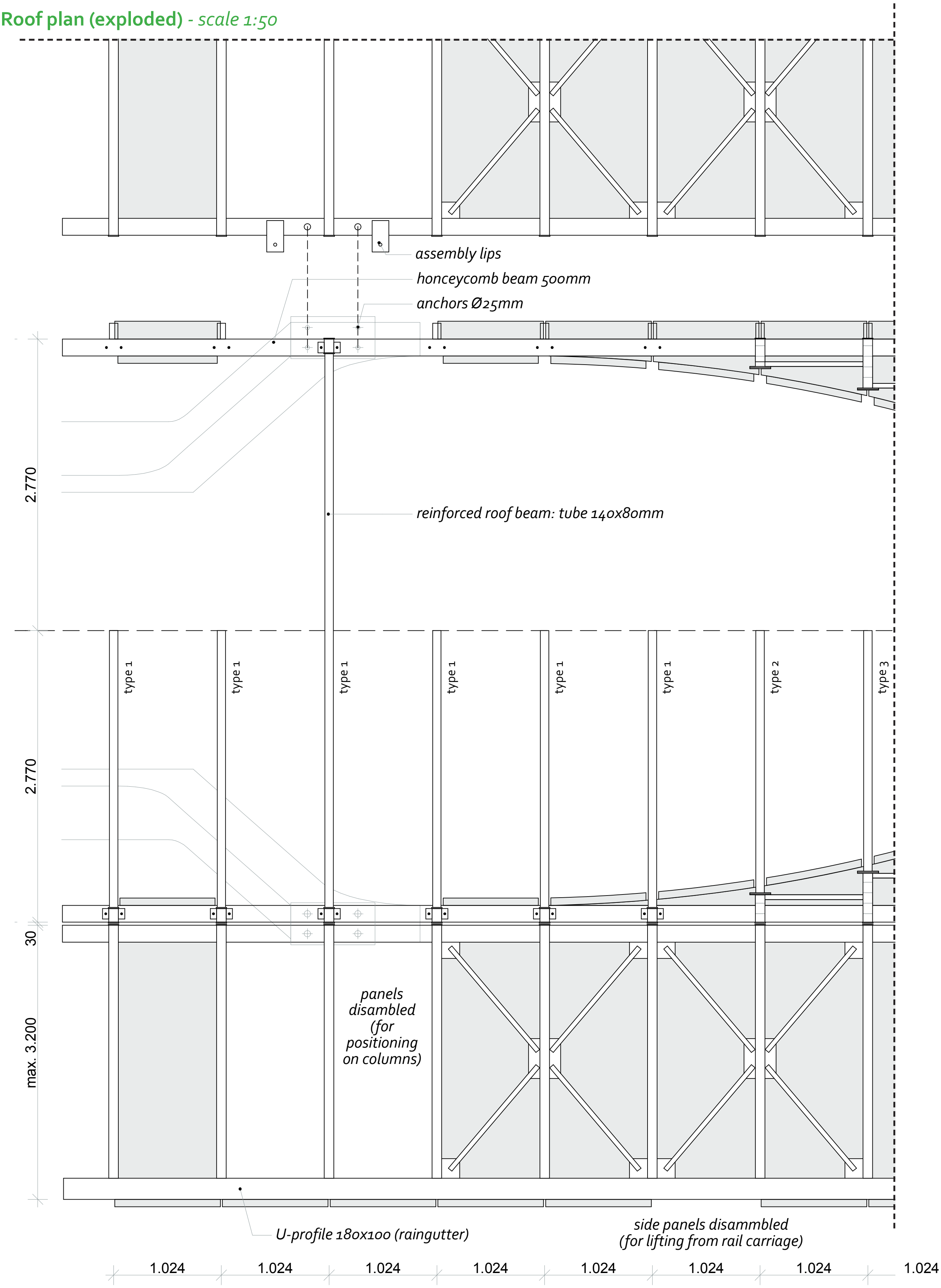


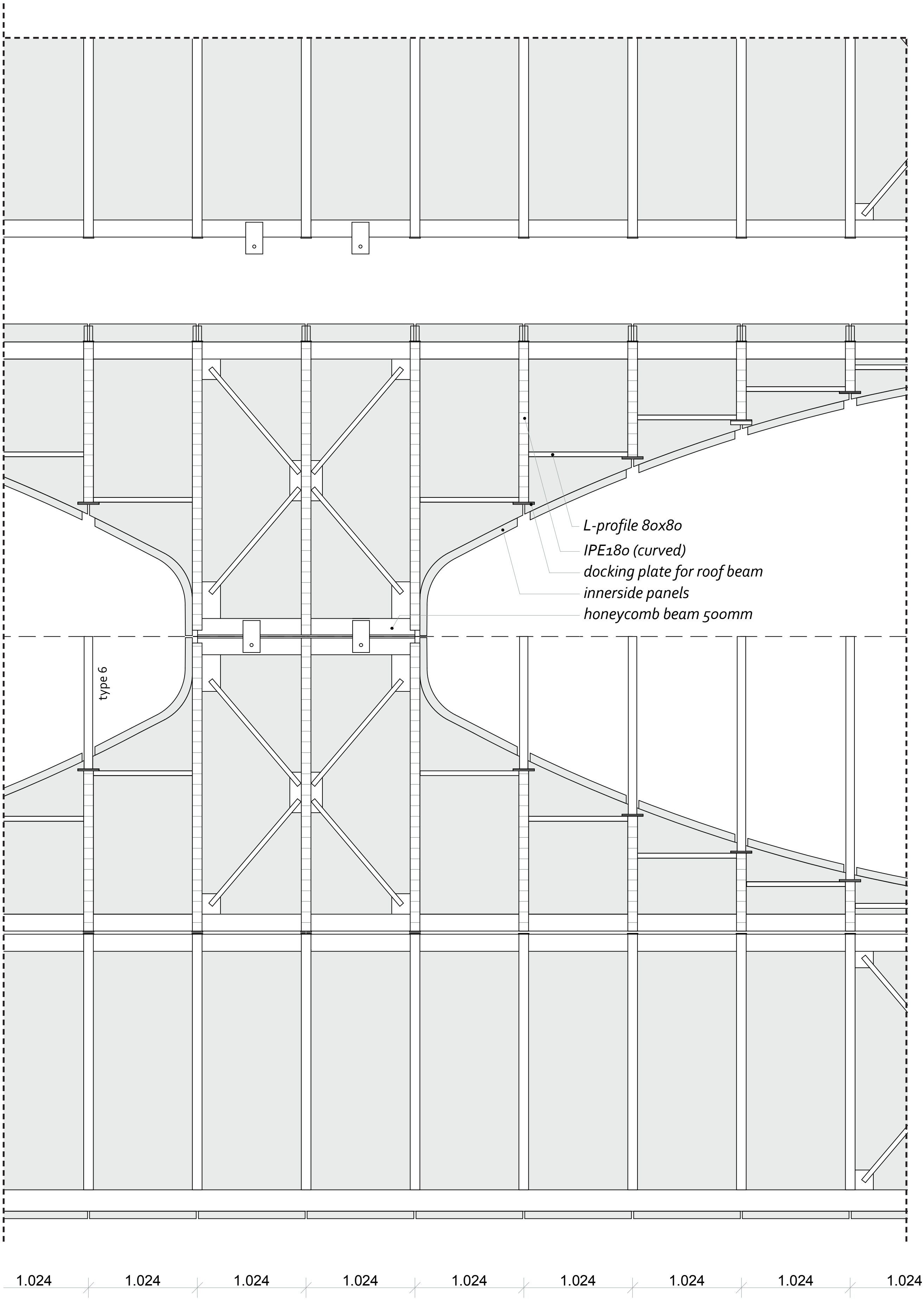


Positioning the prefab elements (section C) - *scale 1:20*

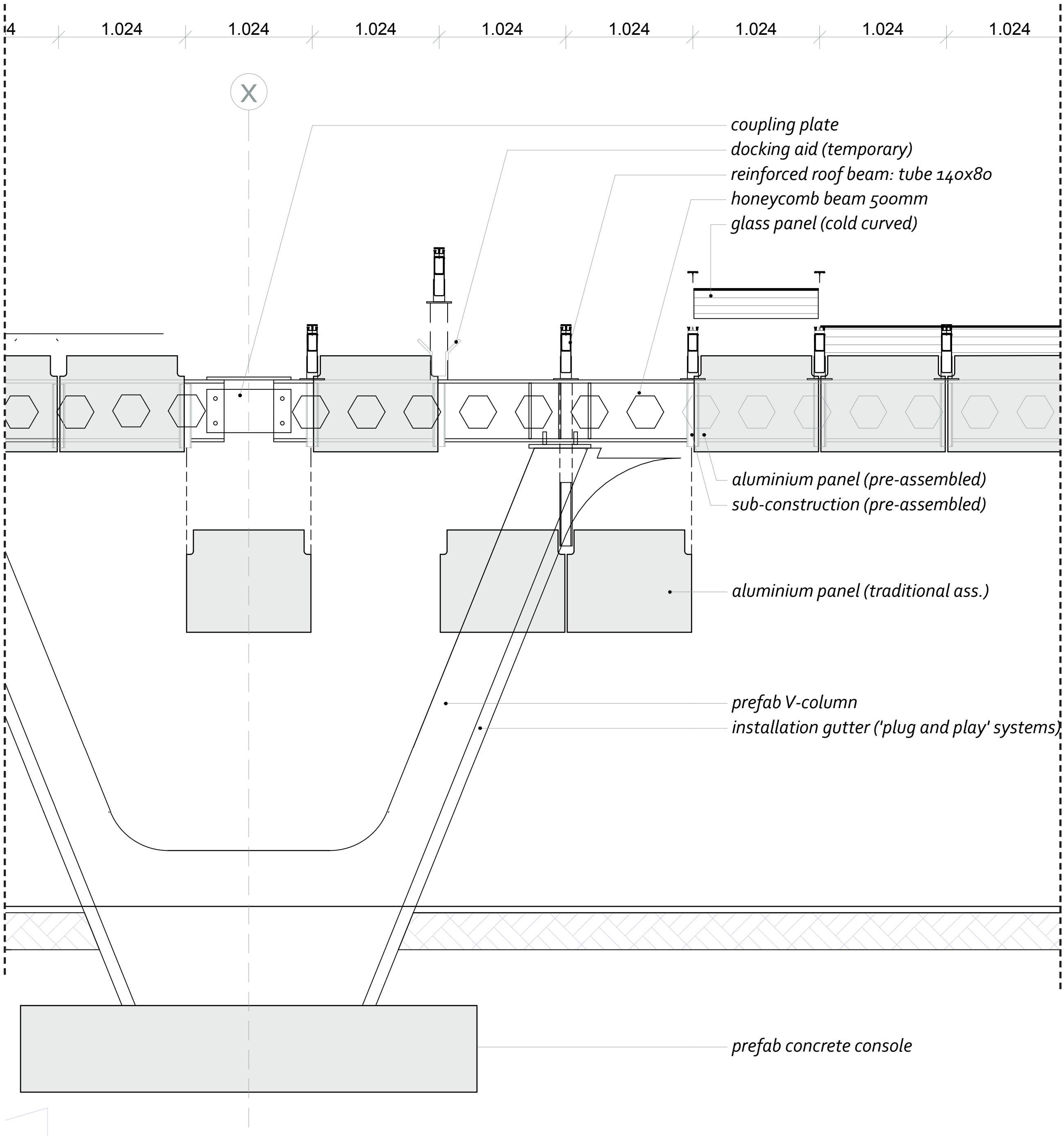


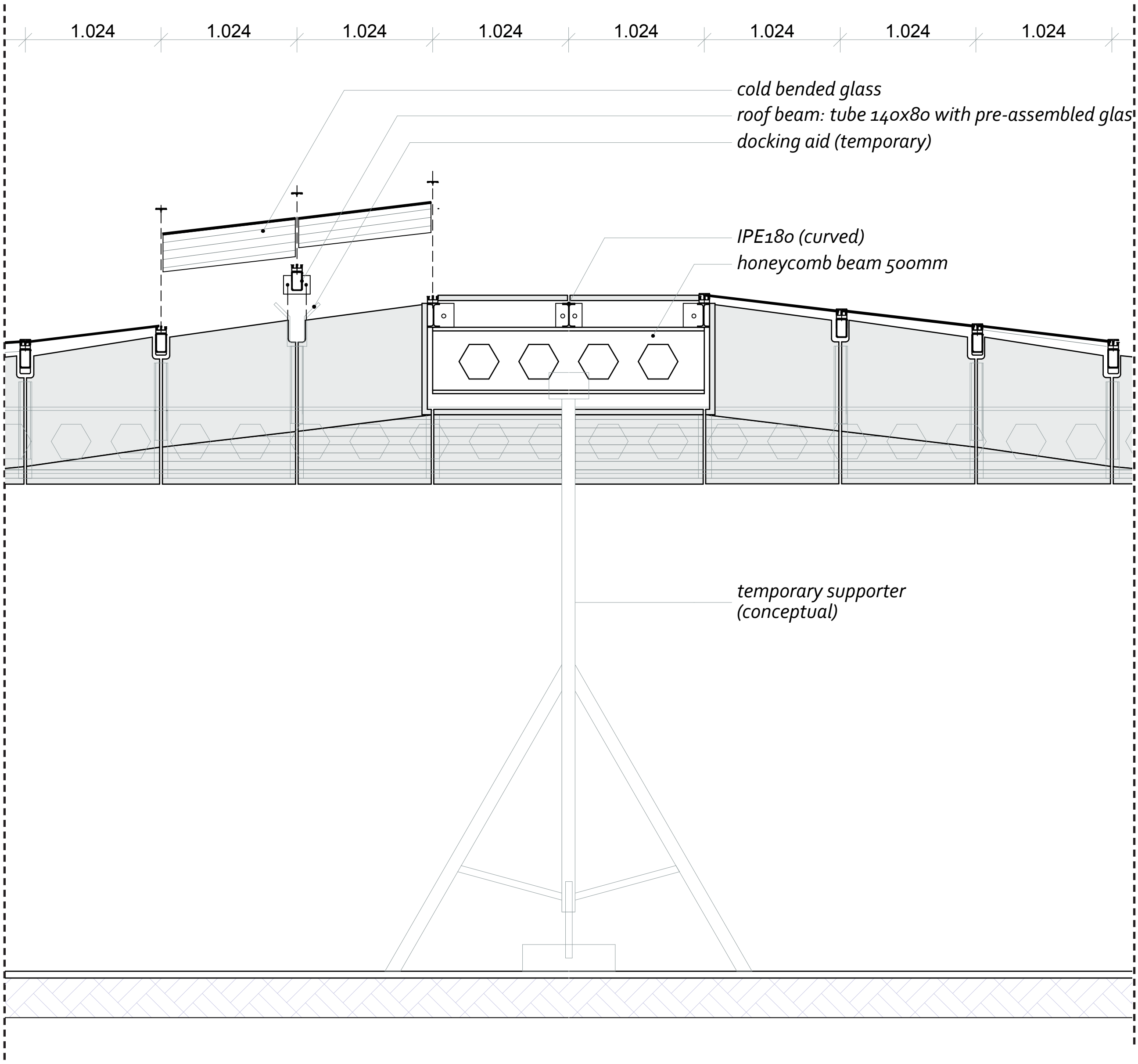
Roof plan (exploded) - *scale 1:50*




L-profile 80x80
IPE180 (curved)
docking plate for roof beam
innerside panels
honeycomb beam 500mm
type 6
1.024
1.024
1.024
1.024
1.024
1.024
1.024
1.024
1.024

Section D (exploded) - *scale 1:50*




1.024
1.024
1.024
1.024
1.024
1.024
1.024
1.024
cold bended glass
roof beam: tube 140x80 with pre-assembled glas
docking aid (temporary)
IPE180 (curved)
honeycomb beam 500mm
temporary supporter
(conceptual)

9.4 Workflow improvements

Although the solution may look very simple, as it is only a technical redesign using large prefabricated components within the architectural boundaries, it will be highly effective for workflow improvement. For detailed calculations see appendix B13, B14 and B15. According the developed workflow model, significant improvements (estimations) will be achieved concerning the following resources:

1. **Material**
2. **Time**
3. **Effort**

Material

The use of prefabrication results in a removal of all craft work on-site associated with ceiling, transforming the construction into assembly only. The new developed ceiling-elements will affect the input (volume) for the following two types of material:

- **Sub-construction and aluminium panels -** The volume of the labour intensive assembly of the ceiling material on-site is completely eliminated (-476 m2) as a result of prefabrication (see table 9.12).

- **Prefab elements -** In the improved stated the number of prefab elements is doubled: alongside the (modificated) wing elements two extra ceiling elements have to be positioned on-site.

In figure 9.17 the material flow is visualized for the 'improved state'. In the improved state the input of sub-construction and plating material will be completely eliminated (except for the ceiling panels near the columns) through adoption of these materials in the prefab ceiling elements. In this way the time consuming assembly of huge stock of components will be eliminated out the on-site construction process.

All material will be delivered just-in-time on based on the daily production capacity (see figure 9.14). The rail carriages will be arranged in a specific order to install the prefab elements directly from the the railway carriage on the columns. During all out-of-service periods two tracks are available alongside the platforms. In this way the rail crane is able to move independently from the rail carriages applied for the arrival and removal of material.

	MATERIAL				TIME													
	Volume (m2)				Productivity (m2/manhour)			Labour (manhours)				Workforce (man)		Lead time (hours)				
	ON		OFF		ON		OFF	ON		OFF		ON	OFF	ON			OFF	
	top	ceiling	wings	total	top	ceiling	wing	top (14,4%)	ceiling (85,6%)	wing	total			top	ceiling	total		
CURRENT STATE	240	476	939	1.655	2,58	0,9	1,2	93	552	767	1.413	5	5	18,6	110,4	129,0	192	
IMPROVED STATE	240	70	1.345	1.655				93	81	1.100	1.274			18,6	16,2	34,8	289	
	0	-406	+406	0					-471	+471	-139				-94,2	-94,2	+97	
Difference (%)		-85%	+43%						-85%	+43%	-10%				-85%	-73%	+51%	

Figure 9.12 'Material' and 'Time' calculations (assembly of sub-construction and alu. panels)

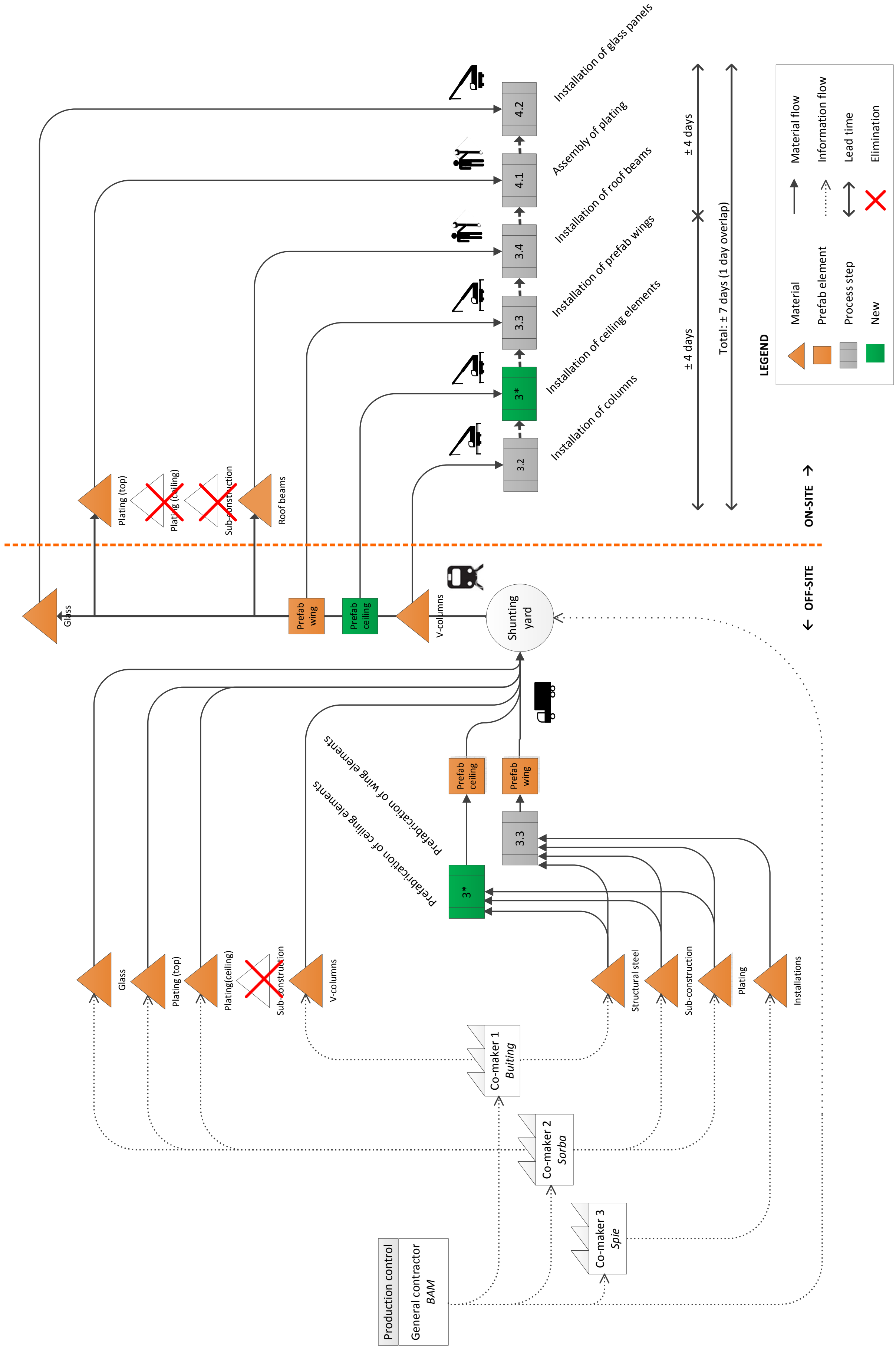


Figure 9.13 Material flow 'Improved State' (logistic system)

Time

The time needed for the assembly of sub-construction and plating material is associated with the volume of the material input. Since we know the specific material volumes (m2) of the improved design and the productivity (m2/manhour) for on-site and off-site assembly, the time consumption can be calculated, taking all other factors as a constant. The data from table 9.12 shows significant improvements:

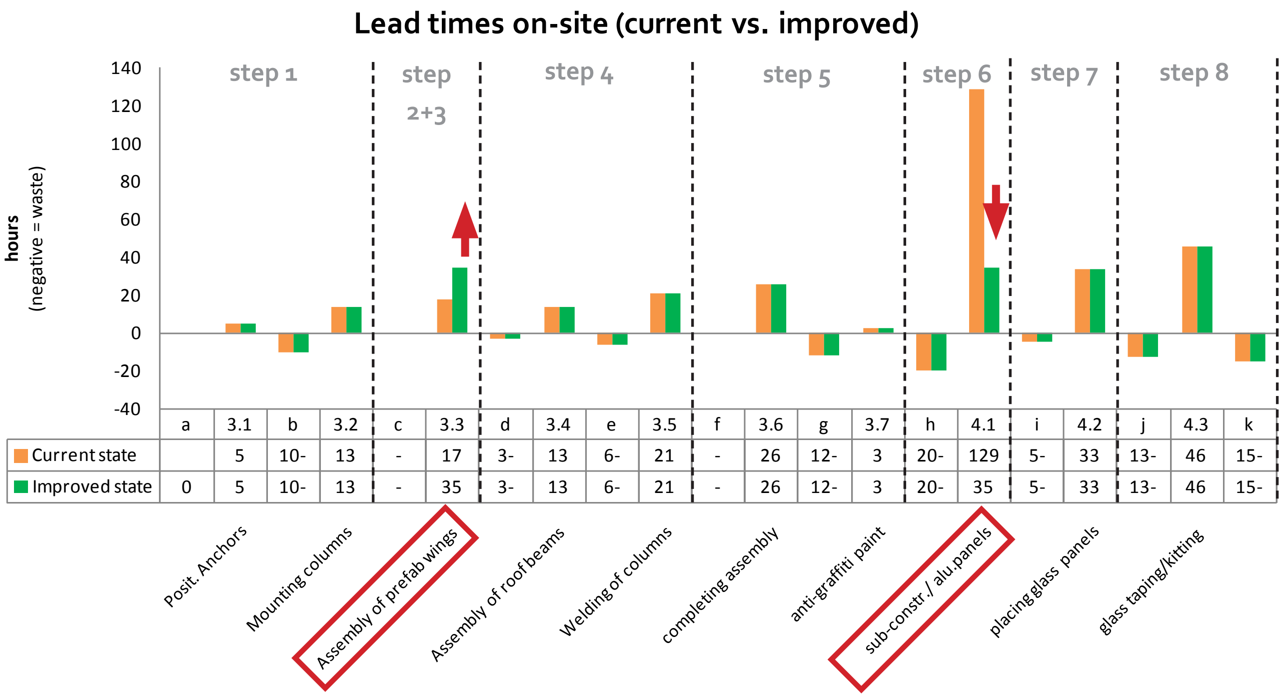
- **Assembly of sub-construction and alu. panels** - A total of 471 manhours on-site will be transferred to off-site manufacturing environments. Since the productivity in the off-site facility is much higher, a reduction of 139 manhours (-10 % of total) is achieved. Besides the absolute reduction of manhours, the work in off-site manufacturing environments can be done with much cheaper workforce what will be calculated in the next paragraph. Lead time on-site is reduced from 129 to 34 hours (with a constant workforce), what increases the total on-site building speed for the assembly of the roof structure by 73%.

- **Positioning prefab elements -** Since the number of prefab components is doubled from 8 to 16 elements for each platform, the number of manhours will equally be multiplied roughly by two.

In figure 9.14 the lead times within the 'improved state' are presented next to the 'current' state. A major distribution of lead times is achieved for both affected type of activities.

This significant reduction of lead times is fundamental for the new developed ('ideal') workflow planning implementing pull production and single piece flow (see figure 9.15). For simplifying this workflow planning, the presented lead times for the value adding work are including the previous necessary work (for example activity 3.2 = b+3.2).

In order to visualize the improved workflow, all the work will be subdivided in a total of eight process steps, distributing the lead times equally. These steps will be simulated in the next paragraph.



	a	3.1	b	3.2	c	3.3	d	3.4	e	3.5	f	3.6	g	3.7	h	4.1	i	4.2	j	4.3	k
Current state		5	10-	13	-	17	3-	13	6-	21	-	26	12-	3	20-	129	5-	33	13-	46	15-
Improved state	0	5	10-	13	-	35	3-	13	6-	21	-	26	12-	3	20-	35	5-	33	13-	46	15-

Figure 9.14 Lead times on-site. Although only two type of activities will be affected, the redesign results in significant reduction of lead time focussing on the identified bottleneck.

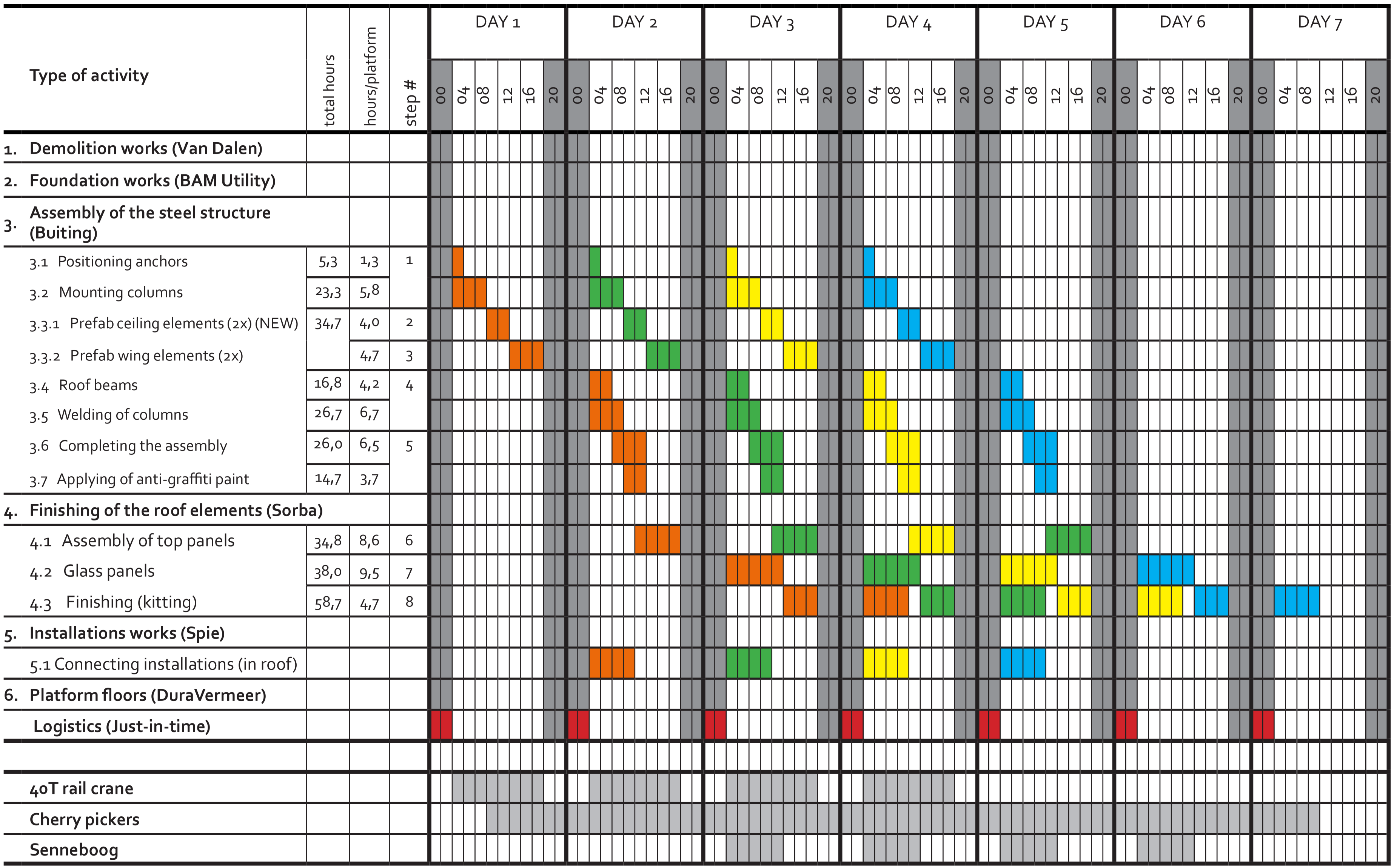


Figure 9.15 *The new (two-hour-block) Lean planning schedule concerning the workflow of the four standard elements (lead times are based on figure 9.14)*

Effort

As can be seen in the workflow model, effort can be divided into (direct) operational costs and (indirect) management cost. These cost are (re)calculated for the current and improved design by which the equipment costs and the management costs are calculated in accordance with the new developed planning schedule of figure 9.14. Due the project SIA contain a total of four platforms, the potential savings in effort must be multiplied by four as a result of the new design.

Operational costs

A total of 21.800 euro will be saved on operational costs (see table 9.16) concerning the affected type of activities. Although the largest amount of cost associated with the assembly of sub-construction and aluminium panels has inclined with 73% (from 59.800 to 18.100), the relative high rental price of the rail crane (required for positioning the doubled number of prefab elements) is retaining the total savings for operational costs by 10%.

Management costs

The savings in management costs (see table 9.17) are more difficult to estimate. The only proper calculations can be made for the building site costs. The building site cost (exclusive the side cost concerning the utility discipline, without general equipment needed by the contractor combination) will be cut in half equally to the lead time on-site, focussed on the standard platform elements only. This has a significant impact on effort, saving 126.000 euro over a total of four platforms. The (unknown) building site costs for the off-site pre-assembly will have no significant impact on costs since all necessary facilities and equipment will be moderated by the co-makers' production facility.
The cost for management staff is too diverged for proper estimations. Although the potential savings are not directly measurable in numbers, the improved state will have a substantial decline in management activities equally to the reduction of lead time.
The costs for 'Design and engineering' will have no substantially differences since the amount of input in the design process is in general the same, only the output of its design is different.

OPERATIONAL COSTS				CURRENT STATE			IMPROVED STATE			Difference	
(direct)	pcs.	euro	/unit	hours	days	euro	hours	days	euro	abs.	rel.
3.1 **Prefab wings**						**11.401**			**22.323**	**10.922**	**+93%**
workers ON	5	50	/hour	17,3		4.325	34,7		8.675	4.350	+101%
rail crane	1	197,5	/hour	32,0		6.320	64,0		12.640	6.320	+93%
cherry pickers	2	126	/day		3	756		4	1.008	252	+33%
4.2 **Sub-constr. & panels**						**59.811**			**41.685**	**-18.126**	**-30%**
workers ON	5	50	/hour	129,0		32.250	34,8		8.700	-23.550	-73%
workers OFF	5	30	/hour	153,5		23.025	219,9		32.985	9.960	43%
cherry pickers	4	126	/day		9	4.536		0	0	-4.536	-100%
Total operational costs						**71.212**			**64.008**	**-7.204**	**-10%**

Table 9.16 Operational costs (single platform): only for the affected type of activities

MANAGEMENT COSTS			CURRENT STATE			IMPROVED STATE			Difference
(indirect)	euro	/unit	hours	days	euro	hours	days	euro	rel.
Management staff	u.k.	payment							-/-
Building site									
ON (exclusive utility)	4500	/day		14	63.000		7	31.500	-50%
OFF (co-maker plant)	u.k.	/day							-/+
Design & engineering	u.k.	payment							-/+
Total management costs									-/-

Table 9.17 Management costs (single platform)

9.5 Assembly guideline

This paragraph can be seen as an 'assembly guideline', linked to the assembly of an IKEA furniture item. As a consequence of the redesign, transforming the process from craft work into assembly only, a visualization of the improved workflow will be presented. The roof structure will be assembled according to the fourth central aspect of Lean production namely 'establish pull production': producing (assembling) only that what is directly needed in the next process step. The following steps are based on the developed planning schedule (see figure 9.15).

Step 1: V-Columns - The construction of the 'standard elements' will commence after the former roof structure is demolished and the prefab foundation consoles are placed by BAM with the use of the rail crane. After positioning the anchors on the right level, the V-columns will be positioned on the concrete consoles.

Step 2: Ceiling-elements - The ceiling-elements will be positioned on the columns using the rail crane. A supporter in the middle, positioned on the ground, is acquired for temporary stability of the first element during assembly of the second. The two ceiling elements will be attached in the middle using a temporary assembly device to avoid damaging of the elements during assembly. Additionally on both sides a (reinforced) roof beam will be assembled to catch up the tensile stress by assembling the wing-elements in the next step.

Step 3: Wing-elements - The wing elements will be positioned with high accuracy using two special developed assembly devices (the same as used in step 2). These devices are mounted on the honeycomb beams of the ceiling elements in shortly in advance. The rail crane will lift the wing-elements near the final position where a secured team on the roof is able to couple the elements to the assembly-devices. The elements will slowly be lowered on the columns guided by the supporters. This will ensure proper installation on the columns along side the ceiling elements (guide margin is 3cm). Additionally this application will prevent damaging the ceiling panels attached to both elements. At this point parallel work under the roof can be initiated since all remaining assembly work considering the roof can be done from top of it.

Step 4: Roof beams - The roof beams will be installed from top of the roof. The wing elements will function as temporary scaffolding since they are calculated for maintenance work. Temporary plating material will protect it for damaging during assembly of the roof beams. The beams will be lifted on the roof from where the crew can bolt all the cross beams in between both sides. When all structural components are bolted, the prefab elements and the columns will be welded together in the final position.

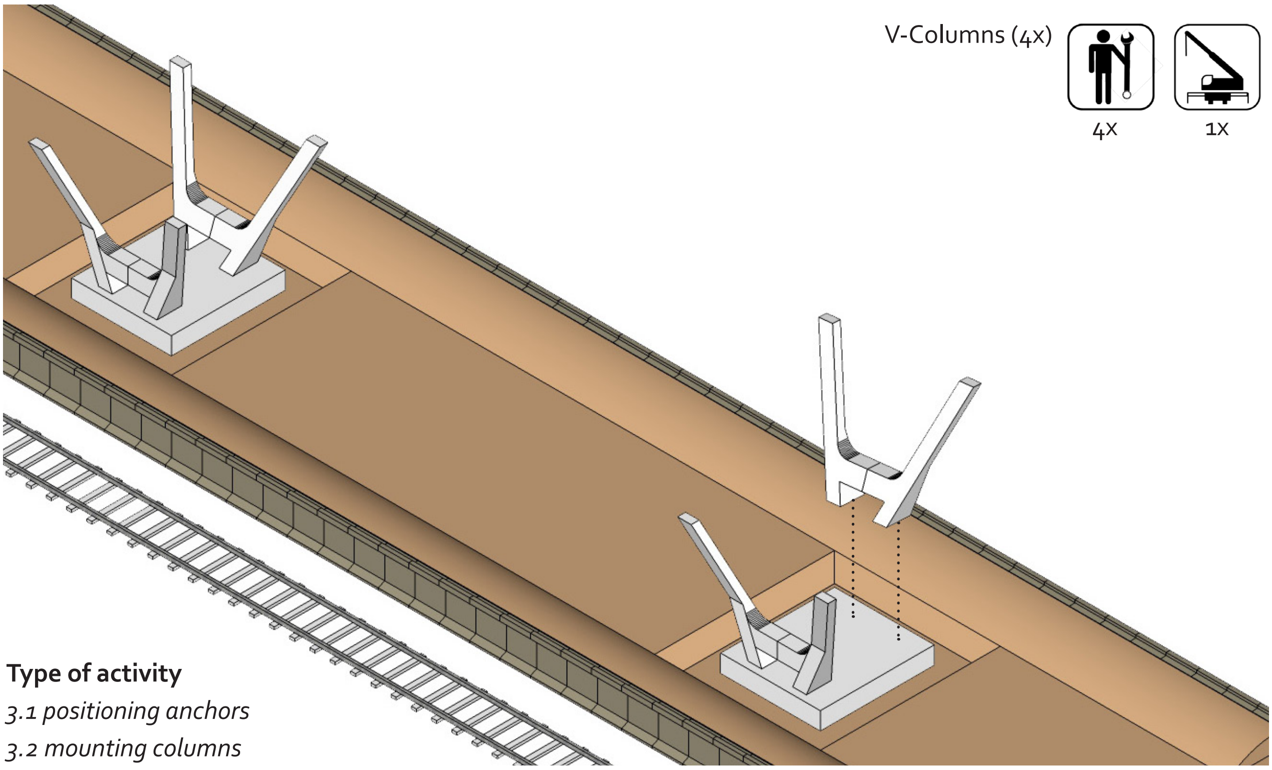
Step 5: Assembly completion - After finishing all the structural work nearby the columns, the ceiling can be completed by assembling the remaining aluminium panels. Additionally the prefab elements will be connected in longitude direction by attaching the honeycomb beams together using coupling plates in between.

Step 6: Top panels - After mounting all structural components (and connecting all wiring and piping systems integrated in the roof) the top of the roof will be covered with aluminium panels. These panels will be assembled from top of the roof by a secured team of assembly workers.

Step 7: Glass - All the glass panels will be installed on the roof beams using a (smaller) rail crane together with special glass lifting equipment.

Step 8: Finishing - In the end the roof structure will be completed by finishing the sky light and installing the remaining components if necessary. This could be done outside an out-of-service periods if necessary, depending on the time needed for connecting and checking all the electrical facilities.

STEP 1: V-columns | Requirements

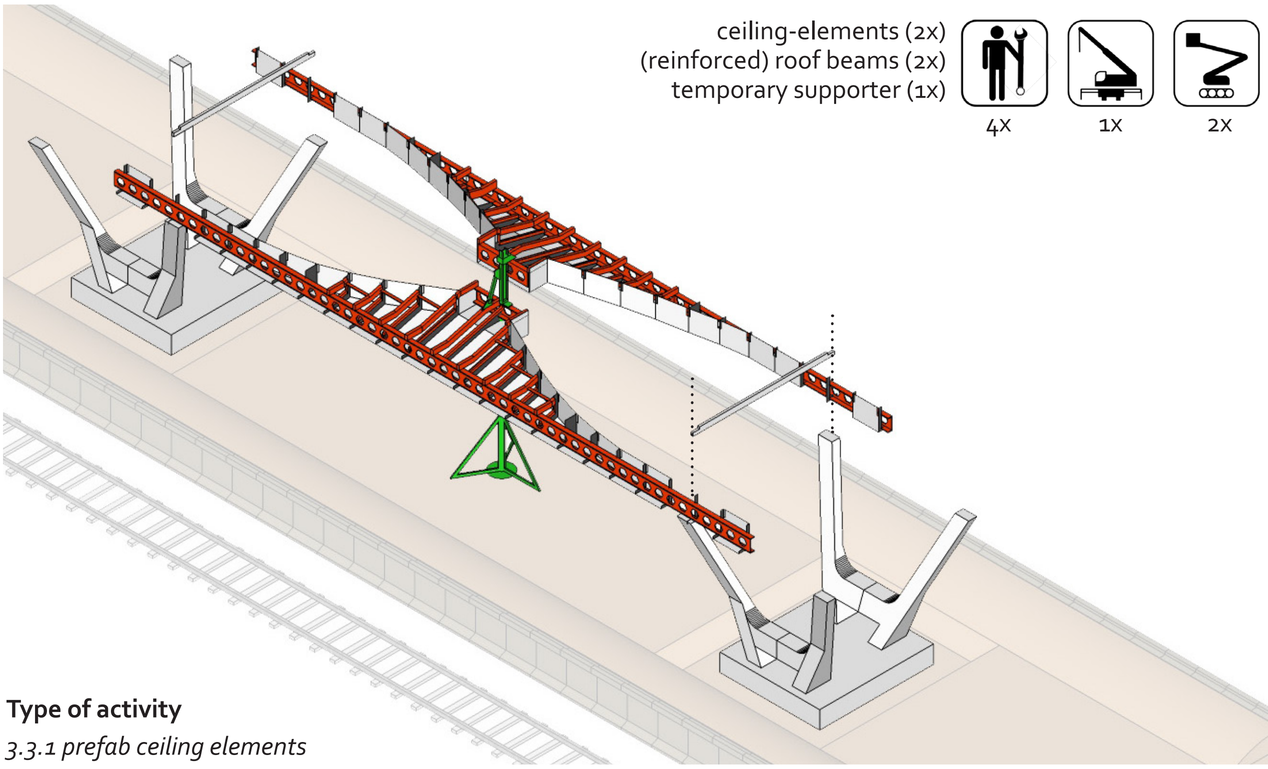


Type of activity

3.1 positioning anchors

3.2 mounting columns

STEP 2: CEILING ELEMENTS | Requirements



Type of activity

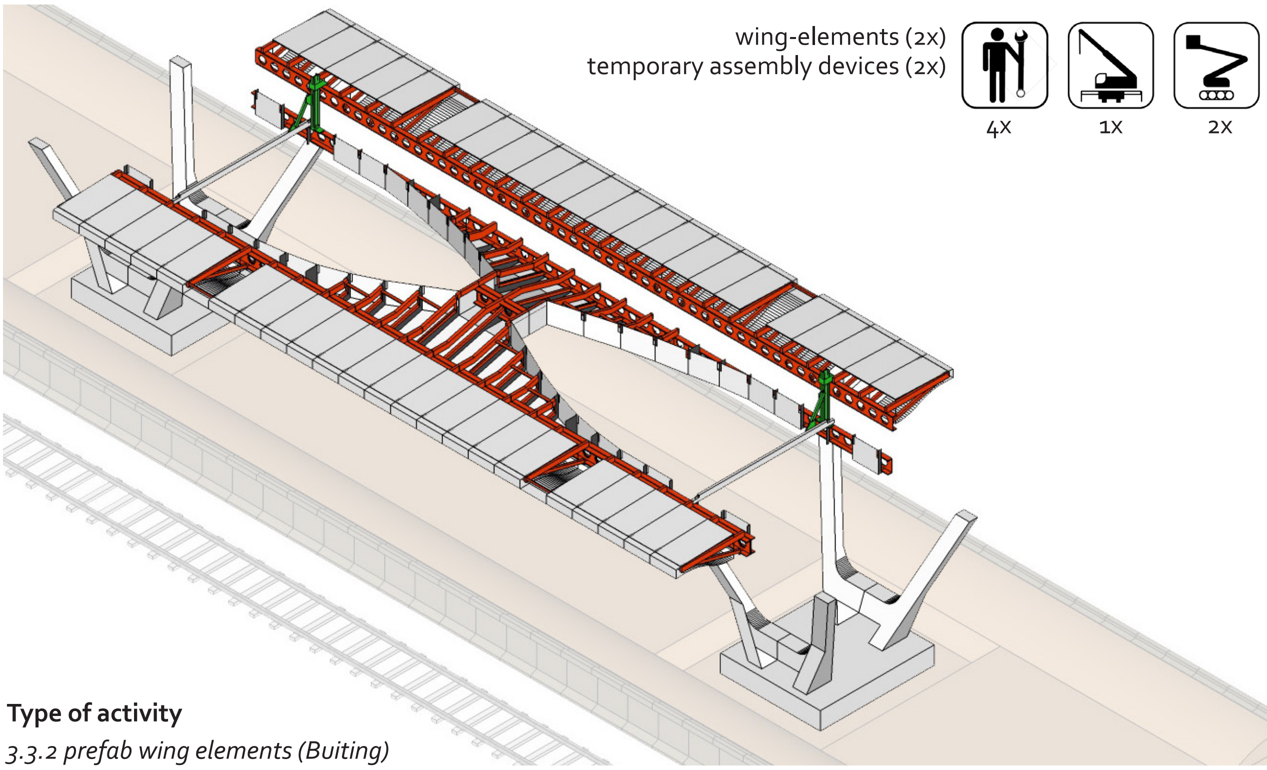
3.3.1 prefab ceiling elements

STEP 3: WING ELEMENTS

Requirements

wing-elements (2x)
temporary assembly devices (2x)

4x 1x 2x



Type of activity

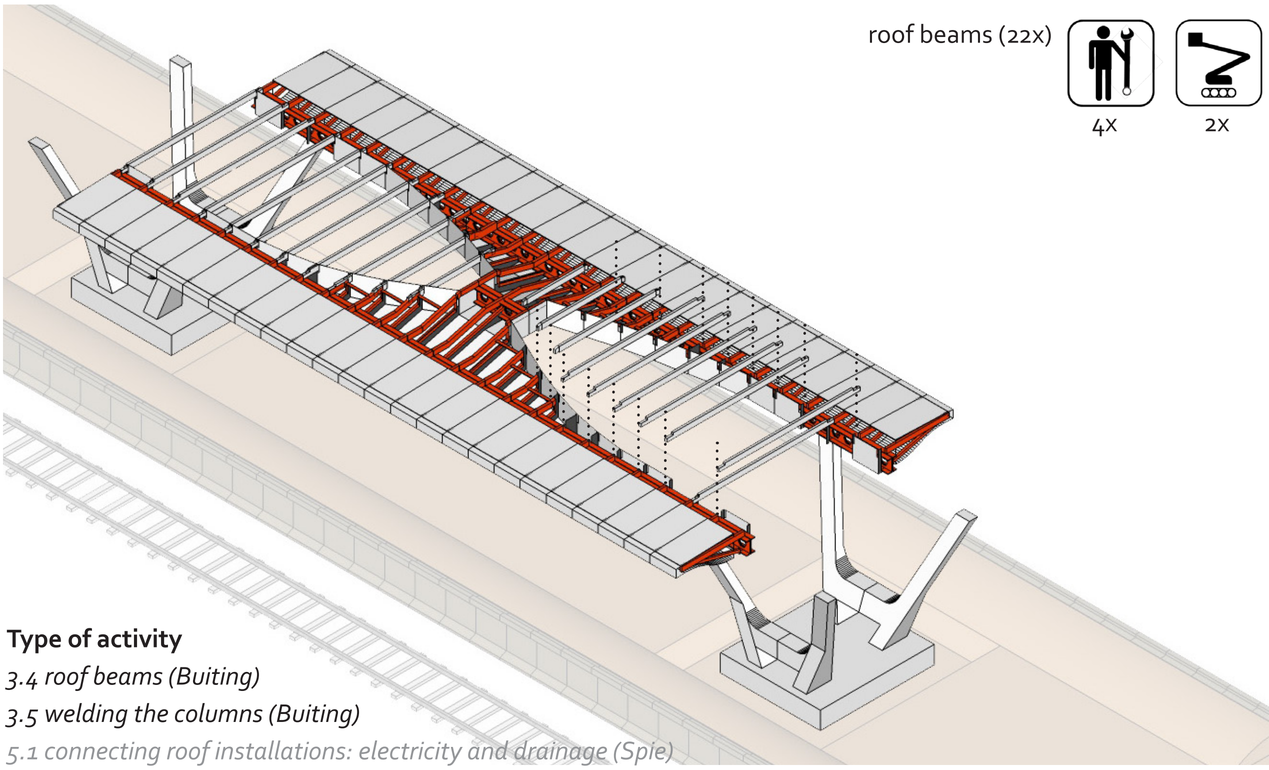
3.3.2 prefab wing elements (Buiting)

STEP 4: ROOF BEAMS

Requirements

roof beams (22x)

4x 2x



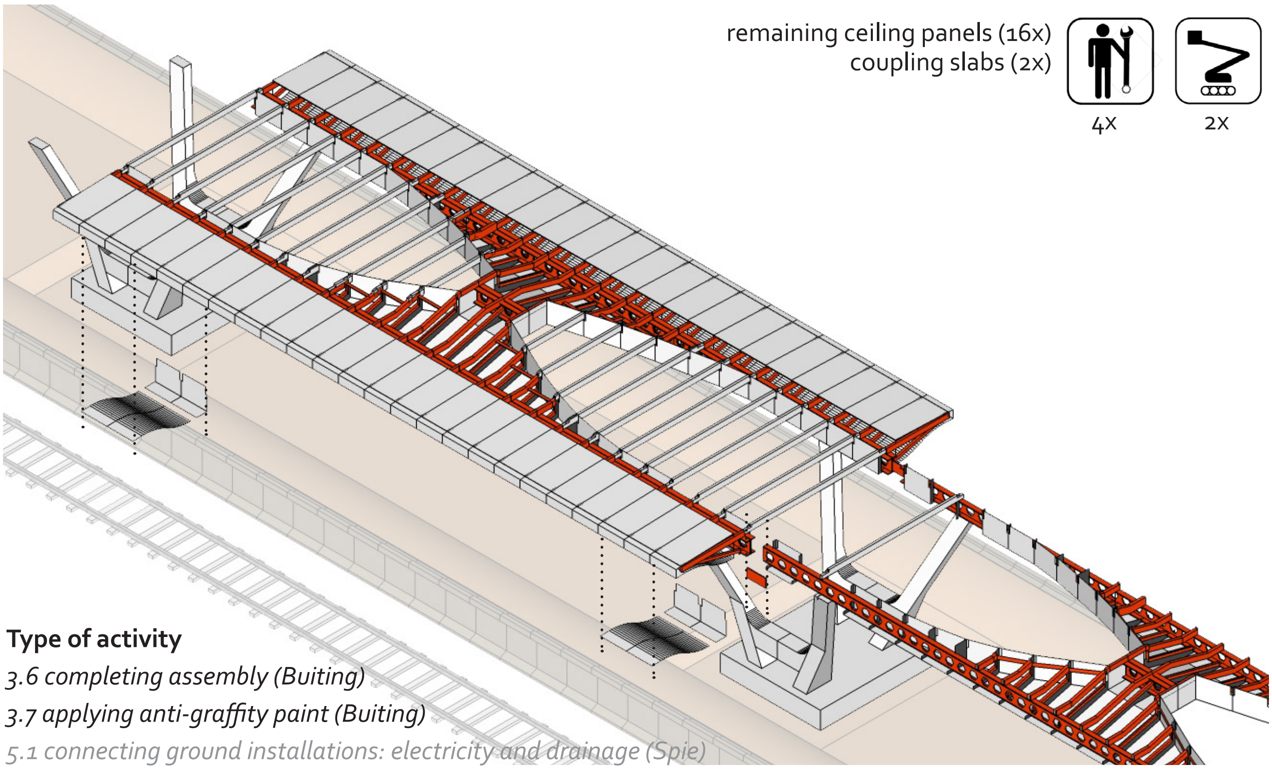
Type of activity

3.4 roof beams (Buiting)

3.5 welding the columns (Buiting)

5.1 connecting roof installations: electricity and drainage (Spie)

STEP 5: COMPLETING ASSEMBLY — Requirements



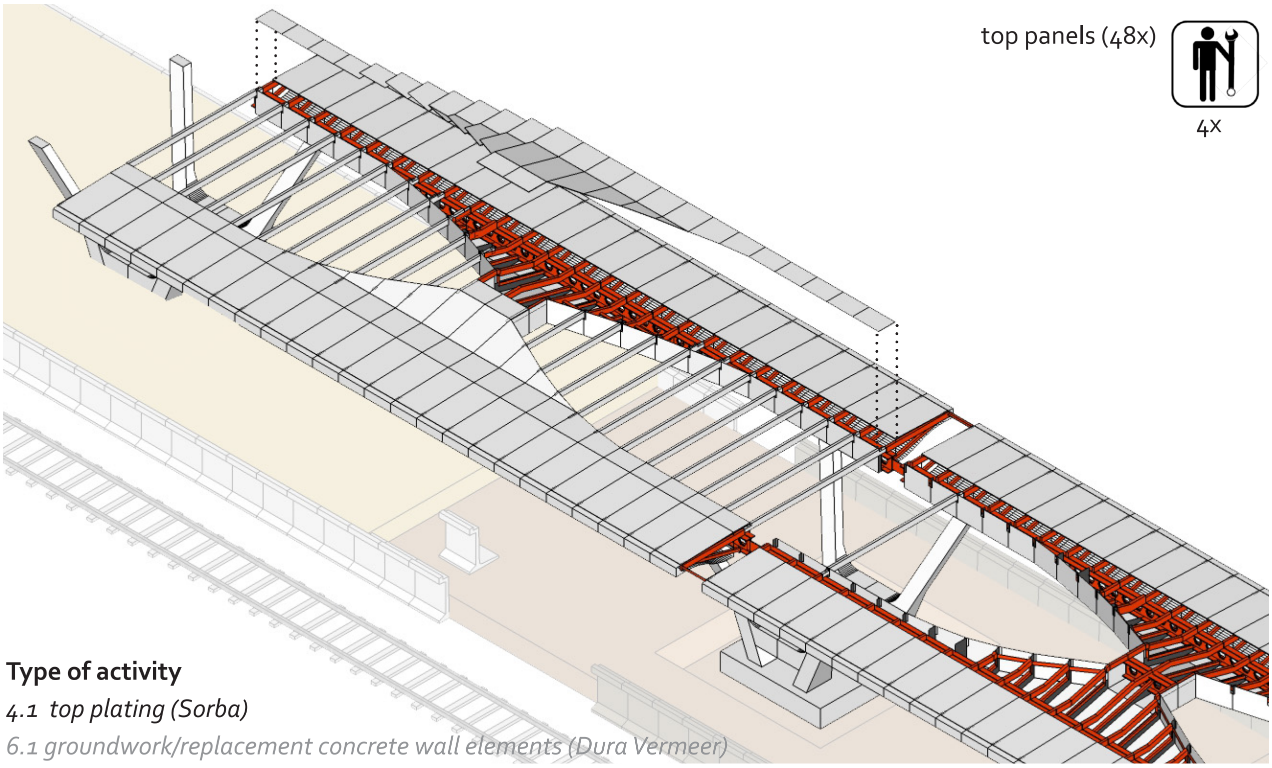
Type of activity

3.6 completing assembly (Buiting)

3.7 applying anti-graffity paint (Buiting)

5.1 connecting ground installations: electricity and drainage (Spie)

STEP 6: TOP PLATING — Requirements

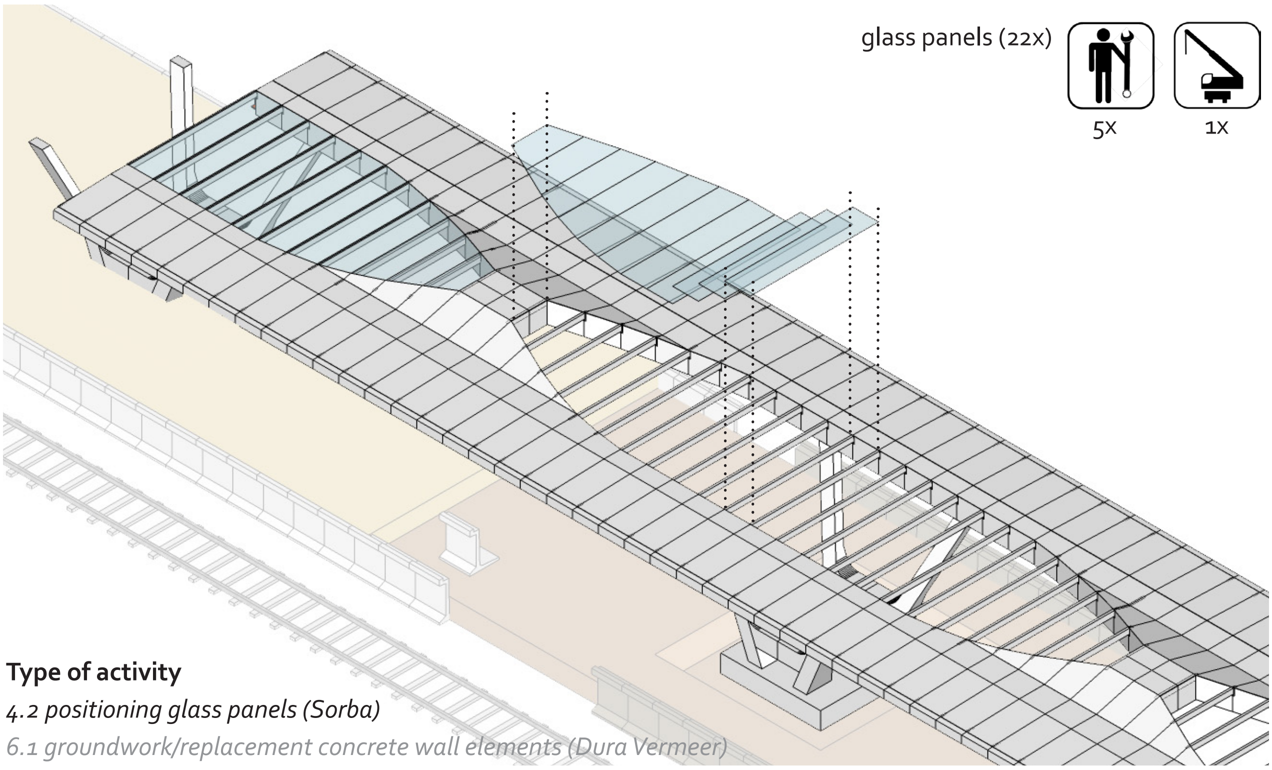


Type of activity

4.1 top plating (Sorba)

6.1 groundwork/replacement concrete wall elements (Dura Vermeer)

STEP 7: GLASS Requirements

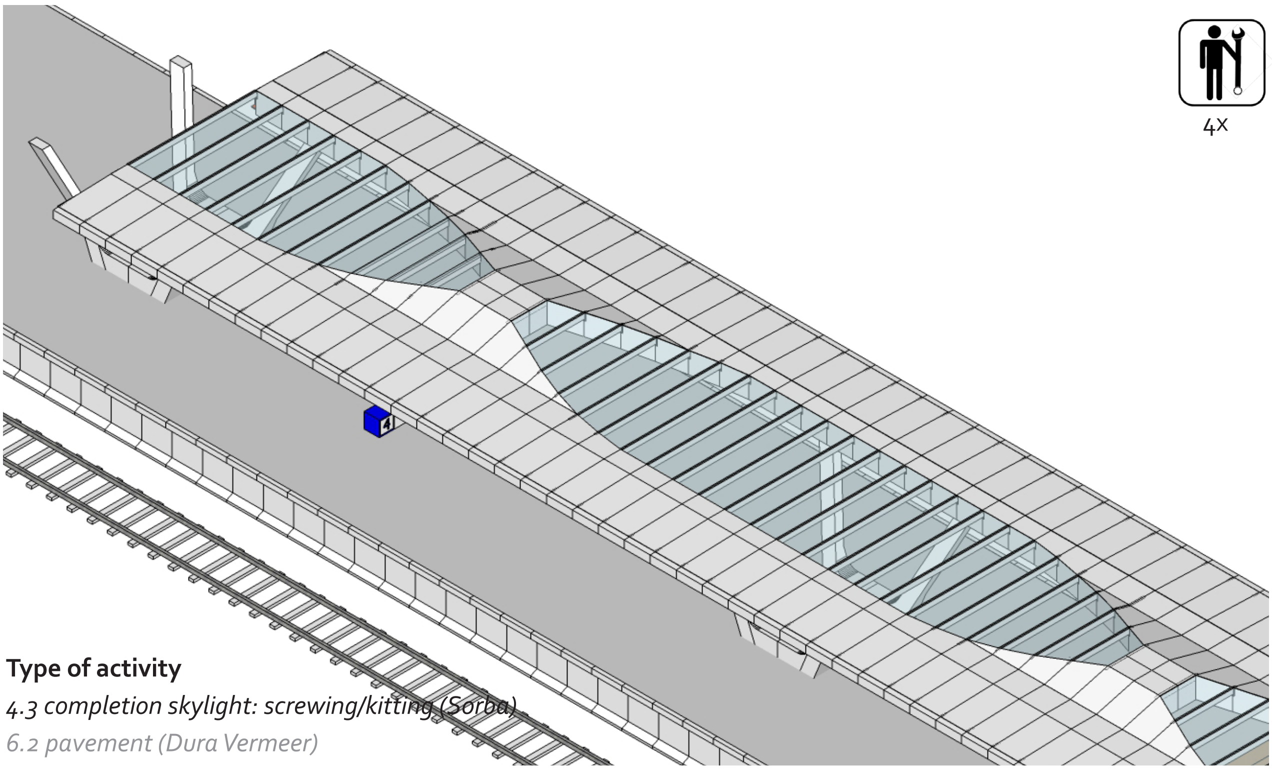


Type of activity

4.2 positioning glass panels (Sorba)

6.1 groundwork/replacement concrete wall elements (Dura Vermeer)

STEP 8: FINISHING Requirements



Type of activity

4.3 completion skylight: screwing/kitting (Sorba)

6.2 pavement (Dura Vermeer)

10. Design results

In the previous chapter a redesign has been presented as a solution for improving workflow according Lean construction. With the developed Lean design significant improvements can be made by eliminating waste with pro-active solutions. This chapter will present the conclusions regarding the workflow improvements according to the workflow model.

10.1 Results improved workflow

The new design, which is based on the concept of 'design for construction' following the product strategy, has improved the workflow drastically by eliminating much waste identified in the field research. A significant reduction of resources material, time and effort is achieved, without misdealing the architectural quality of the end product.

The wasteful craft work associated with the assembly of the ceiling has been eliminated from the process as much as possible by integrating these materials and components in more elaborated prefab ceiling-elements. As a consequence of this transformation, the craft work needed on-site for this particular assembly work is reduced with 73%. Together with a duplication of work positioning the prefab elements on the columns, the total on-site lead time for completion of the roof structure has a significant incline: from an average of 14 days in the current state to only 7 days in the 'improved state'.

Looking to the operational costs in the improved state, the effort needed for the assembly of the ceiling is inclined with 30% due transfer of this work to manufacturing environments. In spite of the raise for the (relatively high) costs for the rail crane by 93%, used for positioning the prefab elements, the total operational cost is reduced with 10% for these standard elements. Over four platforms this will lead to a saving of 21.800 euros.

The management costs are more diverged and therefore difficult to estimate. Only the building site costs can be estimated and will be inclined with 50% equally to the lead time. This will save a total of 126.000 euros over four platforms. In addition to significant lead time reduction, management activities will be simplified by the greater use of prefabricated components and the improved workflow.

Design implications

According the Lean philosophy focus should be moved to the whole process, instead of sub-optimizing an individual resource or particular process. Due the practical application this solution has a narrowed scope focussing only on the standard element design, otherwise the secondary problems within the entire case study project SIA would grow exponentially.

10.2 Discussion

Literature stated that design decisions made early have a major impact on the utilization of resources (material, time, effort) during execution and ultimately on the cost price. Reflecting this to case study research, the statement from literature is legitimate that architect often lacked the knowledge of constructability to make the right decisions. By analysing the evolution of the 'standard element' design, first by the architect, then by the co-makers and finally with the development of this recommended Lean design, it becomes clear that the use of the resources can be declined drastically by taking constructability in consideration. Improving constructability will reduce the on-site waste in a pro-active way.

Implementing knowledge from co-makers in the early design stages will improve the constructability and ultimately the value for money. When this knowledge is not available or inappropriate, the developed workflow model can help to estimate the input of the acquired resources.

During elaboration and assessment of the developed Lean design, it became clear that the resources are highly interrelated. For improving workflow an overall solution is required, concerning the general input of material, time and effort.

Since the context of future construction is generally situated in urban environments, reliable planning becomes more crucial: time and space will be scarce. Therefore the use of resources will be more important in future construction projects.

The implementation of Lean design, together with various Lean construction techniques, will improve both the quality of the product (design) as well as the process in which it is achieved. This will ultimately create more added value for the end customer, general contractor and co-makers.

"There is nothing so useless as doing efficiently that which should not be done at all."

Peter F. Drucker

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Interviewed project participants

- N.B. (Niels) Scholten — tender manager project Sporen in Arnhem (SIA); BAM Utiliteitsbouw (Arnhem)
- E.G.B. (Erik) Willemsen — chief site manager SIA; BAM Utiliteitsbouw (Arnhem)
- H. (Harm) Claus — project engineer SIA; BAM Utiliteitsbouw (Arnhem)
- M.F. (Micheal) Huisman — project engineer SIA; BAM Utiliteitsbouw (Arnhem)
- M.J. (Michael) Veenbrink — project engineer SIA; BAM Utiliteitsbouw (Arnhem)
- B.S. (Ben) Nagengast — project engineer SIA (logistics); BAM Utiliteitsbouw (Arnhem)
- F.J.H. (Ferry) Stoots — project administrator SIA; BAM Utiliteitsbouw (Arnhem)
- R. (Renko) Landeweert — project manager co-maker SIA; Sorba Projects (Winterswijk)

Figures

Figure	Source
frontpage	Presentatie Bouwend NL, juni 2012
2.1	http://www.alicon.nl/images/Lean30_FordIntAssembly1913.jpg
3.1	Edited from: Höök, M., Stehn, L., 2008. Applicability of Lean principles and practices in industrialized housing production. Construction Management and Economics 26, 1091–1100.
4.2	Edited from: Simonsson, P., Björnfot, A., Erikshammar, J., Olofsson, T., 2012. "Learning to see"the Effects of Improved Workflow in Civil Engineering Projects. Lean Construction Journal 2012 pp 35-48.
4.3	http://fundunet-technology.blogspot.nl/2011/05/airbus-380.html
4.4	Edited from: Gannon, T., Feng, P., Sitzabe, W., 2012. Reliable schedule forecasting in federal Design-Build facility procurement. Lean Construction Journal 2012.
4.5	Edited from: Li, H., Guo, H., Skibniewski, M.J., Skitmore, M., 2008. Using the IKEA model and virtual prototyping technology to improve construction process management. Construction Management and Economics 26, 991–1000.
4.6	Handleiding Systems Engineering voor BAM Infra, werkgroep BAM, juni 2008
6.2	Definitief Ontwerp 'Perronkappen Sporen in Arnhem', UN Studio, maart 2009
6.3	Definitief Ontwerp 'Perronkappen Sporen in Arnhem', UN Studio, maart 2009
6.4	Presentatie Aandeelhouders BAM, sept 2011
7.8	Stripboek Lean planning stap 290, BAM
7.16	Presentatie Bouwend NL, juni 2012
7.17	Presentatie Bouwend NL, juni 2012
7.19	Fotoalbum SIA zomer 2010, BAM
7.22	Fotoalbum SIA zomer 2010, BAM
7.24	Fotoalbum SIA zomer 2010, BAM
9.1	Presentatie Aandeelhouders BAM, sept 2011
9.2	Fotoalbum SIA zomer 2010, BAM
9.4	Presentatie Bouwend NL, juni 2012

Appendices

This research report is provided with an attachment containing all the relevant appendices. These appendices are not included within this document due to the unsuitable amount and size of these files. All the relevant appendices, formulated below, could be consulted in the accompanied document 'Appendices'.

A. DOCUMENTATION

A1	Article: Cobouw interview hoofduitvoerder SIA
A2	Article: Nieuwsbrief van Dalen (juni 2011)
A3	Article: LCM and efficiency in the building process (Van den Bouwhuijsen)
A4	Tool: 'Parameters of efficiency' (Van den Bouwhuijsen)
A5	Overview: SIA elements (research focus)
A6	Report: SIA beschrijving fasering 2011
A7	Overview: fasering SIA (Buitendienststellingen)
A8	Report: Contract Alliantie - Systems Engineering (ProRail)
A9	Letter: Brief uitnodiging Lean Bouwen aan co-makers (BAM)
A10	Contract: Opdrachtbeschrijving co-maker (Sorba Project BV)
A11	Lean Planning: Stripboek stap 96 (voorbeeld pagina)
A12	Calculations: Begroting Sorba
A13	Calculations: DBK totaal
A14	Calculations: DBK recapitulatie stap 96; 190; 250; 290
A15	Calculations: ABK stap 96, 190, 250, 290
A16	Calculations: Uitbetaling boete-/bonusregeling

B. WORKFLOW CALCULATIONS (EXCEL SHEETS)

B1	Lean planning - stap 96
B2	Lean planning - stap 190
B3	Lean planning - stap 290
B4	Production planning - stap 96
B5	Production planning - stap 190
B6	Production planning - stap 250
B7	Production planning - stap 290
B8	Workflow data - stap 96
B9	Workflow data - stap 190
B10	Workflow data - stap 290
B11	Workflow data overview
B12	Price list - labour & equipment
B13	Calculations: Volumes sub-construction and panels
B14	Calculations: Manhours on-site (top vs. ceiling)
B15	Calculations: 'Current' and 'Improved' state

C. DESIGN (DRAWINGS)

C1	Design (Architect UN Studio)
C2	Preliminary design standard element (SE) (consultant Movares)
C3	Conceptual design (co-maker Sorba)
C4	Design standaard element (co-maker Sorba)
C5	Cross section roof structure (co-maker Sorba)
C6	Details sub-construction and alu. panels (co-maker Sorba)